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Analysis of A Gravity Hinge System For Wind Deflecting Structures of Roof Top Wind Turbines.

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ANALYSIS OF A GRAVITY HINGE SYSTEM FOR WIND DEFLECTING

STRUCTURES OF ROOF TOP WIND TURBINES.

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ABSTRACT

This study presents a mathematical modeling of behavior of a wind deflecting structure having trap doors supported by gravity hinges. The function of the trap doors is to be fully closed at low wind speeds (under 6.1 m/s), thereby increasing the wind speed, and directing the air flow to a pair of roof top wind turbines (1.3 kW nameplate rating). With wind speeds higher than 6.2 m/s the trap doors will start to open, letting the air move though the structure rather than directing the air flow to the turbines. The opening and closing of the trap doors take place with the help of gravity hinges. Under high-speed wind conditions, the follower of the gravity hinge climbs up the cam surface. As long as the wind speed stays high, the trap door stays open. When the wind speed falls below a prescribed value, the force of gravity acting on the trap doors is a restoring force to bring the trap door into its closed configuration. This study includes the drag force calculations on the trap doors, the torque created by this drag force in an analysis to examine the opening and closing behavior of the trap door under various wind speed conditions. Under the closed trap door position, wind velocity analysis was performed in order to demonstrate the intended function of the wind deflecting structure for amplifying the natural wind speed. A detailed static analysis of the gravity hinge was performed to examine the condition of opening of the trap doors under high wind conditions. A series of parametric studies were performed to demonstrate the behavior of trap doors under low and high wind speed conditions. A gravity hinge of a 5-degree incline was

considered in this study and the analysis shows the trap doors stay closed for wind speeds of 6.2 m/s and below. Furthermore, the analysis shows that the trap door is fully open for wind speeds above 18 m/s. A range of friction coefficient between 0.01 and 0.1 was considered acting on the components of the gravity hinge.

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NOMENCLATURE

g = Gravitational acceleration constant (Meters/seconds^2)

r = Radius of trap door (Meter)

r_o = Outer radius of hinge (Meters)

r_i = Inner radius of hinge (Meters)

H_{cyl} = Height of structure (Meters)

$W_{project}$ = Projected width of the trap door (Meters)

V_{free} = Freestream velocity (Meters/second)

R_{trap} = Radius of the trap door (Meters)

Qty = Number of hinges on a passively controlled trap door (#)

α = Angular opening of the trap door (˚)

θ = Angle of inclination of the gravity hinge (˚)

F_{drag} = Drag Force from the Wind (Newtons)

μ = Friction coefficient (Unitless)

C_d = Drag Coefficient (Unitless)

I = Moment of Inertia (Meters^4)

A_{swept} = Area of wind turbine (Meters^2)

m = Mass of the trap door (Kilograms)

ρ = Density of air (Kilograms/meters^2)

$R_{follower}$ = Distance from axis of rotation to hinge radius of the acting force (Meters)

$F_{n\perp}$ = Normal force to the hinge surface (Newtons)

$F_{g\perp}$ = Gravitational force perpendicular force to hinge (Newtons)

$F_{g\parallel}$ = Gravitational parallel force to hinge surface(Newtons)

F_g = Gravitational force acting on the system (Newtons)

$F_{w\perp}$ = Wind force perpendicular to the hinge surface (Newtons)

$F_{w\parallel}$ = Wind force parallel to the hinge surface (Newtons)

F_w = Wind force acting at the hinge (Newtons)

$F_{\parallel}$ = Parrell force acting along the hinge incline (Newtons)

h_x = Height of the door relative to the closed position (Meters)

C_{OP} = Coefficient of performance of the wind turbine (Unitless)

η_g = Generator efficiency (Unitless)

η_b = Gearbox/Bearing efficiency (Unitless)

Re = Reynolds number (Unitless)

L_c = Characteristic length (Meters)

KE = Kinetic Energy (Joules)

PE = Potential Energy (Joules)

ν = Kinematic viscosity of air (Centipoises)

R_{Wind} = Location of the wind that acts on the trap door (Meters)

A = Projected Area of the trap door ($Meters^2$)

L = Lagrange Factor (Joules)

d_x = Discretization error (unitless)

V_x = Velocity (Meters/second)

V_y = Velocity (Meters/second)

CHAPTER I

INTRODUCTION

Wind energy is the largest portion of renewable energy used commercially in the world. Every year continual improvements are made to increase the efficiency and decrease the cost capital of the wind turbine systems. Wind turbines have been implemented for harnessing energy since the first century AD and will continue to be utilized for the foreseeable future. Many countries currently use wind energy as a part of their overall energy plan with some having a significant percentage and others having a moderate percentage of their plan.

