

Design Considerations for a Stopped-Rotor Cyclocopter for Venus Exploration

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This paper considers the use of a cycloidal blade system as a means of providing lift and propulsive thrust as well as combined with a stopped rotor system, to create a stopped-rotor cyclocopter vehicle, during a mission to Venus. This stopped-rotor cyclocopter will be capable of flying at all atmospheric levels of Venus as well as landing on the surface for scientific investigation. Three reference conceptual designs with different stopped-rotor cyclocopter yaw angles are tested in RotCFD as well as a model of a hovering cyclorotor for comparison with past work in the literature and innovative study for future projects.

Nomenclature

C_D	Drag Coefficient
C_L	Lift Coefficient
C_P	Surface Pressure Coefficient
D	Drag, N
L	Lift, N
MAV	Micro Aerial Vehicle
t	Time, seconds
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take-off and Landing
V_{forward}	Forward (freestream) velocity m/s
ρ	Air density Kg/m ³
ψ	Azimuth angle, Degrees
	Wing Sweep
φ	Cyclorotor Yaw angle

I. Introduction

The use of UAVs have dramatically increased for private uses (e.g. drones filming your holiday), industrial uses (e.g. UAV delivery systems) and space mission uses (e.g. The Mars Helicopter for 2020). This is due to the advantages of low speed forward flight capabilities, VTOL and hovering. This project studies the cycloidal rotor system [1] which is an unconventional rotary wing that can be used for propulsion and VTOL. A cycloidal rotor has the ability to immediately change thrust direction by pitch angle variations of the rotating blades, enabling hover and forward flight competencies. It is different from conventional helicopters in that the axis of rotation is parallel to the blade span rather than normal to it. When also used as a stopped-rotor system this form of propulsion provides a unique capability for Venus exploration. This new UAV configuration is referred to as the stopped-rotor cyclocopter throughout this paper. Benefits of the cycloidal blade system over the conventional rotor systems are: they are not limited to speed and altitude, can provide 360 degrees of vector thrusting, which is favorable for good maneuverability, and have excellent hovering capabilities [2].

The novel aspect of this study is that no other cyclocopter configuration has been previously proposed for Venus, or any (terrestrial or otherwise) exploration application where the cyclocopter's rotating blades are stopped, and act as fixed wings. These design concepts will be analyzed with the computational fluid dynamics tool Rotorcraft CFD (RotCFD) [3], for aerodynamic assessment in the conditions present on Venus accounting for high temperature,

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pressure and atmospheric density while the cyclorotor is in the stopped position. [4] Other assessments include 3D rotation of the cycloidal blades represented by distributed momentum sources for comparison of RotCFD and other CFD tools.

Future exploration missions of Venus will help to understand the evolution of Venus' atmosphere and thereby the atmospheric evolution on Earth and the roles of aerosols and the greenhouse effect. This understanding could help prevent Earth from becoming another Venus in the future. This new knowledge will also assist in categorizing thousands of newly found exoplanets as either being like Earth, Mars or Venus.

The focus of this report is to begin the discussion of cyclocopter uses in space activities and missions and, further, asses multiple design configurations to clarify the potential capabilities of a stopped-rotor cyclocopter. The reason for implementing this vehicle type for a mission to Venus is because the atmosphere is so dense it may be easier to use and maneuver a cyclocopter, than a conventional rotorcraft to better withstand the vast winds and harsh environments that Venus has to offer.

A. The Atmosphere of Venus

Venus, the twin of Earth as it is often referred to, is believed to hold the key to understanding the future evolution of Earth's environment. It has similar size and mass to Earth and was thought to hold an abundance of moisture due to the high reflectivity of the clouds. After the detection of large quantities of carbon dioxide it was assumed that the Venus atmosphere had a runaway greenhouse effect early in its history and temperatures are now much hotter than Earth's. On the surface of Venus, the temperature is 740K and the pressure is 93bar. The upper atmospheric winds of Venus blow up to 100m/s, which is 60 times the speed of rotation of the planet, causing the entire atmosphere to circulate in only four Earth days. This wind speed decreases closer to the surface reaching only 2.8 m/s.

The atmospheric chemical composition consists of mostly carbon dioxide and nitrogen, while the clouds are sulphuric acid. Because of these clouds it is nearly impossible to observationally penetrate from Earth. The use of U.S. and Soviet probes has determined the surface composition and structure we know today.

In 1975, Venera 9, and later Venera 10, carried out studies of the atmosphere during probe/lander decent and found that there were three distinct layers of atmosphere: sulfuric acid cloud layer, troposphere and sulfuric acid haze layer. The atmosphere is split into sections depending on the altitude.

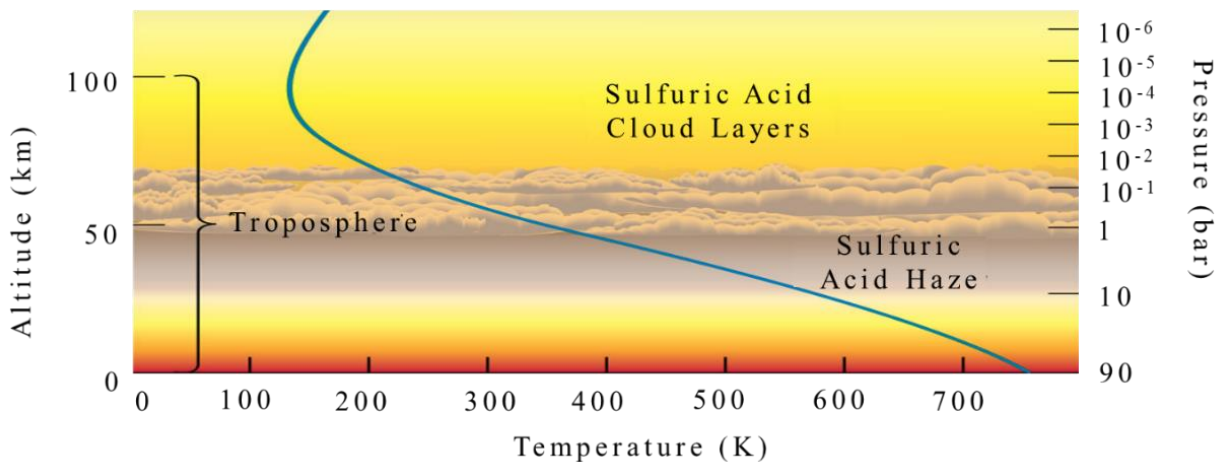


Figure 1: Structure of Venus's atmosphere [5]

The densest part of the atmosphere starts at the surface and extends 65km upwards; this is known as the troposphere. At the top of the troposphere the pressure and temperature are increasingly Earth like but winds move at very high speeds. The normal operational altitude for a conventional aircraft on Venus than on Earth (cruising between sea level and 24km) would be from 50km to 75km above the surface. At this altitude the temperature fluctuates from 350K, at 45km, to 200K at 70km. The acceleration due to gravity on Venus is slightly smaller compared to Earth since the atmosphere is approximately 60 times denser and therefore is easier for powered flight at low speeds. The performance depends on the density, as a function of the altitude, which is affected by barometric pressure, humidity and temperature.

B. Early Missions to Venus

Venera 4 (1967), was the first to return measurements of temperature, pressure and density from another planet's atmosphere and found that 90-95% of Venus's atmosphere consisted of carbon dioxide. It had taken measurements from an altitude of 55km for 93 mins. It was unable to travel lower than 25km because of the atmospheric pressure reaching 22bar. [6] It wasn't until 1970 that a successful landing on Venus occurred, measuring temperatures of 730K to 747K by Venera 7.

Venera 9 was the first orbiter of Venus which also, during the course of its mission, detached a 660kg lander which successfully landed on the surface on Venus and took the first picture of its surface whilst analyzing the crust with a gamma ray spectrometer and a densitometer. On the surface of Venus the average temperature is 740K and the pressure is 93bar.



Figure 2: First pictures of the Venus Surface from Venera 9 [7].

The probes Vega 1 and 2 reached Venus in 1985 each releasing both a balloon and lander. The balloons flew at around 53km above the surface for up to 60 hours. This enabled it to travel 1/3 of the way around Venus, which enabled the study of the most active parts of Venus' atmosphere in wind speed, temperature, pressure and density.

Since the Vega 2 balloon and lander in 1984 no other missions have flown or landed on Venus. Due to the harsh temperature and pressure of the planet's surface all these landers only last for tens of minutes but have been able to find rock samples similar to those on Earth. Subsequent proposals have been made for landing rovers and flying other aircraft in the lower atmosphere of Venus.

C. Proposed Venus Missions

1. VAMP (*Venus Atmospheric Maneuverable Platform*)

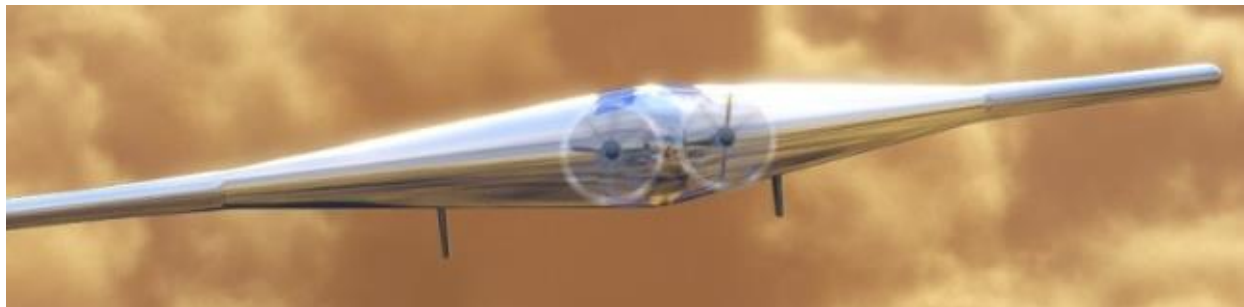


Figure 3: Venus Atmospheric Maneuverable Platform [8]

This proposed Venus mission consists of an inflatable plane with propellers which can cruise for up to a year on the planet, sampling data and observing the surface at 50-70km above the surface [9]. After entering the atmosphere the vehicle would fly in the upper and mid cloud layers to collect science data for transmission to Earth. The low ballistic coefficient of the vehicle means that atmospheric entry is achieved without a heavy aero shell. This allows it to carry a load of up to 100 pounds. [8]

2. *Venus Flagship Study.*

This proposed NASA Venus Design Reference Mission (VDRM) study assessed the science goals and investigations and identified a mission architecture for a possible launch between 2020 and 2025. This reference architecture includes Venus balloons, landers, orbiters and carriers, with hopes of revolutionizing the understanding of the climate of terrestrial planets and habitability of extrasolar terrestrial planets. It could also contribute to resolving the geologic history of Venus, including the existence of a past ocean. [10] Also the use of rotary wing decelerators has been studied for a Venus Mission in order for probes to land safely on the surface. [11]

3. *Venera D*

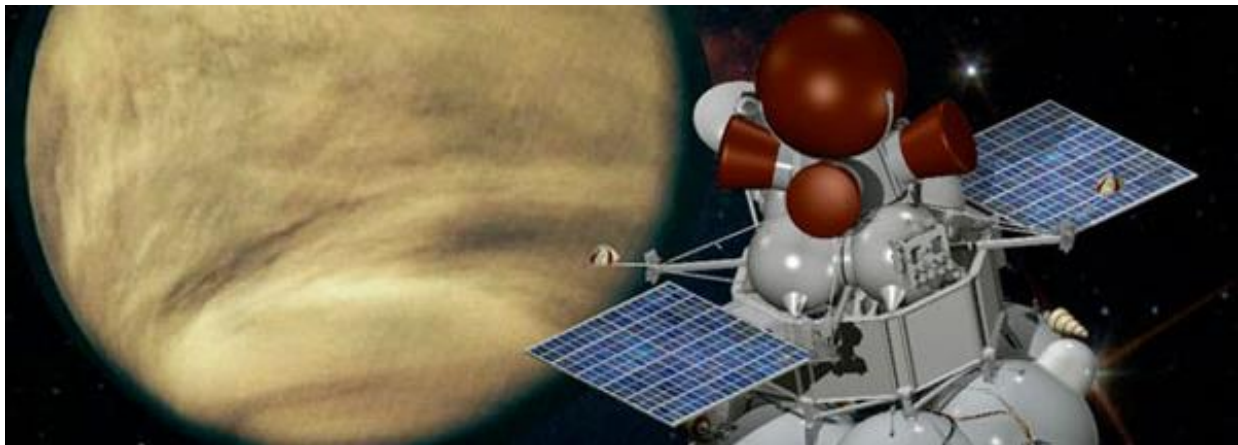


Figure 4: Venera D, Venus Mission [12]

The Venera D mission has been reopened for discussion since its first proposal in 2003 with Russia and NASA. It will involve a lander capable of surviving for a long duration on the surface and an orbiter to be launched around 2025. [12] The main purpose of this mission is to make radar remote-sensing observations around Venus which is similar to the missions of the Venera 15 and Venera 16 probes in the 1980s. This mission will also help to map future landing sites.