1.1 History of Wind Turbines

The use of wind turbines for capturing the wind energy and transforming it into mechanical energy has occurred for centuries. The first account of a wind-driven wheel for powering a machine was developed by Heron of Alexandria (Shahan, 2019). Since this invention, wind powered machines have been used to grind corn, flour, and move water. The primary use for harnessing this energy was to power mechanical machines until 1887, when Professor James Blyth used a charge accumulator to store wind energy as electricity. In the early 1900's, approximately 2,500 windmills were used in Denmark for converting wind energy to mechanical energy. These wind turbines could produce between 5 kW to 25 kW, depending on their size and now has advanced to 14 MW with the Haliade-X14 MW wind turbine (Haliade-X offshore wind turbine).

1.2 Wind Turbine Advantages and Challenges

Wind energy is a preferred source of renewable energy due its many benefits. Wind energy is the largest global source of renewable energy. Wind energy is generally a long-term solution for companies because it is cost-effective. This is due to the ample tax credits and the no fuel cost (wind), to power the turbine. The global cost to the consumer in 2019 for on shore and offshore wind energy was 5.3 and 11.5 cents per kilowatt-hour after including the tax credits (Reve, 2020). Wind turbines do not produce greenhouse gases during energy generation. Only a comparatively minor amount of greenhouse gas is emitted into the environment during the production, transportation, and installation. These greenhouse gases are minor and can be annualized over the long service life.

Unlike other energy resources, the price of the wind energy does not fluctuate within the commodity market because the wind, being at no cost, is not dictated by resource or supply and demand factors. This leads to greater stability for energy pricing for the local community by not being tied to the commodity market for an energy fuel source (Bowers, 2020). With these advantages, wind energy can be a steady corner stone of the energy market given the cost competitiveness and the independence of the fuel source.

Despite the numerous benefits of wind energy, the capital cost and location of generation can be major challenges for consumers to face. The consumer often seeks and focuses on the lowest price for electric without researching the energy production's surrounding benefits, so the wind power needs the ability to compete within this market.

The current ideal location for wind turbines is in a rural setting, which is often a significant distance from the nearest urban areas that would be consuming this electricity. With the source being generated in a separate area, the electricity needs to be transmitted to the consumer markets where combustion plants that require this energy can be constructed. To fulfill this transfer of electricity from the wind turbines in remote settings, installation of transmission lines, with additional cost, is required for the electricity transportation. With this, an additional cost to using this type of product is added. The wind turbine structures are also relatively large, and the turbine generates a non-trivial amount of noise as the turbine blades spin. This type of aesthetic and the added noise pollution are undesirable for a local community, which can make convincing a community to install this type of a structure a challenge.

The wind turbines can only produce electricity when the wind speed is within the operating speed of the turbine. The wind amplification geometry helps with meeting the minimum wind speed requirement, but this also decreases the maximin free stream velocity of the wind turbine. Despite these challenges, multiple countries have divulged strategies for overcoming them.

1.3 Country Breakdowns

The benefits and disadvantages on installing wind turbine structures are major factors on how each country incentivizes renewable energy. Overall, in 2019, the world produced 26,913 terawatt hours of electricity and only 26.6% of the energy was renewable. The United States of America produced 4385 terawatt hours and 17.9% was renewable resources. Sweden produced 157 terawatt hours of electricity in 2019 and 58.7% of it was renewable energy. Saudi Arabia produced 350 terawatt hours with 0.3%

being renewable (2019). Each area's local environment and incentives play major factors in the renewable energy production of their country.

1.4 Wind Amplification Concepts

The ability to capture more wind energy has driven the industry to invent new concepts for increasing the power output of the wind turbine. These concepts range from increasing the size of the turbine to capture more wind energy, to strategically placing wind turbines in an arrangement to maximize the output, or to diverting the free stream velocity towards the wind turbine. The larger the wind turbine is, the higher the power output is, but this also attributes to a higher capital cost. The larger wind turbine size becomes, the more difficult it is to implement in a rural setting. The rural setting does not allow for a wind farm where one turbine is fed off another wind turbine. The best approach to incorporate when using urban wind turbines, is a wind deflecting structure. This is due to a lower capital cost and maximizing the wind energy while maintaining a smaller system.

The Wind Turbine concept introduced by Dr. Rashidi consists of a cylinder as a wind deflecting structure to amplify the free stream velocity. At least two turbines are placed in the amplified wind zone near the wind deflecting structure as shown in Figure 2. This will essentially increase the power of the turbine and allows this turbine to be placed in lower wind speed environments where the use of a traditional turbine would not be economically feasible. The Cleveland State University wind turbines, that are based on the patented Rashidi design, were destroyed during Hurricane Sandy (2016) when the wind speeds were well above the operation condition of the electronics of the power generation system. Dr. Rashidi proposed using a gravity hinge to open the wind deflecting structure during the high wind speed period. The concept of using a gravity hinge for controlling the wind speed will maximizing the operational range for the turbine while limiting the potential for turbine damage during high wind speeds.

1.5 Gravity Hinge Background

Wind turbines can become self-destructive if the turbine speed is not controlled during a period of high wind speeds. The failures of the wind turbine can include, but are not limited to, destroyed bearings, overheated electronics, catastrophic failure of the turbine blades, and fire. A wind turbine that is used in conjunction with a wind amplification structure is at a higher risk of these failures if the system doesn't have a secondary protection method for controlling the turbine speed.

The challenge with the wind structure's wind speed is the potential for exceeding the cut off speed of the wind turbine. The typical industry standard for cut-off speed of a wind turbine is 25 m/s. Therefore, a solution is needed for protecting the system. The cylindrical structure in Figure 4 that uses gravity hinges to control the trap doors, provides a solution to maximize the wind speed range the turbine can operate under. The increase in the wind speed range will equate to a higher power output of the turbine over a larger wind velocity range.

The gravity hinge provides the system with a self-return mechanism using the gravitational potential energy of the moving door. The gravity hinge is typically found on a double swing door such as those found in restaurants, to make sure the doors automatically close. The mechanism is shaped so that when the external forces are no longer applied, the system will seek the lowest potential energy of the system which is the close position. The gravity hinges are constructed with using a V cam, where the lowest point is the closed position and has a follower that slides along the cam during action. Figure 1 shows the main components of a typical gravity hinge.