II. Mission Concept

This project focuses on a proposed mission to Venus, which would gather further information of all layers of the Venus atmosphere as well as the surface by using a capable novel design. The main purpose of doing this would be to learn more about the atmospheric composition of Venus and the surface chemical composition.

A. Mission Aims

- Gather scientific data on the atmosphere at multiple altitudes
- Gather scientific data on the surface of Venus

B. Mission Objectives

The objectives of the missions are:

- Interchange from high to low altitudes on Venus which will allow for deep radar penetration of the surface as well as atmospheric sampling.
- Find appropriate surface sampling areas via vertical take-off and landing.
- Mission capable of lasting days on the surface of Venus, not hours.

C. Design Considerations

The design considerations of the novel aircraft will include:

- The temperature and pressure difference between the surface of Venus and the entry altitudes.
- The vast wind speeds in higher altitudes.
- Lower wind speeds in lower altitudes.

The temperature and pressure on the surface of Venus does pose as a difficulty for this mission but further study is required for these considerations. This study is purely based on the use of stopped-rotor cyclocopters and their advantages for use on Venus or other planetary missions. The combination of a stopped rotor and cyclocopter is novel in itself and is likely easier to implement than a stopped rotor using a conventional helicopter-type rotors.

D. Mission Description

The following describes the different stages of the Venus Mission shown in Figure 5 as well as when the cyclocopter will be used:

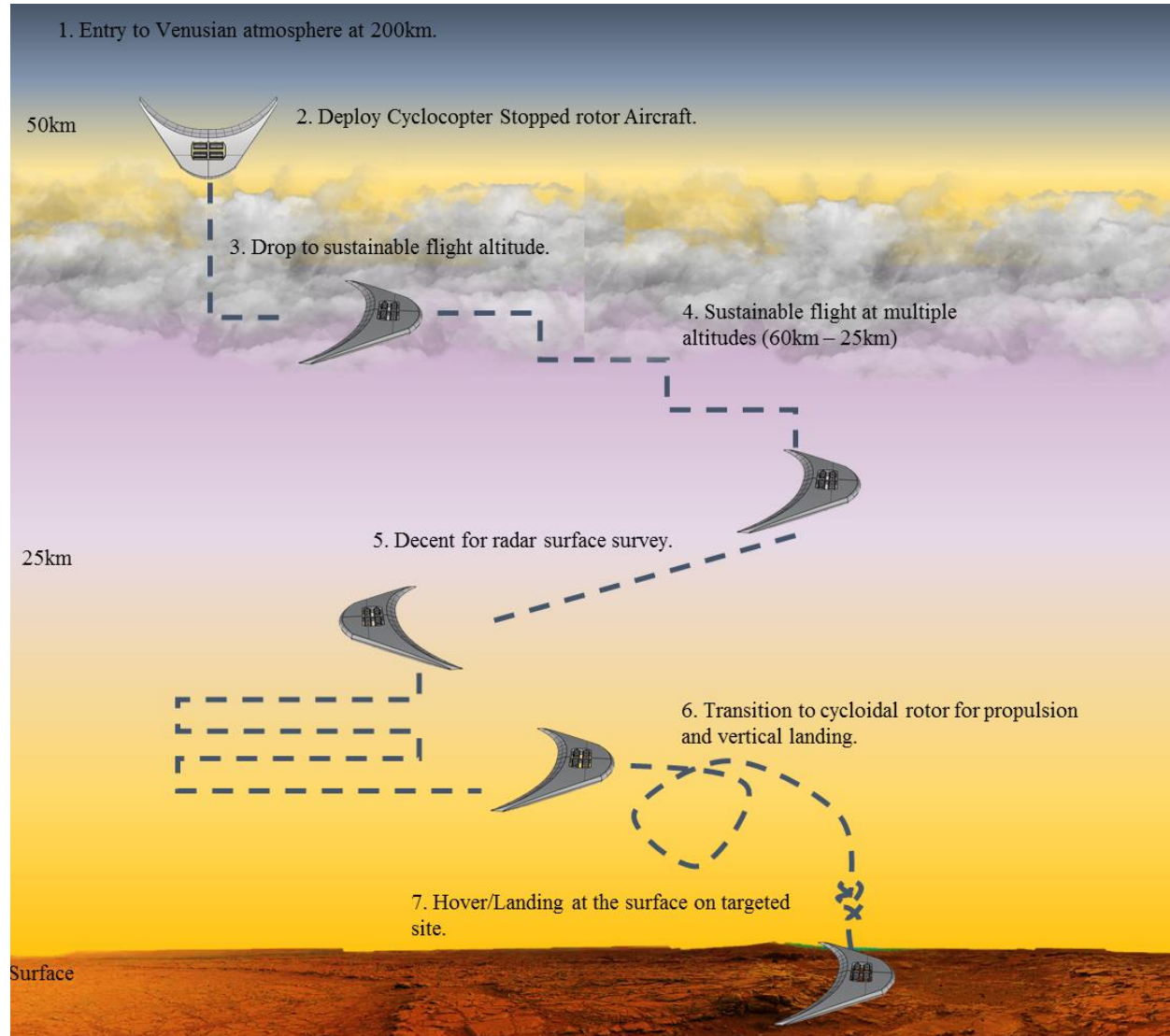


Figure 5: Mission Description

1. The atmosphere of Venus is entered at 200km from the surface.
2. The Cyclocopter Stopped rotor is ejected.
3. The Cyclocopter Stopped rotor will drop/glide to the suitable altitude for higher atmospheric measurements and flight.

4. The Cyclocopter Stopped rotor will continue to descend to an altitude of 25km above the surface while taking measurements.
5. The Cyclocopter Stopped rotor descends for radar measurements of the surface of Venus.
6. The cyclorotors are switched on and allow for rotor propulsion and surface scouting for landing sites.
7. The Cyclocopter Stopped rotor uses the cyclorotor for hover and vertical landing onto the designated landing site for surface measurements. The Cyclocopter Stopped rotor will then use the cyclorotor for vertical take-off once surface measurements are complete.

III. Design Heritage

A. Fixed Wing vs Rotary

For this mission to Venus it is important to justify how the aircraft will meet the specific requirements of the mission. This means that all possible types of aircraft for planetary exploration will need to be identified before a decision on the best design can be made. There are two main types of UAV that are available for planetary exploration such as fixed wing and rotary. Fixed wing UAVs have a simpler structure and the advantage of longer flight durations at higher speeds which makes them ideal for aerial mapping and modelling of larger areas. [13] The disadvantage of using a fixed wing is that they need more space to take off and land which isn't guaranteed on another planet. They also rely on continuous forward movement to create lift.

In comparison with the fixed wing type of UAV the rotary blade system is more complex and generally has shorter flights at lower speeds. Advantages of this system are the ability for vertical takeoff and landing, can fly in any direction and hover in a fixed position. This makes it perfect for detailed inspection on a single target for extended periods of time and maneuverability in tight and hard to reach areas. They also have a larger flexibility on payload type. [14] [13]

B. Stopped Rotors

Stopped rotors are designed to act as a fixed wing during forward flight. When stopped, they provide some, if not all, of the lift. This system can be used for vertical flight and hovering. When in forward flight it can be stopped to act as a fixed wing. Other rotors and propellers can be added to stabilize the aircraft. Much research has been done on stop rotors including the research done by the US Naval Research Laboratory (NRL) and StopRotor Technology Pty Ltd, Australia, who have created a prototype which has been tested in transition flight. A stopped rotor concept will be implemented in the design for this mission to Venus. It will allow for stable travel through the harsh winds and save power during the mission.

C. Cyclorotor Flight

The cyclorotor, also known as the cyclogyro [15], is the main type of UAV rotary system to be explored for this mission to Venus. This system can use two or more rotating blades rotating about the axis parallel to the blades to create lift, propulsion and control of the aircraft. The difference between the cyclocopter and a normal helicopter rotor system is that they are not subject to the same disadvantages such as speed and altitude limit and can also provide 360 degrees of vector thrusting which is favorable for good maneuverability. The airfoils on the wing are either adjusted in the positive pitch direction collectively, or individually by the control system to enable forward thrust and lift. The adjusted pitch can also change the thrust profile which enables the cyclocopter to move in any direction. The disadvantage of this system is that the structure can be heavy to support the blades and the control mechanism can be complex.

Figure 6 diagram shows a typical cyclorotor and its direction of rotation about the central axes. This creates a constant velocity at high speed forward flight.

Figure 8 shows the typical pitching motion of the blade during rotation. In the top and bottom positions the blade produces an upward force whereas the blades on the left and right produces a small amount of force due to little angle of attack. In order to produce the propulsive forces needed for forward flight the leading edges of all blades must be directed in the forward direction.

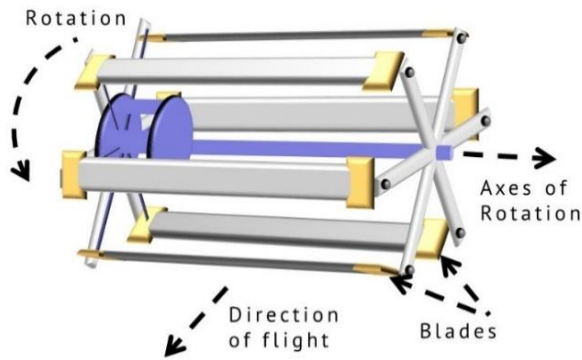


Figure 6: Cyclorotor blade rotation

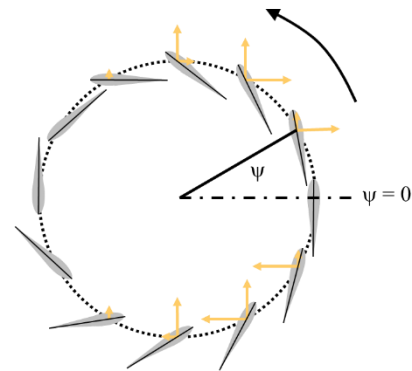
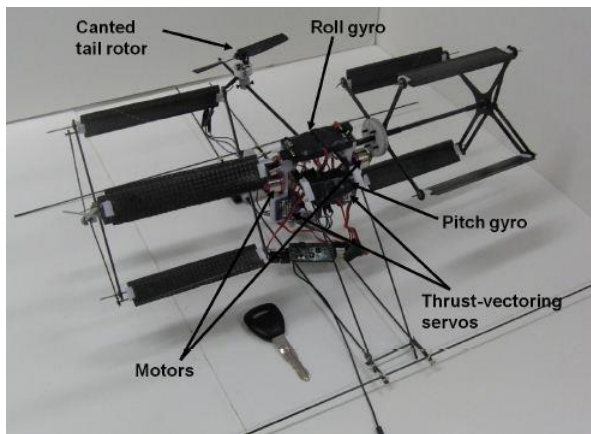


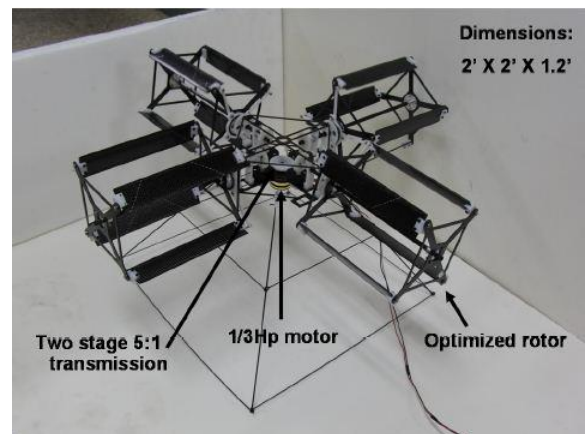
Figure 8: Blade pitch angle variation during a revolution of a cyclorotor. [2]

D. Types of Cyclocopter

The cyclocopter has been developed in the University of Maryland and demonstrated the first stable flight of a cyclocopter MAV. This used two 1-inch diameter rotors side by side and a tail rotor for pitching stability. They have developed this cyclorotor system using carbon fiber and titanium applied to a quad cyclocopter and twin cyclocopter and successfully demonstrated them hovering in a stable position. [16] The research at the university initially indicates that the horizontal axis propulsion is aerodynamically more efficient than the existing helicopter design because of its maneuverability and ability to rapidly change thrust.



(1) Twin Cyclorotor



(2) Quad Cyclorotor

Figure 9: Twin Cyclorotor and Quad Cyclorotor [17]

These figures show the two current types of cyclorotor that has been built and tested. The twin cyclorotor and the quad cyclorotor. The twin design needs a tail rotor for stabilization and directional changes whereas the quad design does not and uses all four cyclorotors for forward and backward thrusts as well as direction changes and hovers.

E. High to Low altitude flight and landing

High and low altitude flying on Venus will require different characteristics of the vehicle. For instance, in the high altitudes of Venus the environment is much like Earth's apart from the incredibly high wind speed. In lower altitudes there are much lower wind speeds but factors like high temperature and pressure will need to be taken into account. Due to the density of the atmosphere at lower altitudes a cyclocopter rotor would be better fitting for vertical take-off and landing.