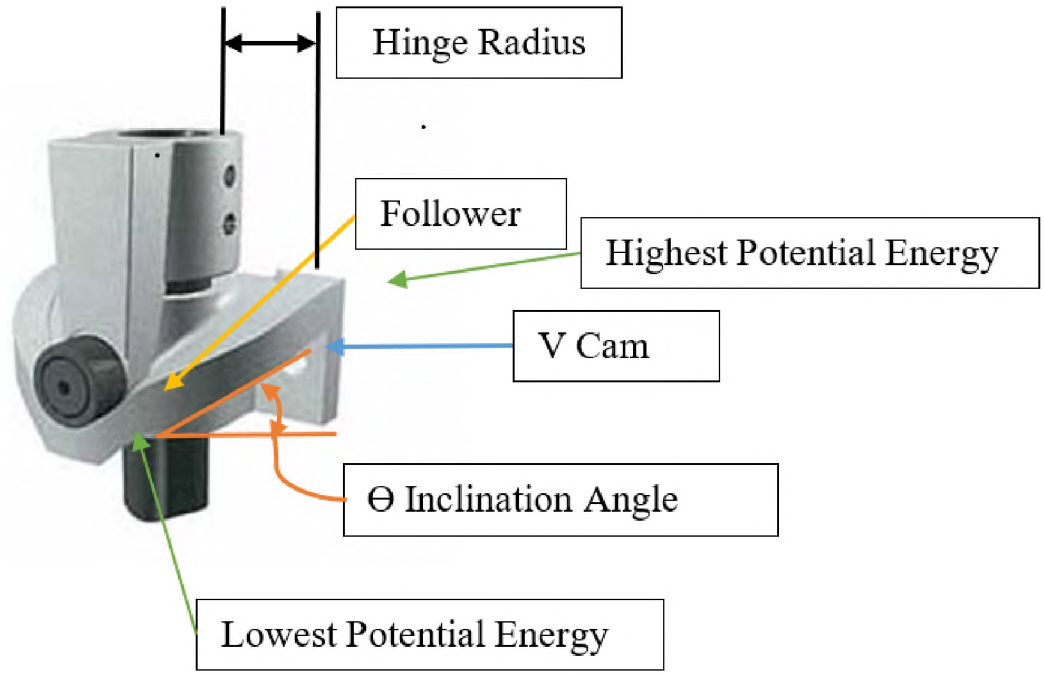


Figure 1: Example of a gravity hinge.

Figure 1 above shows the hinge mechanism in the lowest position. This hinge can rotate about the axis, driving the roller up the cam against gravity as the angle of opening.

Wind turbines have been used throughout history for generating mechanical and electrical energy for performing work. Wind energy is a promising source for electricity because the fuel source is free and only requires the capital costs for generating the system necessary for converting the energy into a useable form. The proposed wind deflecting structure has proven to be successful in amplifying the free stream velocity for capturing more wind energy. The main driving challenges for wind turbines are the location of the large powerful turbines to the area of use, the aesthetic and sound of the equipment, the required speeds necessary for generating electricity, and the wind speed exceeding the wind turbine system. The proposed solution is for when the prevailing wind speeds surpass the wind turbine cutout speed. The addition of passively controlled trap doors can mitigate the dangers of the high wind speeds. This passive control mechanism for actuating the trap door, is a gravity hinge that can be designed to increase the operating range of the wind turbine. When used in conjunction with a wind amplifying structure, this adds a layer of protection to limit the amplification factor during extreme wind conditions.

CHAPTER II

SYSTEM OVERVIEW

The original design of the structure is shown in Figure 2 where the system has 4 wind turbines mounted on the outside of the cylinder. The local velocity of the wind increases as the structure pushes the wind along the wall of the cylinder. This is shown in Figure 3, where the amplified wind zones are located.

Figure 2: Wind deflecting structure at CSU. (Rashidi et al, 2016)

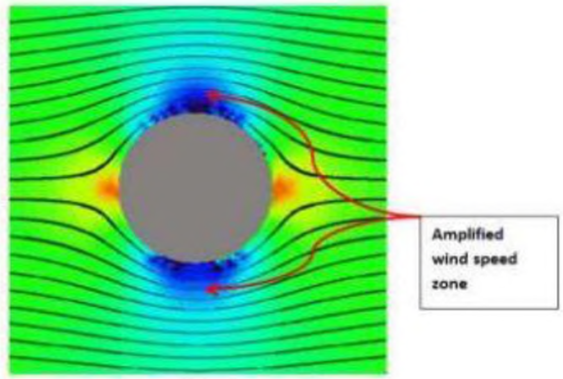


Figure 3: Air flow around the structure. (Rashidi et al, 2016)

The blue areas in Figure 3 show the increased velocity of the air due to the flow around the cylinder. The reason for the increased velocity around the structure is due to the continuity and conservation of mass equations of the fluid. The increased wind speed is captured by the wind turbine for increasing the power generation of the system. The challenge with this increased velocity is that the wind turbine will be damaged when exceeding the designed cutoff speed. The typical industry cut-off speed of a wind turbine is 25 m/s. Once this speed is met, the turbine must stop producing electricity due to the potential damage caused by excess rotational speed of the wind turbine.