IV. Design Space

The design considerations for this Venus mission aircraft will include a cycloidal rotor and a stopped rotor system. A cyclorotor has the ability to change the direction of thrust instantly by periodic pitch angle variations, and this characteristic enables a cyclocopter to hover and fly in forward flight [2]. There are multiple ways of implementing a cycloidal rotor onto an aircraft and the most popular are deemed to be twin rotor systems and quad rotor systems. Even though the idea of cyclorotors has been around since 1927, successful flights only began from 2007 after the concept was introduced to UAV. The University of Maryland has successfully built and tested a cyclocopter.

Cyclorotors can also be used in multiple orientations. When applying the stopped rotor system the ideal is to create the least amount of drag possible. By orientating the rotors in line with the air vehicle body and the freestream this will reduce drag but impact forward motion capabilities. An additional tail rotor may need to be added for stability.

Cyclorotor blades normal to air freestream are another option and enable forward propulsion capabilities. In order to prevent these rotors creating excessive drag once stopped, a fixed surface area can be designed around the rotors, diverting airflow over the top of the rotors rather than through.

Other design considerations can include hybrid and parasite flyers where the fixed-wing vehicle is separated from the cyclocopter when no longer in use. This is dependent on the need for vertical landing and take-off. The mission requires this for surface measurements but in the case of a onetime landing it may be beneficial to save power and implement a gliding system for the remaining mission time.

A way of analyzing these two systems is a two parameter design characterization which can be implemented by considering the fixed wing and cyclorotor combination where the relative sweep of the cycloidal rotors can be varied with respect to the fixed wing sweep.

A. Previously Proposed Hybrid Fixed-Wing/Cyclocopter Vehicles

Listed below are proposed air vehicles with cyclocopter usage for propulsion capabilities. Each of these has a different cyclorotor usage to fixed wing surface area ratio which corresponds to the requirements of the aircraft:

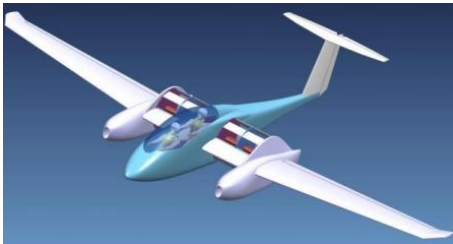


Figure 10. Cycloplane (Pascoa, 2014)

The project ‘Cycloidal Rotor Optimized for Propulsion’ (CROP) designed uses for cyclocopter rotor blades in conventional air vehicles. This Cycloplane in Figure 10 showed that the presence of the wing increased the rotor efficiency during the analysis. This was due to the creation of trailing vortices. [18] Rotor mostly used for take-off and landing only. Rotors are stopped when plane is gliding.



Figure 11. FanWing [19]

This image shows a FanWing aircraft which involves a large wing made of cylindrical turbines. To provide lift and forward thrust the turbines pull the air in at the wing enabling it to be stable at high flights during turbulence. This design also has a short take-off and land and with this structure it is used as a normal airfoil creating higher lift and more load capacity. The flight speed ranging between 20 Kts to 70 kts and rotor speed 1,500 rpm. [19] FanWing rotors are used for flight, take-off and landing. Fixed surface only used for aerodynamic purposes, not airfoil purposes. Not a stop rotor design.



Figure 12. D-DALUS L3 [18]

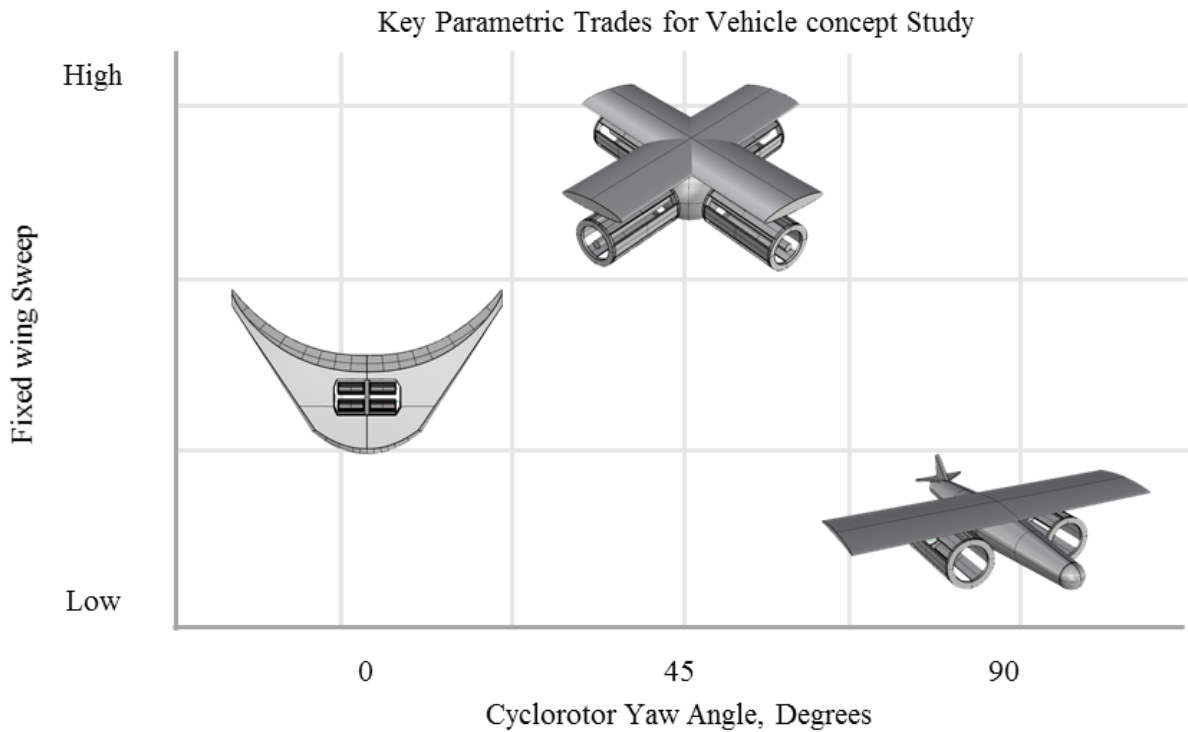
The D-DALUS L3 has a hover efficiency that is comparable to that of a tilt rotor and tilt wing aircraft. It uses 4 rotating carbon fiber disks that are attached to six blades and a fixed wing structure. The blade’s angle of attack is controlled by moving an offset point located inside the hollow axis of the rotating disks. This design relies on the cycloidal rotors more than the cycloplane does and acts more like a rotorcraft than a plane during take-off and landing. The system can adjust for turbulence and heavy winds by increasing opposing thrust as instructed by the servo motor communication system and therefore keeping it balanced. [20] Cycloidal rotors used for flight, take-off and landing. Better maneuverability and surface structure used for aerodynamic purposes. Not a stop rotor design



Figure 13: D-Dalus Drone

This aerial vehicle works similarly to that of the D-DALUS L3 with the same four cycloidal rotors used for propulsion that spin at 2,200 rpm. This aircraft can launch vertically, hover, fly and rotate in any direction, and thrust upwards. The unmanned air vehicle design is based on the idea of the D-DALUS L3 but as a more compact approach allowing it to become more stable and unmatched maneuverability. It measures at roughly five feet by three feet square and can lift about 100 pounds. A design close to this would be preferable for a mission to Venus since it is capable of matching the design requirements for atmospheric flight. [20] Only cyclorotors used for flight, take-off and landing. Surface platform used for streamline perposes. Not a stop rotor design.

B. Stopped Cycloidal Rotor Vehicle Trade Space



This trade study of the stopped-rotor cyclocopter includes a small percentage of possible design scenarios. The three that are shown in the figure above are three possible cases for implementing the cyclorotor at a yaw angle of 0, 45 and 90 degrees from the forward motion direction. Each design also varies in fixed wing sweep which contributes to the aircraft's ability to glide once the cyclorotors are stopped.

Some vehicle configuration trades that can be performed for this analysis could be: embedding the cyclorotors in the fuselage and/or wings, increasing the number of fixed wing surfaces, looking at the fuselage versus the fixed wing body or collapsing the cyclorotors into a more wing like stopped/stored configuration (these can be seen in the images below). Other consideration can include the use of elliptical airfoils or airfoils with deployable surfaces for improved lift characteristics for hovering and cruise flight.

Figure 14 (1) shows a foldable cyclorotor with blades that become the wing surface for gliding or storing making this design completely reliant on the stopped rotor cyclocopter blades in order to glide.

Wing design 2 (2) shows a foldable wing will allow for the UAV to have less weight as it will only comprise of a cyclorotor and scientific instrument load. The transition from cyclorotor to wing will need to be analyzed and tested

to make sure the UAV still has complete stability throughout. Any large additional force could prevent the transition and therefore the transition will not be mechanical as such but more reliant on the forces and atmospheric conditions.

Other consideration can include the use of elliptical airfoils or airfoils with deployable surfaces for improved lift characteristics for hovering and cruise flight.

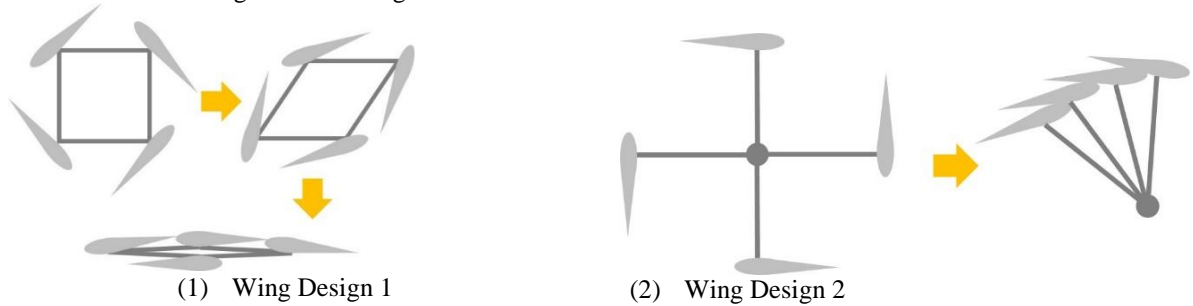


Figure 14: Collapsing the cyclorotors for wing like stopped/stored configuration

C. Current Study Reference Designs (Design1, 2 and 3)

The following designs are based on the different orientations cyclorotors can be used in. This will help identify which orientation and design would be more favorable when the rotors are stopped and auxiliary propulsion (such as conventional propellers) are being used for transition/cruise flight.

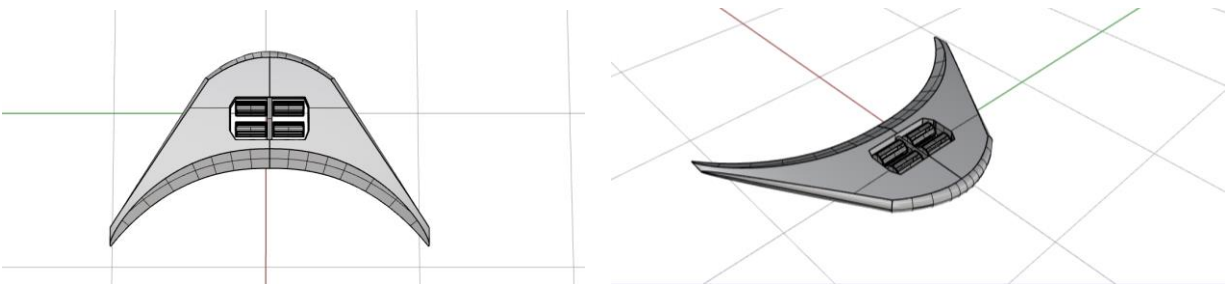


Figure 15: Cyclocopter UAV Design 1

This particular design position the cyclorotors within the airframe normal to the free stream. This orientation enables forward propulsion as well as hover and VTOL. In order to prevent these rotors creating excessive drag once stopped, a fixed surface area can be designed around the rotors, diverting airflow over the top of the rotors rather than through. This allows the rotors to act as a surface when stopped and contribute to the shape of the aircraft. This simple UAV design can hold all necessary measuring equipment within the airframe, keeping a streamlined finish.

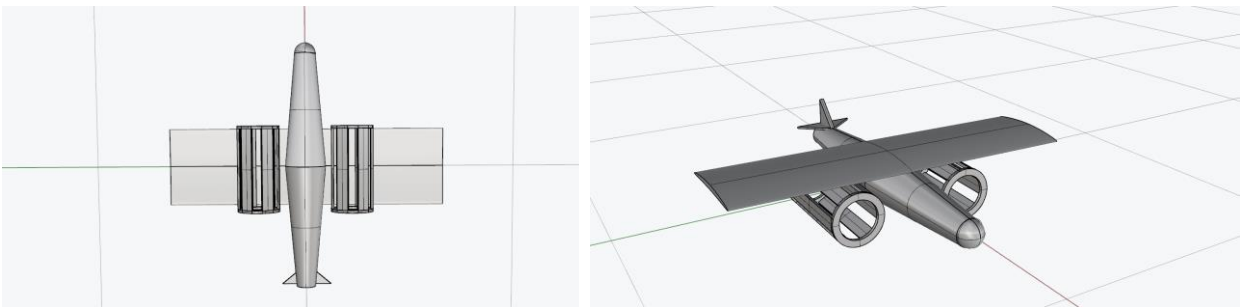


Figure 16: Cyclocopter UAV Design 2

Design 2 is based off of a conventional plane type UAV. The exception of this particular design is that the cyclorotors are parallel to the body of the aircraft and is more stable for yawing capabilities then forward motion. It is however, still suitable for VTOL and when the cyclorotors are stopped the aircraft can still create lift from the fixed wings and tail.



Figure 17: Cyclocopter UAV Design 3

Design 3 is a form of quad-cyclocopter and has the ability to use its rotors for propulsion in any direction. This is more favorable for maneuverability considerations but may produce more drag when the rotors are stopped for gliding. The idea of the fixed wing area above the rotors is to create a good airfoil for parts of the mission that don't require the rotors. Instrumentation can be carried within the center of the aircraft for good central balance and protection in case of an emergency.

All Rhino Models have roughly the same area and use the same scale of cyclorotors for easy comparison.

Design 1 and 3 will require the use of elliptical airfoils or airfoils with deployable surfaces for improved lift characteristics in hovering and/or cruise flight; however, Design 2 will not, as the cyclorotors are not only stoppable in mid-flight but are inherently trailed in low-drag arrangement when stopped.

V. RotCFD Analysis

RotCFD is an analysis tool used for rotorcraft analysis and is a combination of Computational Fluid Dynamics (CDF) and Integrated Design Environment (IDE). Rotor blades are represented by momentum sources which forms the basis of this tool. [3]

A. Simulation Value Calculations

Each simulation was run in its own project file and simulations run at high altitude used the same flow properties as well as simulation run at low altitudes used the same values. Please see Table 1 for these values used.

Table 1: High and Low Altitude Flow Property Values

Altitude	60km	5km
Wind Speed, [21]	100 m/s	2.8 m/s
Static Density, [22]	1.225 kg/m ³	67 kg/m ³
Static Temperature, [21]	263.15 K	735.15 K
Gas Constant	192.5 m ² /(s ² ·K)	192.5 m ² /(s ² ·K)
Specific Heat Ratio, [23]	1.4	1.368
Dynamic Viscosity	1.6658x10 ⁻⁵ Pa·s	3.4368x10 ⁻⁵ Pa·s
Static Pressure	62.057 kPa	9486.7 kPa

The boundary conditions are set to free flight and the flow properties are set to the high or low altitude atmospheric conditions on Venus. Using the equation below, the estimate time for the model to run can be calculated and set in the program.

$$t = \frac{l}{V_{forward}}$$

Therefore the time entered in the time grid solver would be the following:

High Altitude:

$$\frac{1.3 * 2}{100} = 0.026$$

Low Altitude

$$\frac{1.3 * 2}{2.8} = 0.9286$$

The Time step can be calculated using the following equation:

All simulation models have a body refinement level of 11. The Time Step value can be calculated as

$$\frac{0.31}{0.5} \times 3 \times 2^{(11-1)} = 1904.64$$

This value can be rounded up to 2000 time steps.

Each design has a simulation for high altitude properties at a pitching angles from -2 degrees to 10 degrees. They have also been tested under lower altitudes properties. All simulation are to give an idea of how the design would act in the environment of Venus once the rotors are stopped. They do not show the movement of the cyclorotors, only the body of the aircraft with cyclorotors in a stopped position. Due to the CFD program used the designs were drawn in a basic way and don't represent actual blades and orientation. This was to allow the program to run and solve in a reasonable time for the results of this project.

B. Simulation Results Design 1: High, Low Altitude and pitch variation Simulations

1. Design 1: Velocity Vector

The following Simulation results show Design 1 at both high and low altitudes on Venus. Figure 18 compares Design 1 Velocity Vector for high Altitude flow properties and low altitude flow properties. The pressure bar at the top shows the pressures represented in Pa and it can be seen that the pressures on Design 1 in the lower altitude is much greater but displayed very similar velocity vectors even though the free stream velocity is 100m/s and at the surface 2.8m/s.

The velocity vectors for different pitches varying from -2 to 10 degrees demonstrate how Design 1 would act whilst gliding through the high altitudes on Venus. During this stage of the mission the rotor is stopped and the aircraft would be gliding whilst taking measurements of the atmosphere. See Graph 1 for lift results.

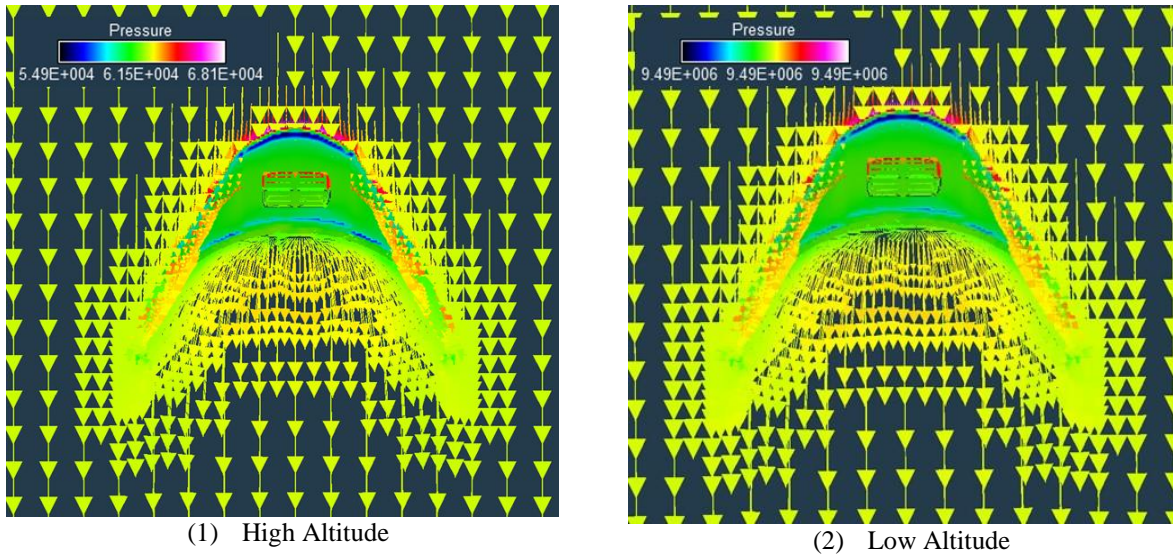
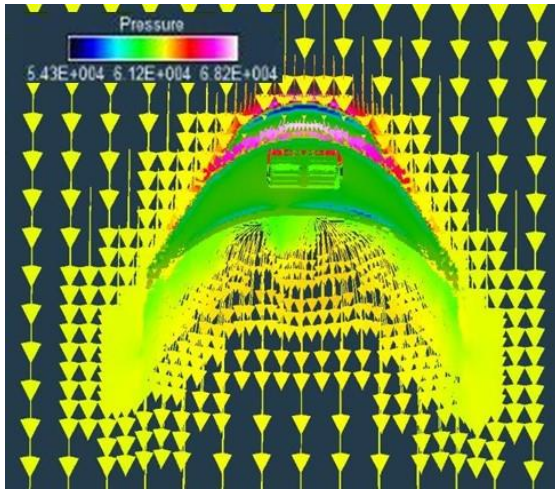
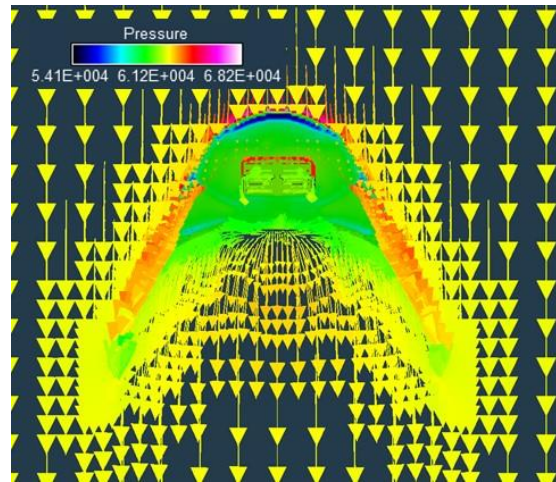


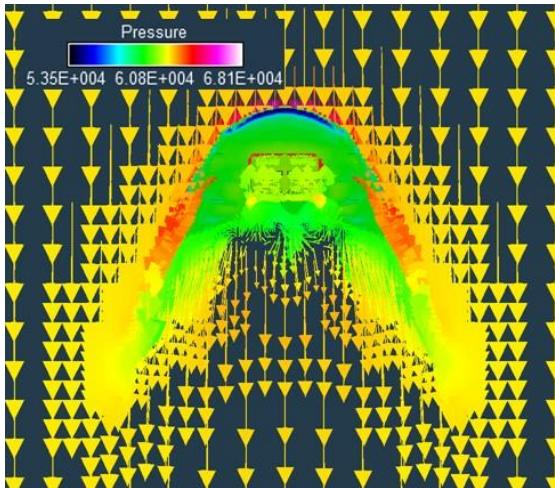
Figure 18: Design 1, 0 Pitch, High and Low Altitude, Velocity Vector, RotCFD



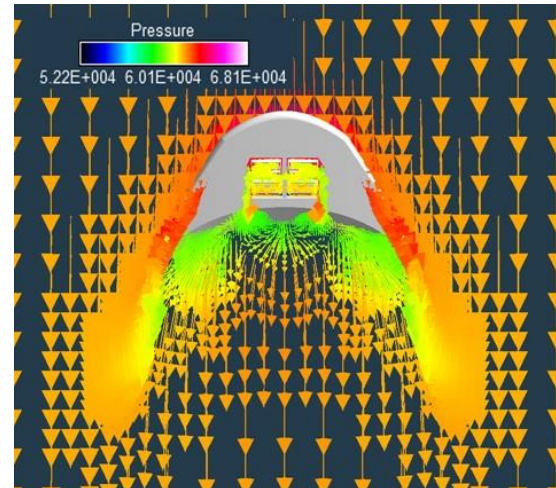
(1) -2 Degree Pitch



(2) 2 Degree Pitch



(3) 6 Degree Pitch

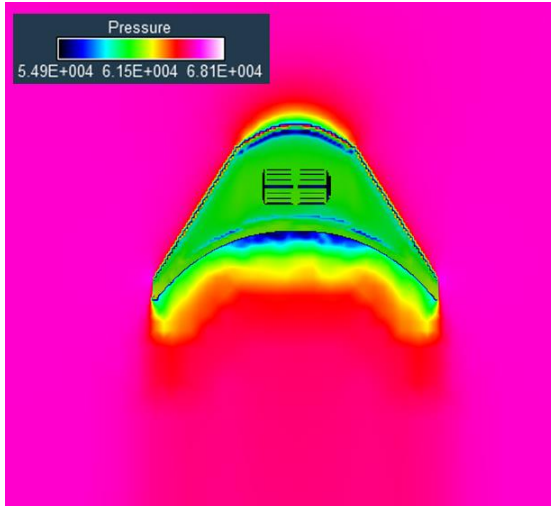


(4) 10 Degree Pitch

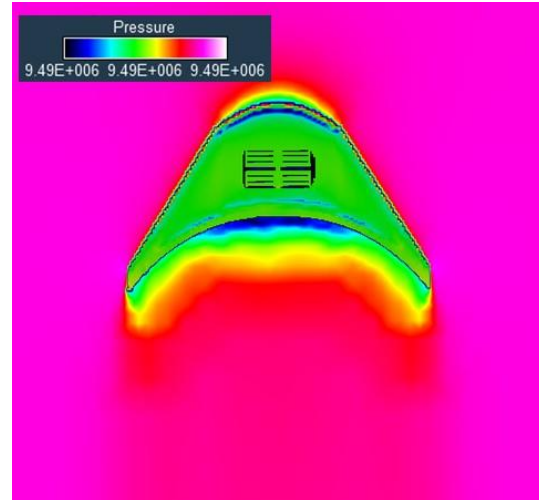
Figure 19: Design 1 at -2, 2, 6, and 10 degree pitch, High Altitude, Velocity Vector

2. Design 1: Velocity Magnitude

The images below show the velocity magnitude for Design 1 at both high and low altitudes for comparison. As shown the pressure distribution is very similar for both cases and the low altitude configurations shows a slightly longer wake than the high altitude simulation. This Design seems to be a well design for aerodynamic purposes and the stopped-cyclorotors do not create too much drag. The pitch variation shows the greater the angle the greater the pressure and turbulent flows behind the body. This is to be expected and shows a good representation of how the aircraft will act on Venus during gusty conditions.