This proposal is to implement a smart wind deflecting trap door that will open based off the free stream velocity. This device can be active or passively controlled but the focus on the design is to limit the complexity and installation costs of the system. Due to these constraints, a passive solution will be investigated. A few passive solutions include using a spring hinge, a gravity hinge, or magnetic latches. The example in Figure 4 shows where a gravity hinge is implemented. The implementation that is most interesting, is the gravity hinge because the returning force can be varied. The varying factors are due to the following parameters such as the inclination angle of the gravity hinge, coefficient of friction, trap door weight, and the hinge radius. Figure 4 shows the trap doors in the closed configuration during the low wind velocity.

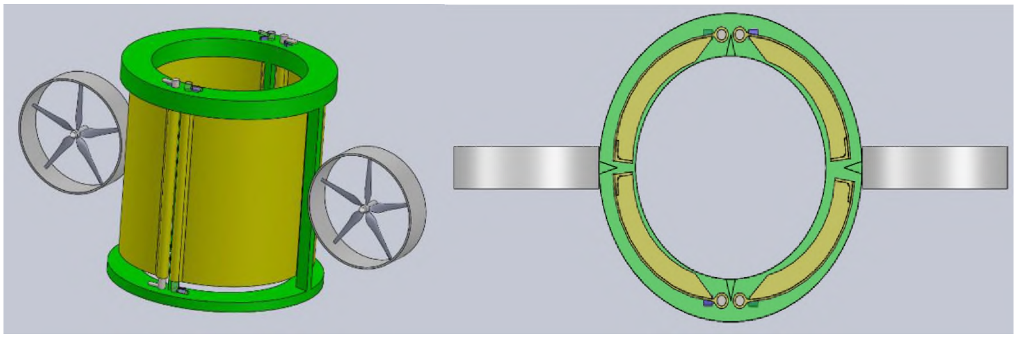


Figure 4: Wind deflecting structure with the doors closed.

The wind energy system consists of many key elements. These elements include the main structure, passively controlled trap doors, wind turbines, and electronic systems. The main structure is shown in green and gives the system the static support necessary to contain the trap doors, house the electronics, and mount the wind turbines. The main structure is designed to be as minimalistic as possible to give the trap doors the maximum change in projected height as possible. The trap doors are the gray sheets that are formed in the shape of a cylinder. The trap door is connected to the gray rotating shaft for holding the system in place. The gray discs shown to the right and left of the main structure are the wind turbines for capturing the wind energy and turning it into mechanical energy. The electronics are not shown in this figure, but they convert the mechanical energy into the electrical energy and connect to the turbine. The blue cam is a part of the gravitational hinge that is shown in Figure 4.

The trap doors are passively actuated by the drag force on the door's skin due to the free stream velocity. The trap doors are shown below in the two extreme positions of being opened and closed during high wind speeds (Figure 5). The implementation of having four trap doors on the structure was chosen because having the outer surface of the trap door as far away from the wind turbine will reduce the localized wind velocity the wind turbine captures.

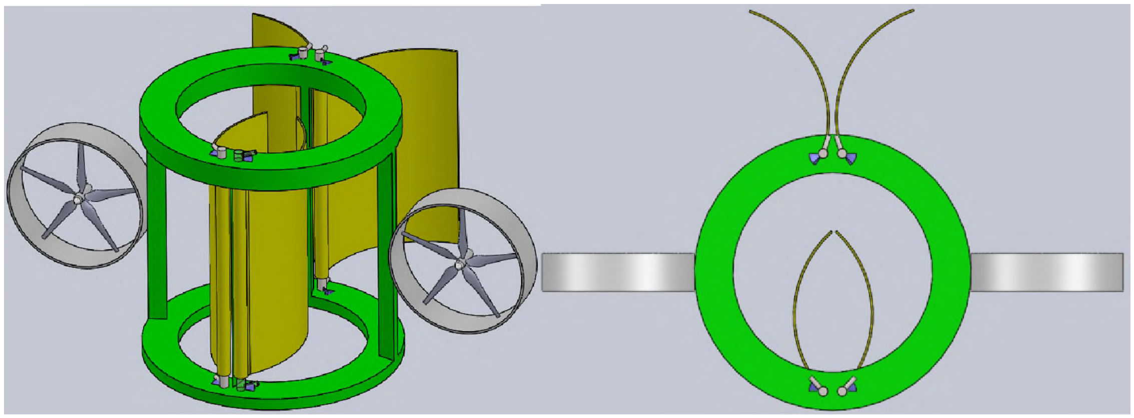


Figure 5: Trap doors open top view.