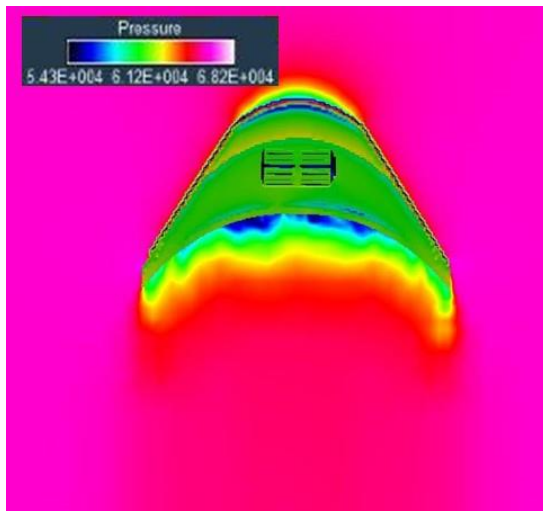


(1) High Altitude

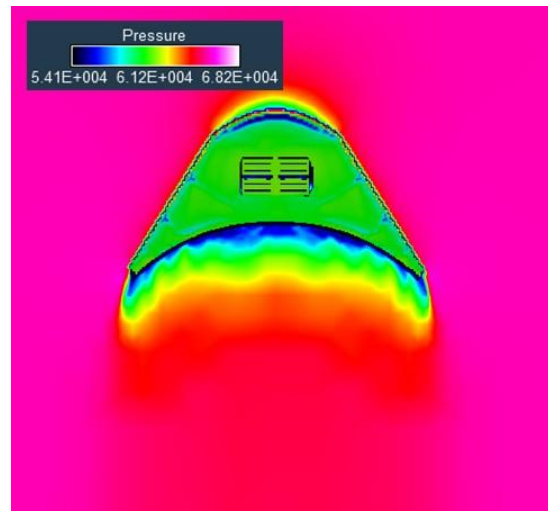


(2) Low Altitude

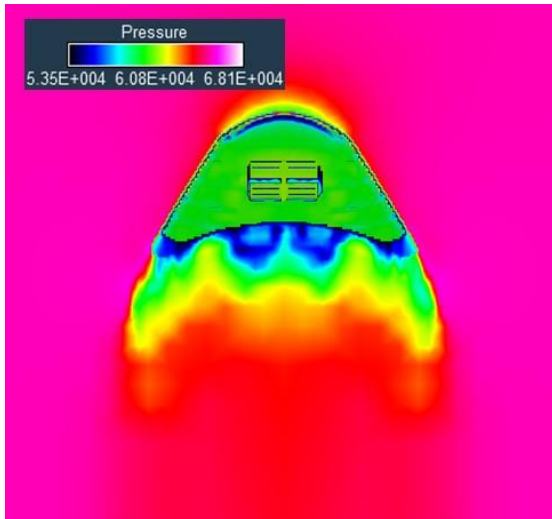
Figure 20: Design 1, 0 Pitch, High and Low Altitude, Velocity Magnitude, RotCFD



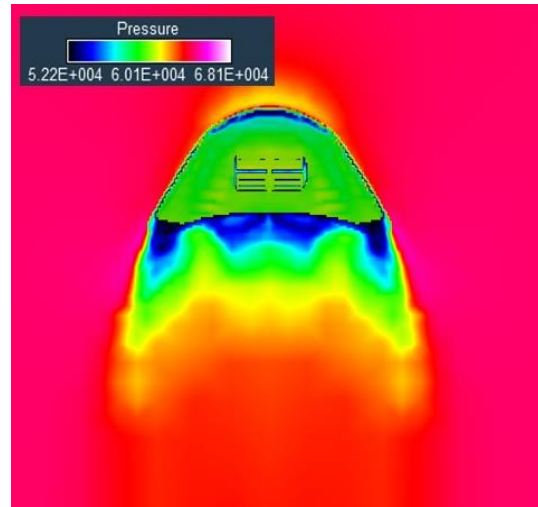
(1) -2 Degree Pitch



(2) 2 Degree Pitch



(3) 6 Degree Pitch

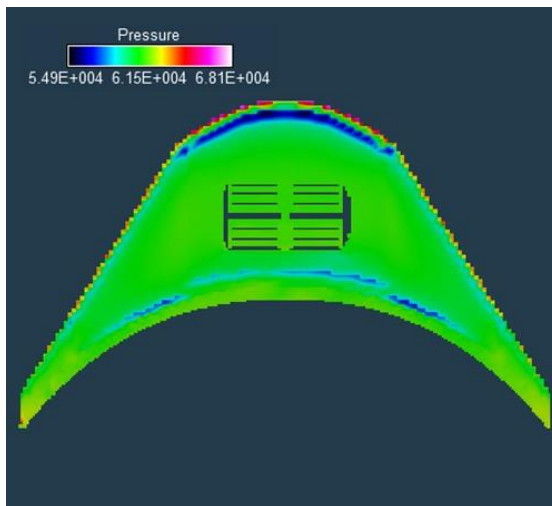


(4) 10 Degree Pitch

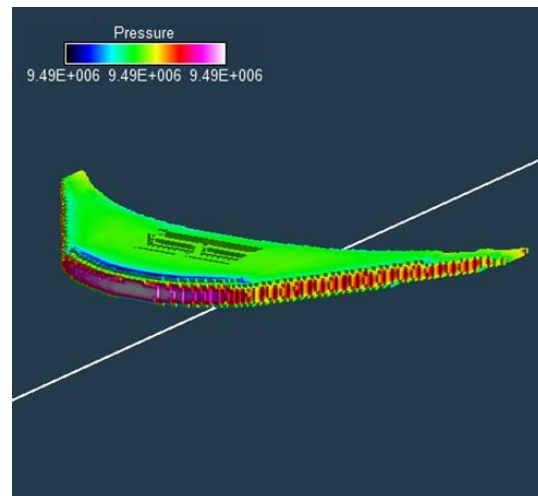
Figure 21: Design 1 at -2, 2, 6, and 10 degree pitch, High Altitude, Velocity Magnitude

3. Design 1: Body Pressure

These simulation results show the pressure on the body of Design one at high altitude flow properties and low altitude flow properties. There is obviously a much greater pressure on the front of the aircraft which faces the oncoming free stream velocity. The body pressure is much greater on the surface of Venus and this should be taken into account when designing the materials and scientific instrument selection. See Graph 1 for lift results at different angles of attack.

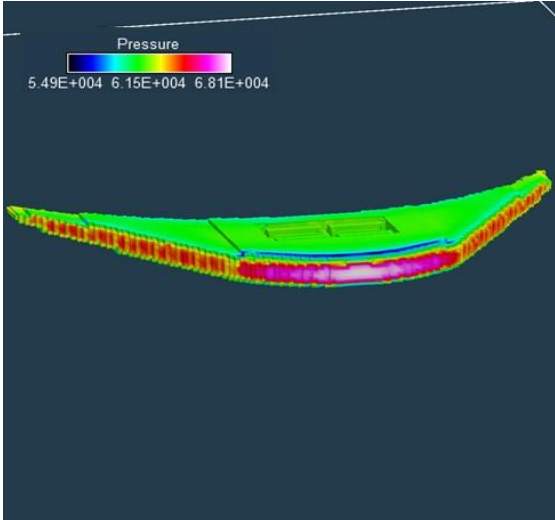


(1) High Altitude

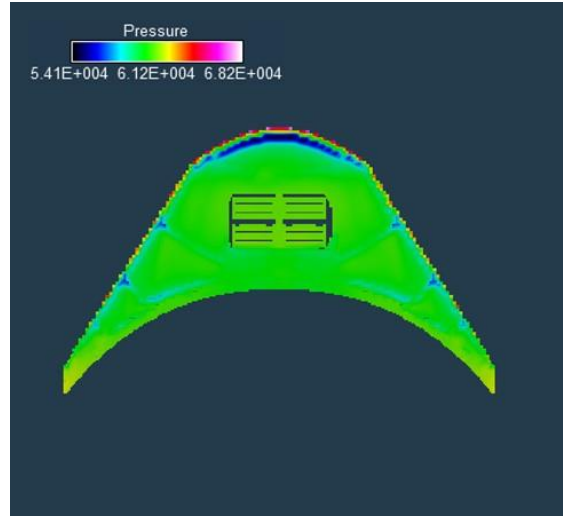


(2) Low Altitude

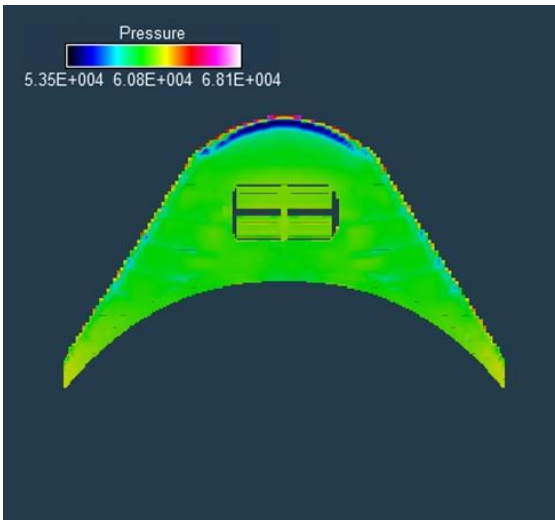
Figure 22: Design 1, 0 Pitch, High and Low Altitude, Body Pressure, RotCFD



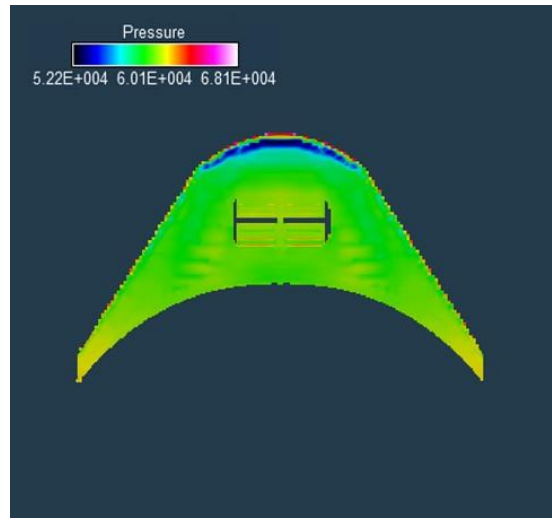
(1) -2 Degree Pitch



(2) 2 Degree Pitch



(1) 6 Degree Pitch



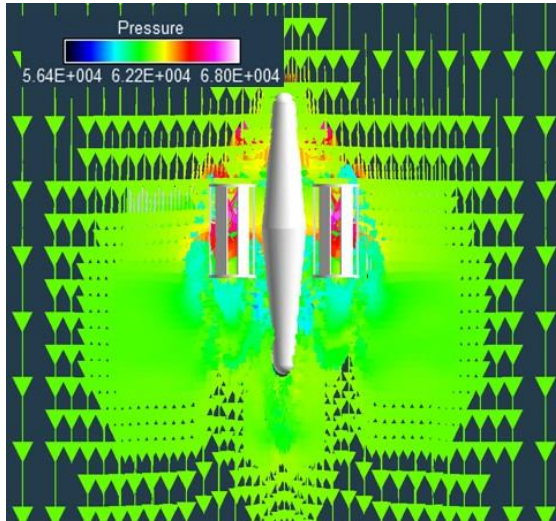
(2) 10 Degree Pitch

Figure 23: Design 1 at -2, 2, 6 and 10 Degree Pitch, High Altitude, Body Pressure

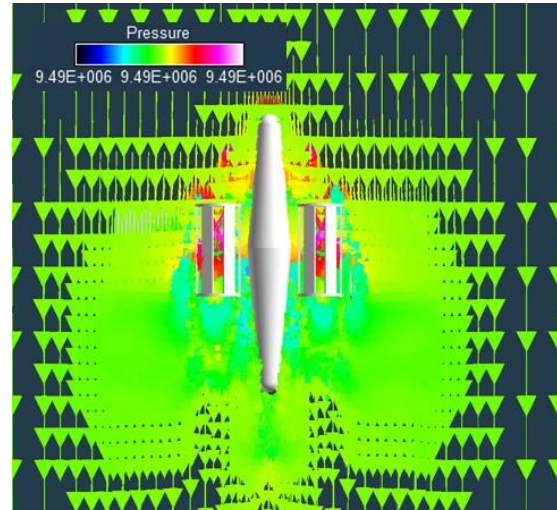
C. Simulation Results Design 1: High, Low Altitude and pitch variation Simulations

1. Design 2: Velocity Vector

These figures show Design 2 model Velocity Vector at high and low altitudes on Venus. Figure 25 also shows the pitch variation and results. See Graph 3 for lift results at different angles of attack.