The gravity hinge is located at the top and bottom of the rotation shaft of the trap door. Figure 6 shows a detailed image of the V cam surface and follower for one of the doors.

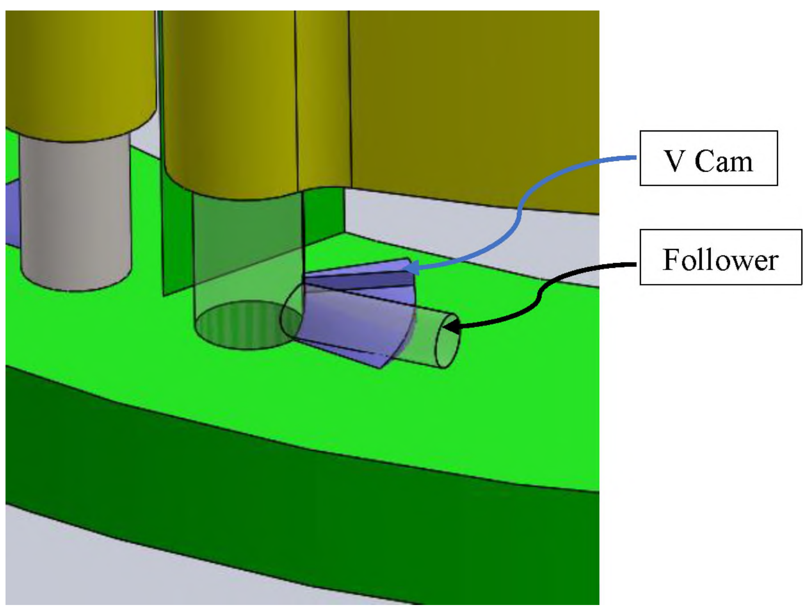


Figure 6: Enlarged image of the gravity hinge.

The wind deflecting structure with four passively controlled trap doors will maximize the wind speed range the turbine can safely operate at. The gravity hinge mechanism is the passive control mechanism that can be fine-tuned with various parameters in the design. The trap doors have the largest angle opening the cylindrical structure can offer. The gravitational hinge provides a solution to maximizing the safe operational speed of the turbine by changing the wind speed amplification factor with opening and closing of the trap door based off the prevailing wind speeds.

CHAPTER III

MECHANICAL ANALYSIS

The wind deflecting trap door cases that need to be analyzed are the closed and open positions. The closed position (Figure 4) is when the wind speeds are in the allowable designed range. The open position (Figure 5) is where the wind speeds exceed the designed limits. In the open position, the trap doors function to limit the amplification factor of the wind, limiting potential damage to the wind turbines. The open case is critical because when the wind speed slows down, the trap doors need to return to a closed configuration so the wind speed amplification factor will be maximum during the low wind speeds. A force analysis for the opening and closing of the wind deflecting structure was conducted in both scenarios.

Two frontal facing trap doors are configured in Figure 7. These four trap doors will be split into four sections to maximize the operation of the wind turbine. The two doors facing the free stream velocity will split the structure in half and hinge vertically per Figure 7. This figure shows the two extreme positions which minimize the wind amplification factor in the trap door open position.

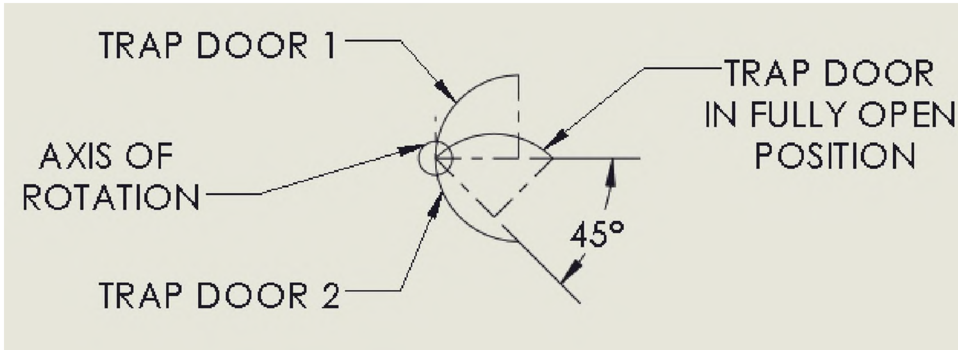


Figure 7: Plan view of the structure.

The 45-degree angle shows the range of motion for the trap doors and this is also the angle "α" in Figure 8. Figure 8 shows the dimensions of the trap door after the door has rotated open to the maximum position.

3.1 Wind Loading on the Trap Door

The free stream velocity of the wind will cause a drag force (F_d) on the structure as the air moves around the trap doors of the wind deflecting structure. The drag force on the structure is shown in Equation (1):

$$F_d = C_d A \frac{\rho V_{free}^2}{2} \qquad (1)$$

The drag coefficient (C_d) will be changed based on the flow phenomenon laminar or turbulent flow Reynold's number (Re) and the length to height ratio of the diameter of the wind deflecting structure. The drag coefficients that were used are listed below in Table 1 for a short cylinder:

Drag Coefficient for a Short Cylinder		
L/D	Laminar (C_d)	Turbulent (C_d)
1	0.6	-
2	0.7	-
∞	1.2	.3

Table I. Drag Coefficients of a cylinder and short cylinder (Drag Coefficients of Common Geometries, 2006)

The flow around the cylinder is categorized as laminar if the Reynold's number is below 5 x 10^5 and turbulent for anything above. Whether or not the flow is categorized as a laminar or turbulent flow is determined by the Reynolds Number in Equation 2. The trap door is considered to be a flat plate for determining the flow phenomenon.

$$Re = \frac{V_{free} L_c}{\nu} \quad (2)$$

Where V_{free} is the free stream velocity (15 m/s), L_c is the characteristic length (the diameter of the trap door (1 meter), and ν is the kinematic viscosity of air at 20˚C (15.16 centipoise). The resulting Reynolds number is 1x 10^6, which places the flow phenomenon in the turbulent region.

This fluid flow can be approximated using the inviscid flow with the assumption that the boundary layer is thin and negligent to the area of concern. Since the edge of the wind turbine is not located inside of the boundary layer, this provides an accurate modeling technique of the flow field the wind turbine will experience.

3.2 Kinematics of the Trap Door

The drag force relies upon the projected frontal area as a variable, and since the trap doors move during different loading conditions, a solution for solving the frontal area of the trap doors needs to be solved. The frontal area will depend on the rotation of the trap door which is determined by the static equilibrium of the system. The trap door's movement is shown in Figure 8.

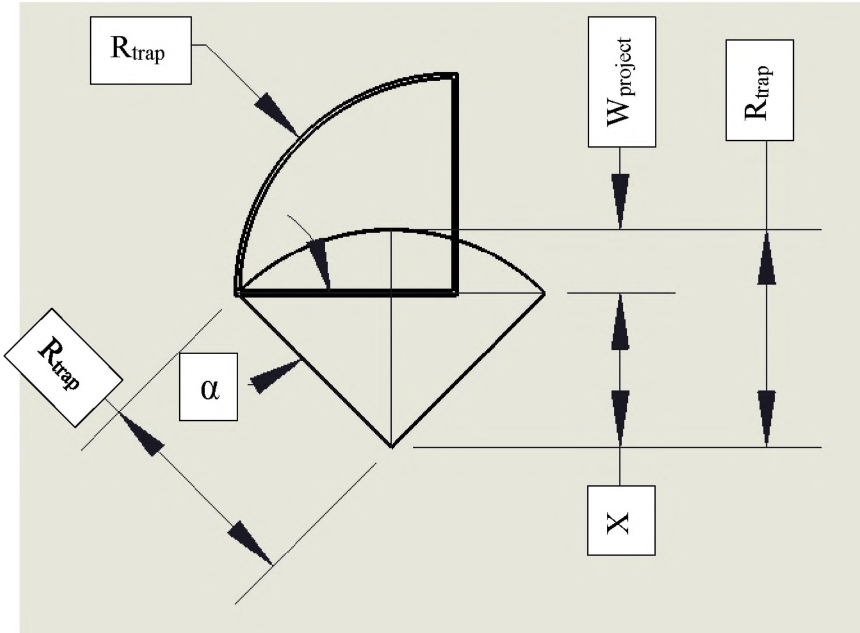


Figure 8: Trap door range of motion.