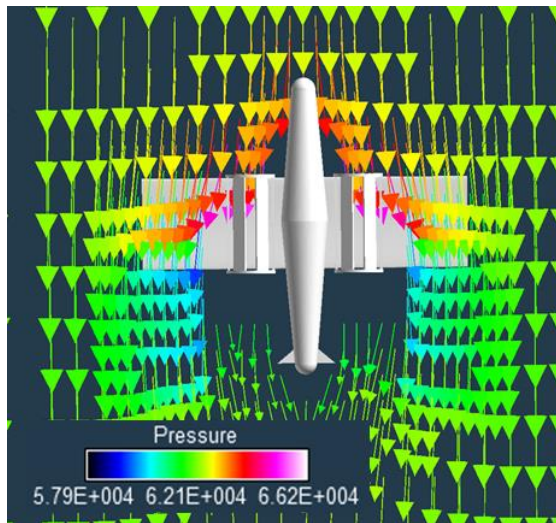


(1) High Altitude

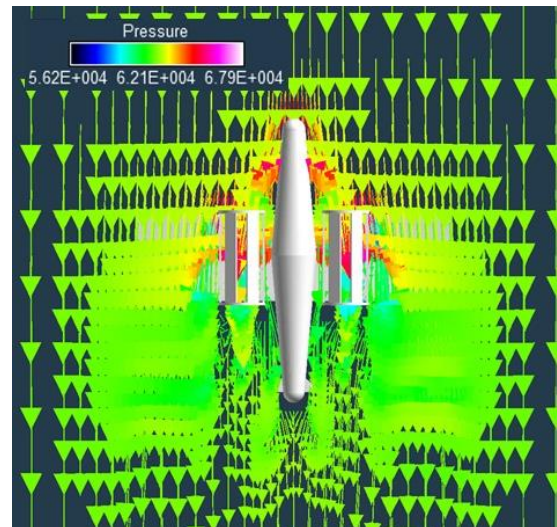


(2) Low Altitude

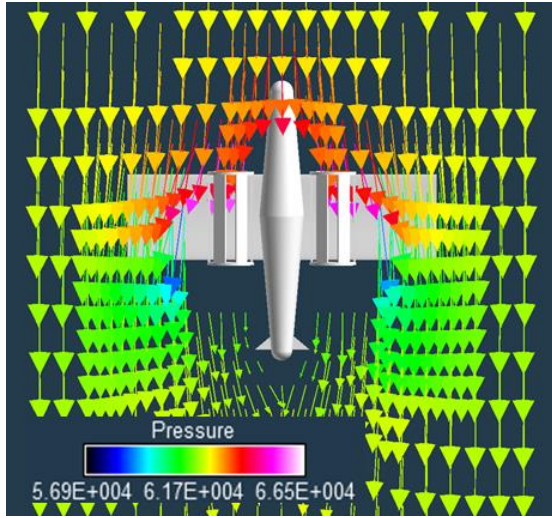
Figure 24: Design 2, 0 Pitch, High and Low Altitude, Velocity Vector, RotCFD



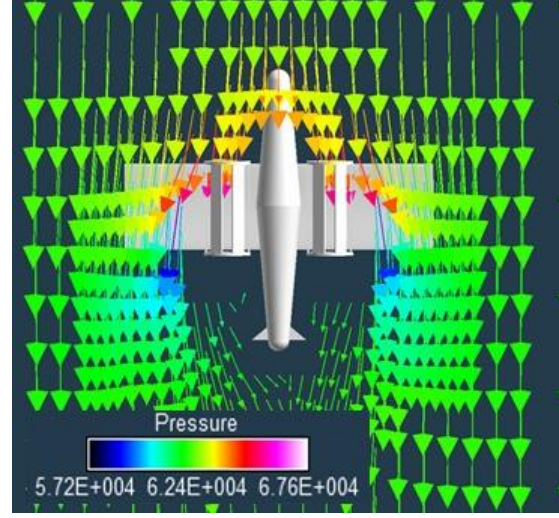
(3) -2 Degree Pitch



(4) 2 Degree Pitch



(5) 4 Degree Pitch

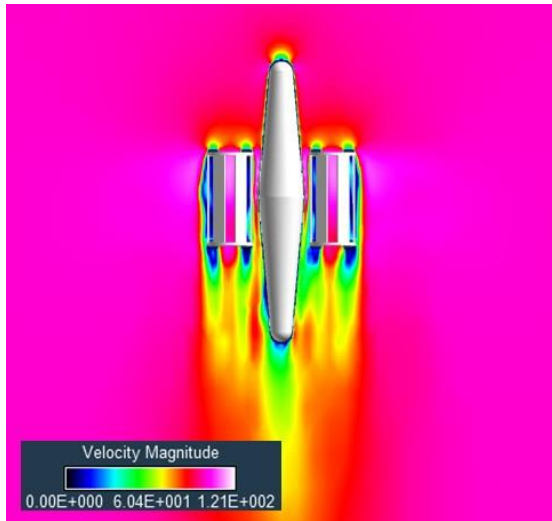


(6) 6Degree Pitch

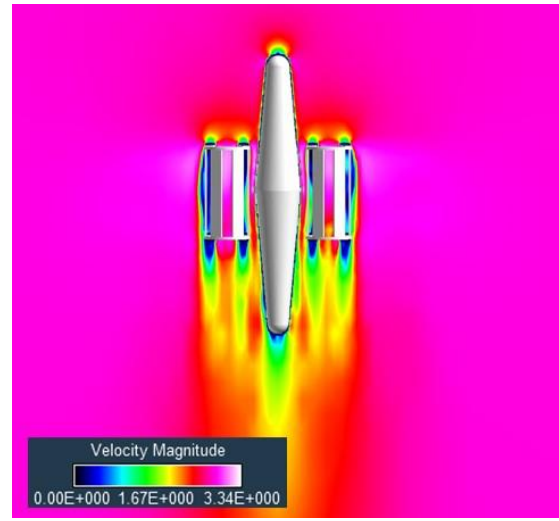
Figure 25: Design 2 at -2, 2, 4, and 6 degree pitch, High Altitude, Velocity Vector

2. *Design 2: Velocity Magnitude*

The following images show the velocity magnitude of Design 2 at high and low altitudes for comparison. They also show the pitch variation results and high altitude for gliding when the rotor is stopped.

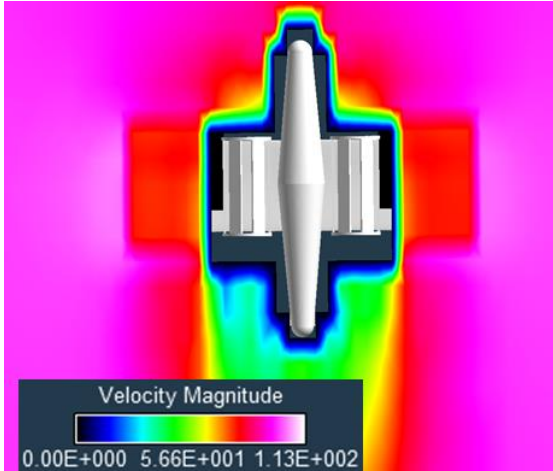


(1) High Altitude

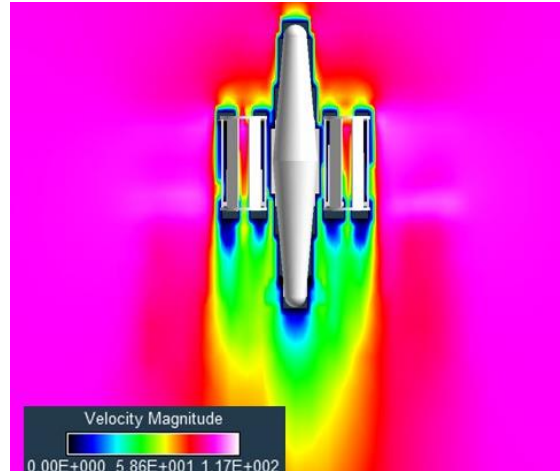


(2) Low Altitude

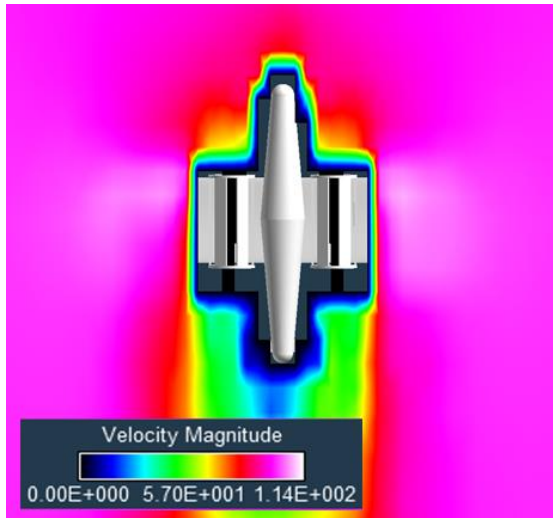
Figure 26: Design 2, 0 Pitch, High and Low Altitude, Velocity Magnitude



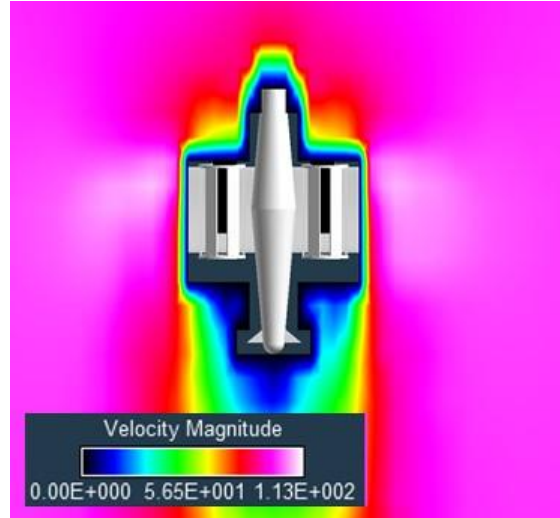
(3) -2 Degree Pitch



(4) 2 Degree Pitch



(5) 4 Degree Pitch

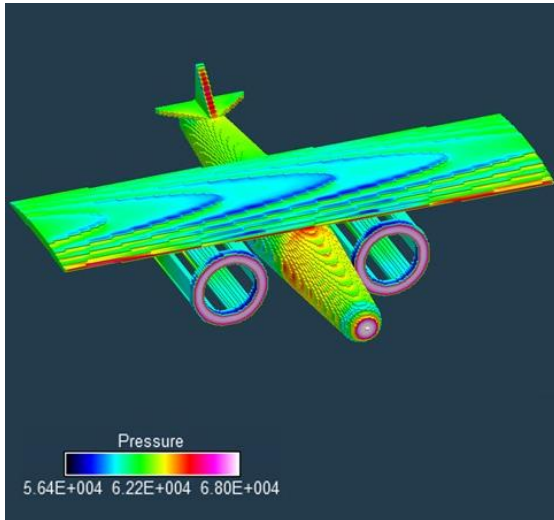


(6) 6 Degree Pitch

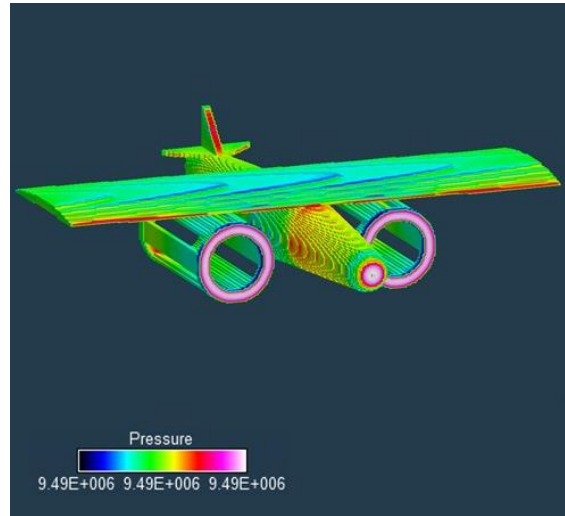
Figure 27: Design 2 at -2, 2, 4, and 6 degree pitch, High Altitude, Velocity Magnitude

3. Design 2: Body Pressure

The figures below show the pressure on the body of Design 2 at high altitudes and low altitudes of Venus. They also show the Pressure for varied pitch angles. The grids used were coarser for some simulations to allow the simulation to run and complete for a rough estimate. More detailed simulations can be done if needed.

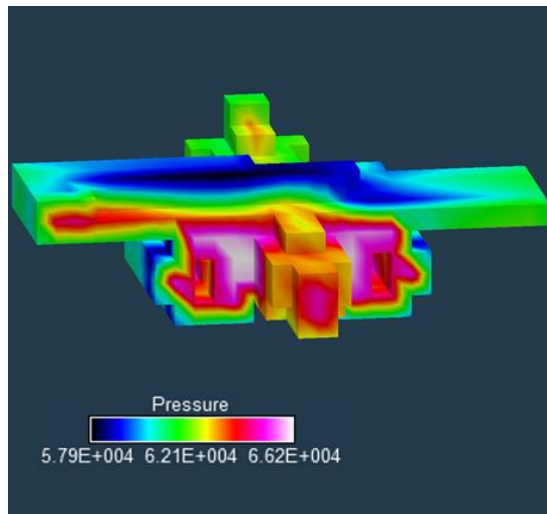


(1) High Altitude

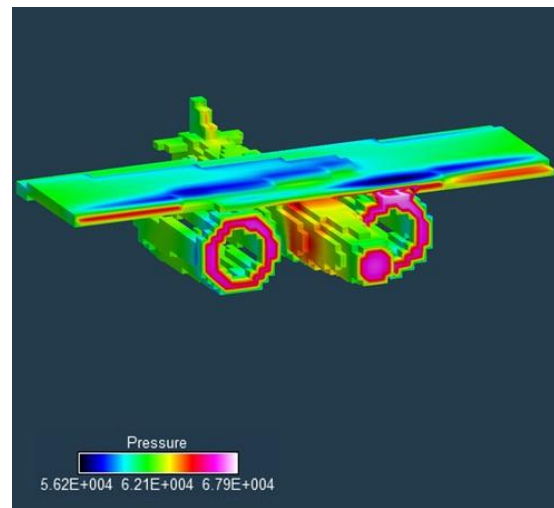


(2) Low Altitude

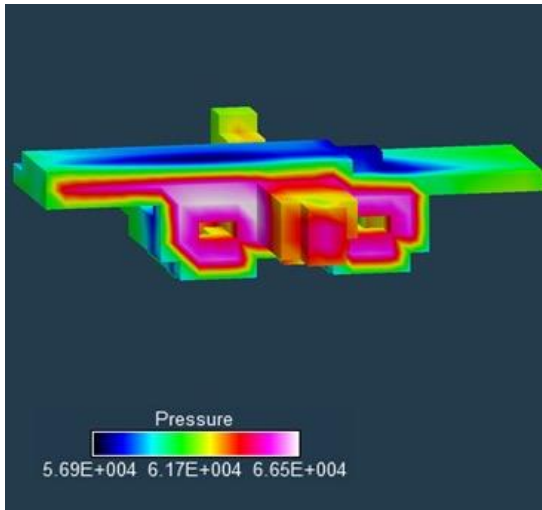
Figure 28: Design 2, 0 Pitch, High and Low Altitude, Body Pressure



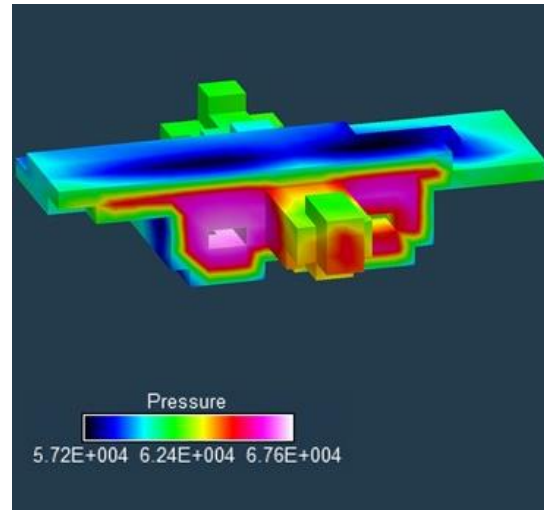
(1) -2 Degree Pitch



(2) 2 Degree Pitch



(3) 4Degree Pitch



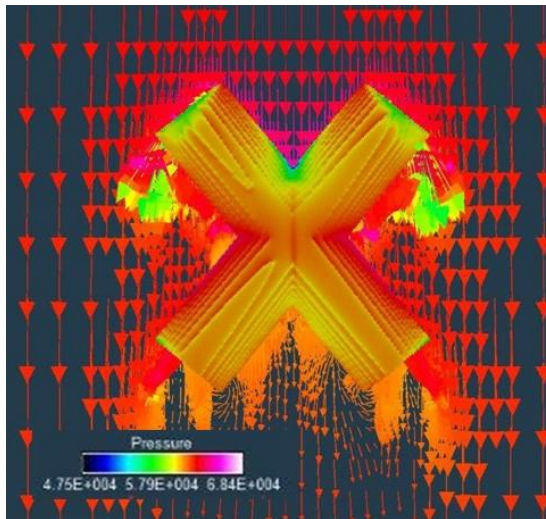
(4) 6 Degree Pitch

Figure 29: Design 2 at -2, 2, 4, and 6 degree pitch, High Altitude, Body Pressure

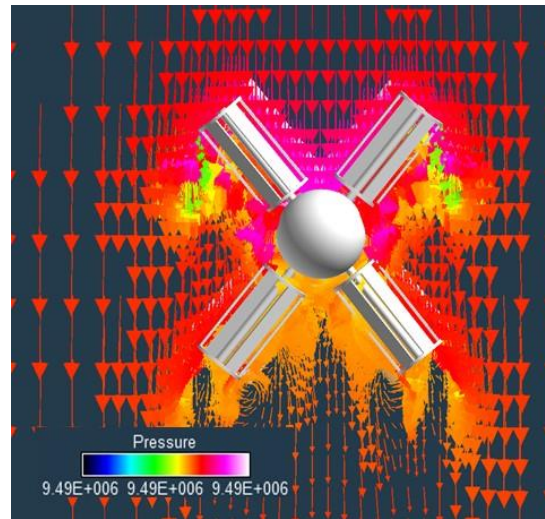
D. Simulation Results: Design 3, High and Low Altitude Simulation Comparison

1. Design 3: Velocity Vector

The figures below show the velocity magnitude for Design 3 at high and low altitudes for comparison. The simulations are conducted to represent the gliding part of the mission where the rotors would be stopped. This design shows higher amounts of pressure on the small airfoils (these can be smaller since the atmosphere on Venus is very dense).



(1) High Altitude

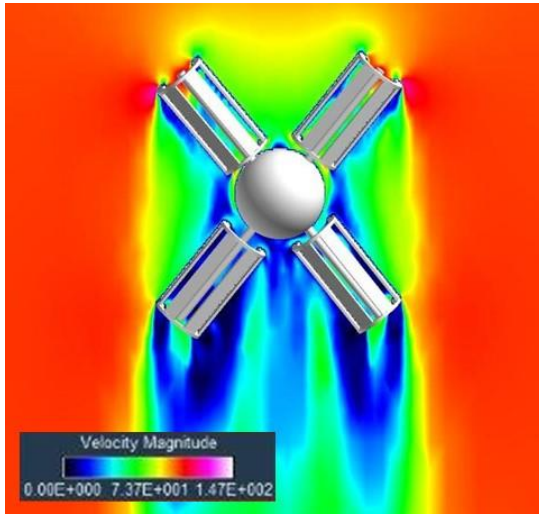


(2) Low Altitude

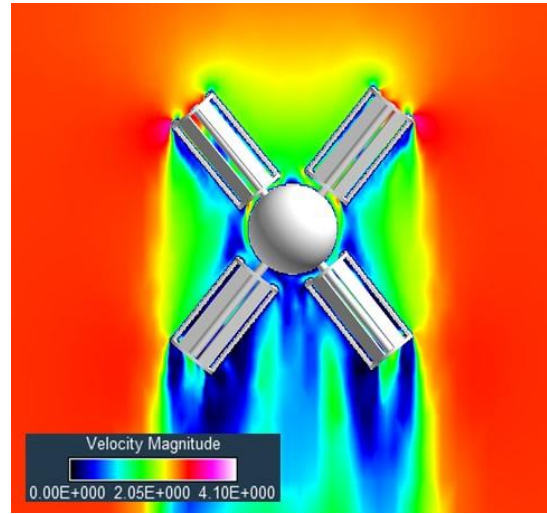
Figure 30: Design 3, 0 Pitch, High and Low Altitude, Velocity Vector

2. *Design 3: Velocity Magnitude*

The velocity magnitude of the quadrotor cyclocopter design 3 can be seen in the images below.



(1) High Altitude

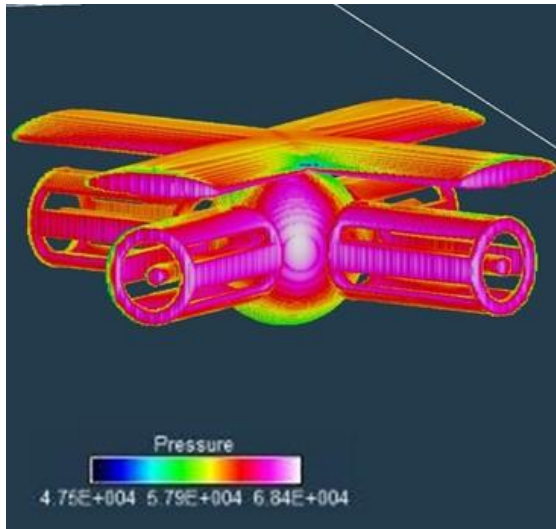


(1) Low Altitude

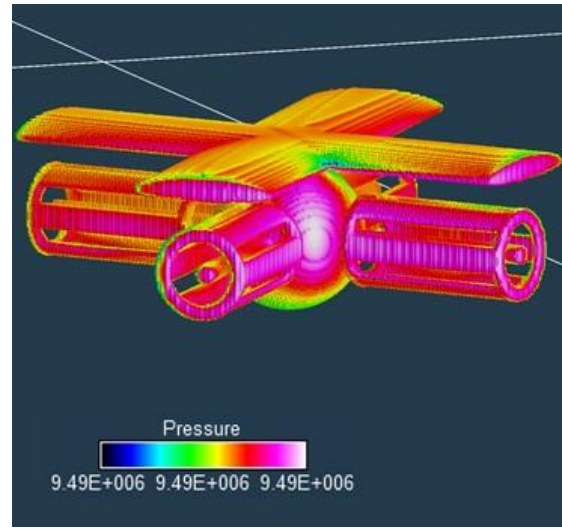
Figure 31: Design 3, 0 Pitch, High and Low Altitude, Velocity Magnitude

3. *Design 3: Body Pressure*

The figure below show the pressure on the body at high and low altitudes on Venus.



(1) High Altitude



(2) Low Altitude

Figure 32: Design 3, 0 Pitch, High and Low Altitude, Body Pressure

E. Velocity Magnitude Iso-surface Comparison – Sideview/Midspan

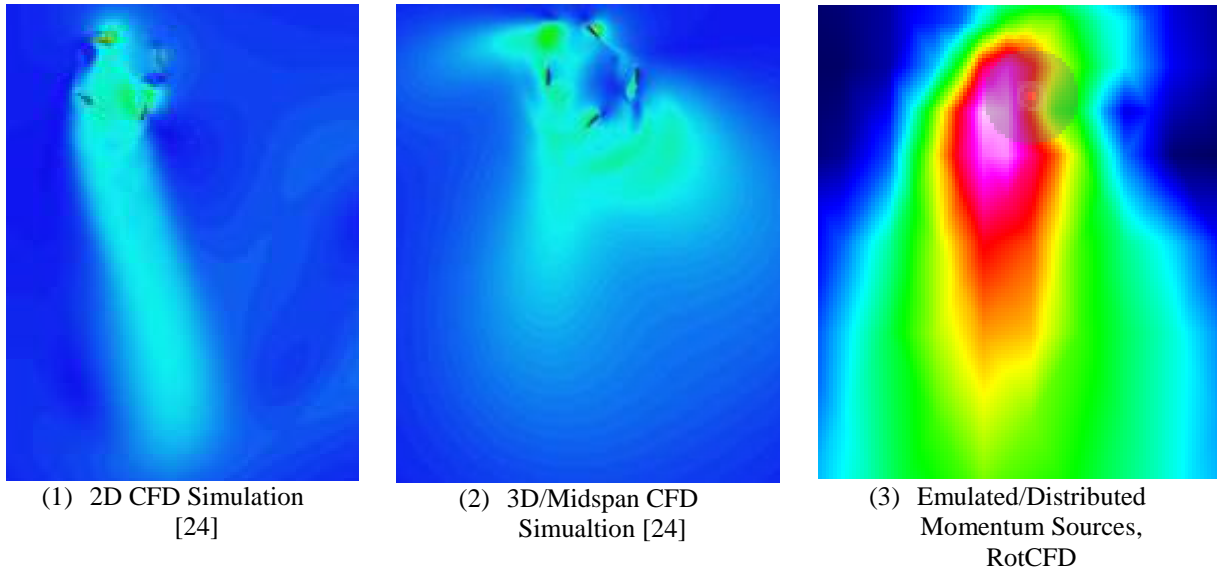


Figure 33: CFD Comparison of Cyclorotor Motion

Figure 33 (1) and (2) are models from the paper entitled ‘Two dimensional and three dimensional numerical simulation of cycloidal propellers in hovering status’ from Northwestern Polytechnic University. Here they had tested the cyclorotor in a CFD program to view its 2D and 3D wake of the analyzed 4 blade cyclorotor. This simulation was re-conducted in RotCFD to identify where this wake can be seen in this CFD program. Since the use of direct blades are not possible in this program, a distribution of momentum forces were used to imitate the movement of the cyclorotor in Earth surface flow properties. This analytical model represents the cycloidal blade system as a pair of actuator disks in tandem. The actuator disk perpendicular to the generated thrust vector is capable of imparting axial momentum. [2] Comparing these simulations, it can be seen that the air velocity increases within the cyclorotor and the swirl velocity is counter clockwise, minimizing with velocity. This demonstration proves that Rot CFD can be used for simulating the motion of cyclorotors.

F. Velocity Magnitude Iso-surface Comparison – Frontview/Midplane

These figures represent the rotated blades at 90 degrees which displays the span of the blades. This identifies the roll off velocity. Again actuator discs represent the blades for the RotCFD simulation model and by comparison the rotors show similar flow characteristics.

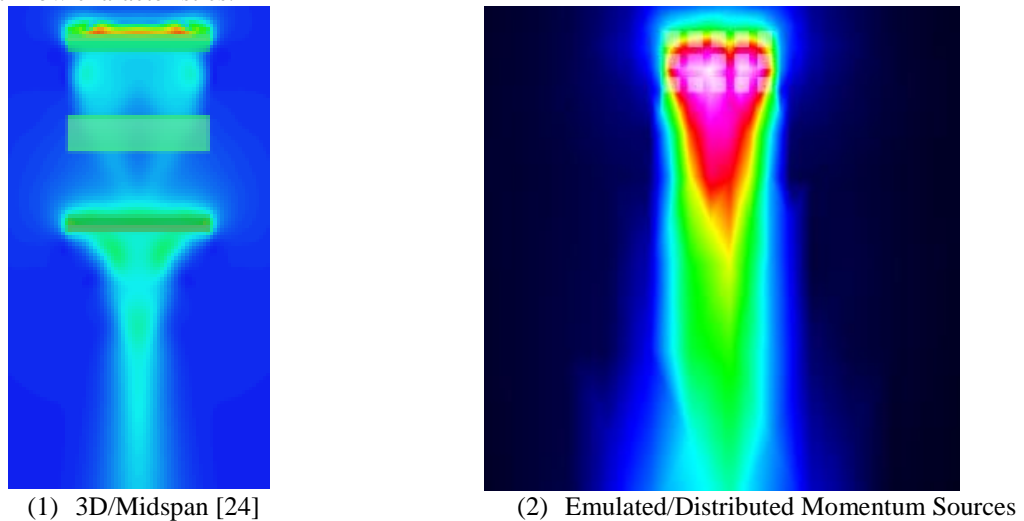
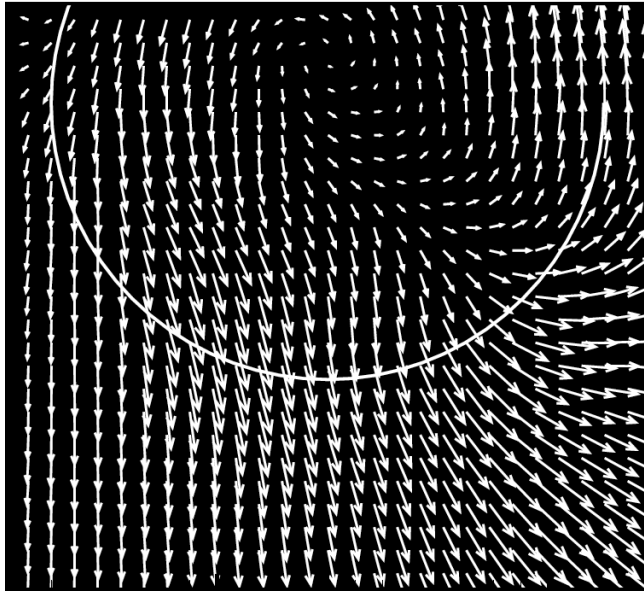


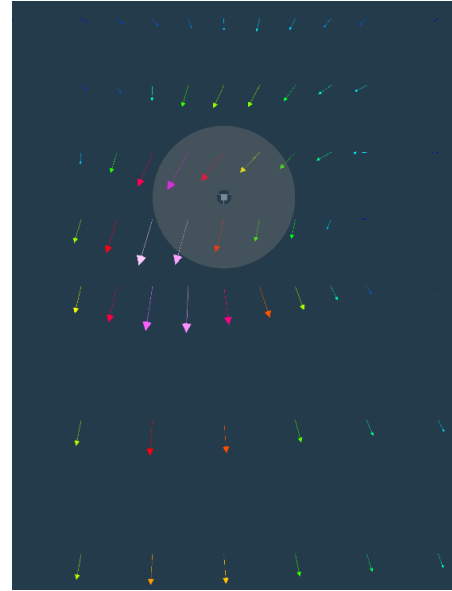
Figure 34: Span of the blades, roll off velocity

G. Time-Averaged Velocity Vectors – Sideview/Midspan

The figures below demonstrates the flow field inside a four-bladed cyclorotor in hover compared with the emulated distribution of momentum model run in RotCFD. By comparison the flow of velocity is very similar creating an asymmetry of the inflow about the Z axis.



(1) Non-dimensional distance from the rotor center, [25]



(2) Emulated/Distributed Momentum Sources

Figure 35: Time-averaged velocity measurements showing the flow field

VI. Results Analysis

Three conceptual design were created to test the cyclorotor at different yaw angles when stopped during flight in the high and low altitudes of Venus. Several simulations were conducted in RotCFD at high altitude flow properties for pitch angles ranging from -2 to 10 degrees and these were then analyzed and displayed in the graphs below.

Design 1, which is the four rotor cyclocopter with a fixed wing area at 0 degree yaw angle, has been tested in RotCFD using high altitude flow properties of Venus at varied pitching angles from -2 to 10 degrees. Design 2 had two cyclorotors orientated parallel to the body with a 90 degree yaw angle, this was also tested at different pitch angles from -2, to 6 degrees. Graph 1 below shows the lift coefficient at these angles. It can be seen that a steady increase of lift is generated by Design 1; even at 10 degrees the aircraft does not stall. Design 2 has a stalling angle of 4 degrees pitch which is realistic for the type of design. Design 3 is a quad-cyclocopter with a yaw angle of 45 degrees and during stopped rotor flight it displayed a stalling angle of 6 degrees which follows a similar lift curve to Design 2. The cyclorotor yaw angle of 0 degrees and rotors within a fixed wing surface shows the best lift to pitch ratio whilst the cyclorotor is stopped and the aircraft is in the gliding phase of the mission. These are non-dimensional results for the purposes of the project.

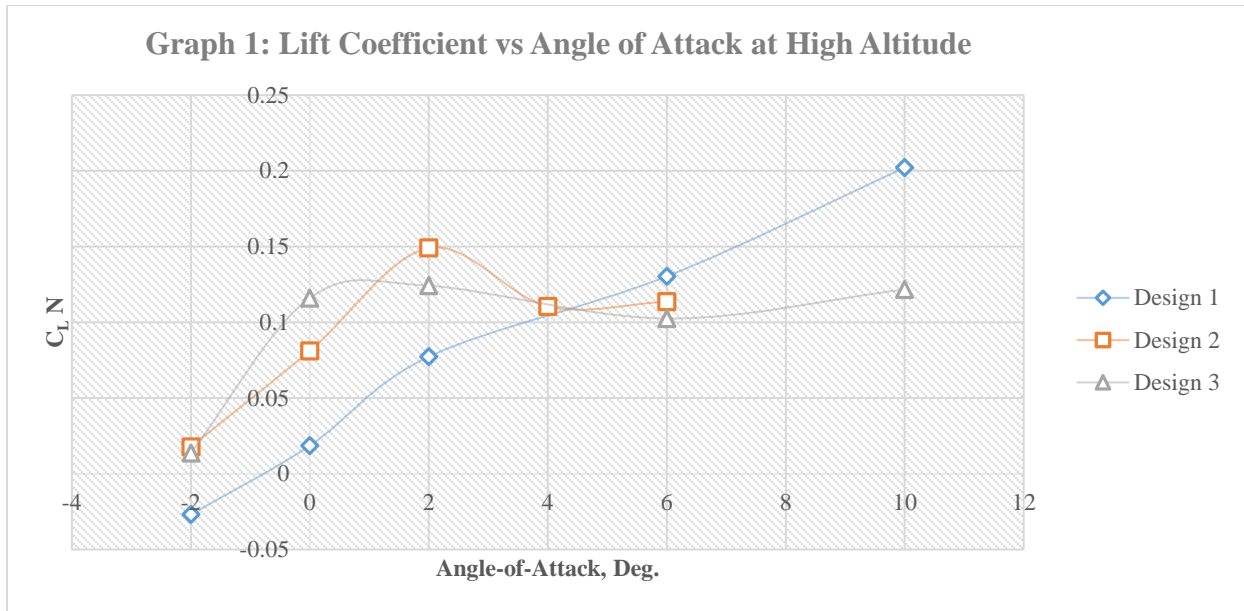


Figure 36: Lift Coefficient vs Angle of Attack at High Altitude for Design 1 and 2

Graph 2 shows the Lift coefficient vs the Drag coefficient for Design 1 and 2. By comparison they have very different lift curves and this will be due to the aerodynamic structure of the design as well as the cyclorotor orientation to the free stream. I believe Design 1 is a more reliable design than 2 since it has a higher stalling angle and lower drag coefficient generation. Design 3 has a much higher drag coefficient than 1 and 2 but follows a similar pattern to Design 2. Design 1 configuration would be useful in the high winds on Venus when the cyclorotors are off and the aircraft is set to glide and take measurements of the atmosphere and the radar imaging of the surface.

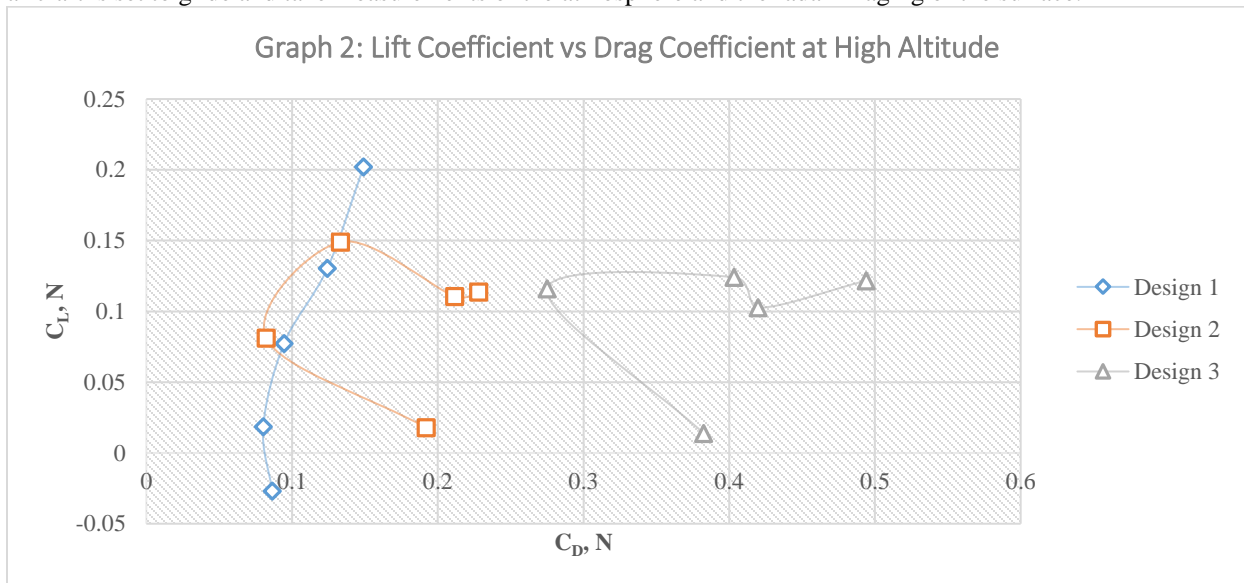


Figure 37: Lift Coefficient vs Drag Coefficient at High Altitude for Design 1 and 2

This is a good start to analyzing the yaw angles of cyclorotors when stopped during flight. More testing is needed but these results of three different cyclorotor yaw angles can produce lift in the high atmosphere of Venus and Design 1 has better Lift coefficient generation than the others. This may be due to the surface area and streamline shape of the aircraft. It would be beneficial to continue testing cyclorotor configurations to determine the reliability and capability of the cyclorotor of a mission to Venus.

VII. Conclusion

This project focused on the design considerations for the implementation of a stopped rotor cyclocopter to be used for a mission to Venus. The aircraft should be capable of flying in all atmospheric layers of Venus, taking measurements and scouting for beneficial landing locations. The cyclorotor blades would be used as both a propulsive system and for VTOL during the mission. During the project three main design were tested with three different yaw angles of a cyclorotor in the stopped position. These cyclorotor yaw angles varied from 0 to 90 degrees with a varied wing sweep value. The models were created in Rhino and simulated in RotCFD for both high altitude properties on Venus and low altitude flow properties. Simulations were also run for different pitch angles at high altitude and it was found the each design had the ability to create lift whilst the cyclorotors were stopped.

The results identified by the simulations and lift graphs show that Design 1 with four stopped cyclorotors at 0 degree yaw angle within a fixed wing surface showed more promising lift generation during the gliding phase at high altitude. Design 2 which had two cyclorotors at yaw angle 90 degrees had a larger drag generation and a stalling angle of 4 degrees pitch when rotors were stopped during gliding phase of the mission. Design 3 quadcopter at yaw angle 45 degrees and fixed wing surface created the most drag when the cyclorotors were stopped and simulated during the gliding phase of the mission but would be the most useful for maneuverability. Plots of lift coefficient vs angle of attack were created to find the stall angle of these designs and lift to drag plots also revealed the lift to drag ratio for each. This was useful in identifying the cyclorotor yaw angle with the least drag compared to lift and how wing sweep plays a role in the gliding phase of the mission when the rotors are stopped.

As well as these three yaw angle variant designs for stopped-rotor configuration, moving cyclorotor configuration simulations were run in RotCFD using distributed momentum sources to compare the wake and velocity vectors with previous results from the University of Maryland.

Recommendations for this project would be to continue identifying the possible cyclorotor yaw angles vs wing sweep design for the stopped-rotor cyclocopter in Venus conditions. Also considerations for materials in respect to the Venus temperature and pressure values to enable the aircraft to last for days on the surface without disruption. The stopped rotor may also have the potential to be used for commercial uses and this can be identified as a spin-off for future work on Earth and space.

Acknowledgments

I would like to thank Bill Warmbrodt for giving me this opportunity of working in the Aeromechanics department at NASA. I would also like to thank my project mentor Larry Young for all his help, guidance and support for this project and giving me the opportunity to come up with my own novel and exciting idea for an internship project.

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