The frontal area is the length (normal to the view) of the trap door by the projected width ($W_{project}$). Equations 3-7 show how the projected width of the trap door is calculated based off the angle of opening (α) of the trap door.

$$sin(\alpha) = \frac{x}{R_{trap}} \qquad (3)$$

$$x = (R_{trap})\, sin(\alpha) \qquad (4)$$

$$W_{project} = (R_{trap}) - x \qquad (5)$$

$$W_{project} = (R_{trap}) - (R_{trap})\, sin(\alpha) \qquad (6)$$

$$W_{project} = (R_{trap})(1 - sin(\alpha)) \qquad (7)$$

The projected width of the trap door is given in Equation 7. The resulting frontal area of the trap door is the projected width multiplied by the height of the trap door as described in Equation 8.

$$A = H_{cyl} * W_{project} \qquad (8)$$

The trap doors in this configuration can only open 45 degrees, so the projected area will decrease up to 30% when the trap door is fully opened. This reduction in projected area directly relates to the drag force equation (Equation 1) where the applied force will be reduced as the trap doors reach their open position.

The wind deflecting structure contains passively controlled trap doors by way of a gravity hinge mechanism. The proposed structure will result in the wall of the trap door moving up to 30% of its diameter away from the turbine. This movement away from the wind turbine will decrease the wind speed amplification factor. The flow field of the structure needs to be analyzed to solve for the impact of the wall of the trap door moving up to 30 % of the diameter away from the turbine location.

3.3 Wind Drag Force (Density and Velocity)

The cut-off speed for a typical wind turbine is 25 m/s, but this is the local wind speed prior to being amplified by the wind structure. The cylinder shape increases the wind speed by an amplification factor of 1.6 times so the critical free stream velocity is defined by Equation 9.

$$V = \frac{cut\text{−}off\ speed}{amplification\ factor} \qquad (9)$$

The resulting free stream velocity acting on the trap doors is 15.6 m/s and this will be used to determine the resulting drag force on the trap door. The drag force acting on the projected frontal area will be in the center of the chord of the trap door. This information is used for the force analysis of the structure and then is used for the contact pressure and force analysis of the gravity hinge.

CHAPTER IV

FLUID DYNAMIC ANALYSIS

The critical aspect of the wind turbine and structure is to maximize the power output and maintain a safe working speed below the cut-out speed. A typical industry cut-out speed for wind turbines is 25 m/s and the wind amplification factor for a cylinder has been determined to be 1.6. The relationships between the wind speed and amplified wind speed are listed in Equation 10:

$$V_{amplified} = V_{free}\,(amplification\,factor) \qquad (10)$$

$$V_{free} = \frac{V_{cut-off\,speed}}{amplification\,factor} \qquad (11)$$

Using the industry cut out speed and 1.6 for the amplification factor, the maximum free stream velocity that the system can see is 15.6 m/s prior to cutting out electricity generation. This analysis is done for the closed position, but the trap door in the open position will have a different amplification factor due to the angular position of the trap door in relationship to the incoming free stream velocity. When the trap door opens, the structure and the trap doors change from a cylinder to an air foil that will experience a lower drag force due to the change in projected area of the trap door.

The wind amplification factor is dependent on the geometry of the structure and the location of the wind turbine. The opening of the passive trap door will vary the wind amplification factor that the wind turbine experiences. The geometry and angular position of the trap door needs to be analyzed to determine what the wind amplification factor will be. The goal is to determine a relationship between the wind velocity (free stream and amplified) and the angular position of the trap door.

4.1 Computational Fluid Dynamics Code

A MATLAB program was written to analyze the flow field around the structure in the closed position. The analysis was setup as shown in Figure 9 which depicts the velocity in each of the directions x and y and the boundary conditions.

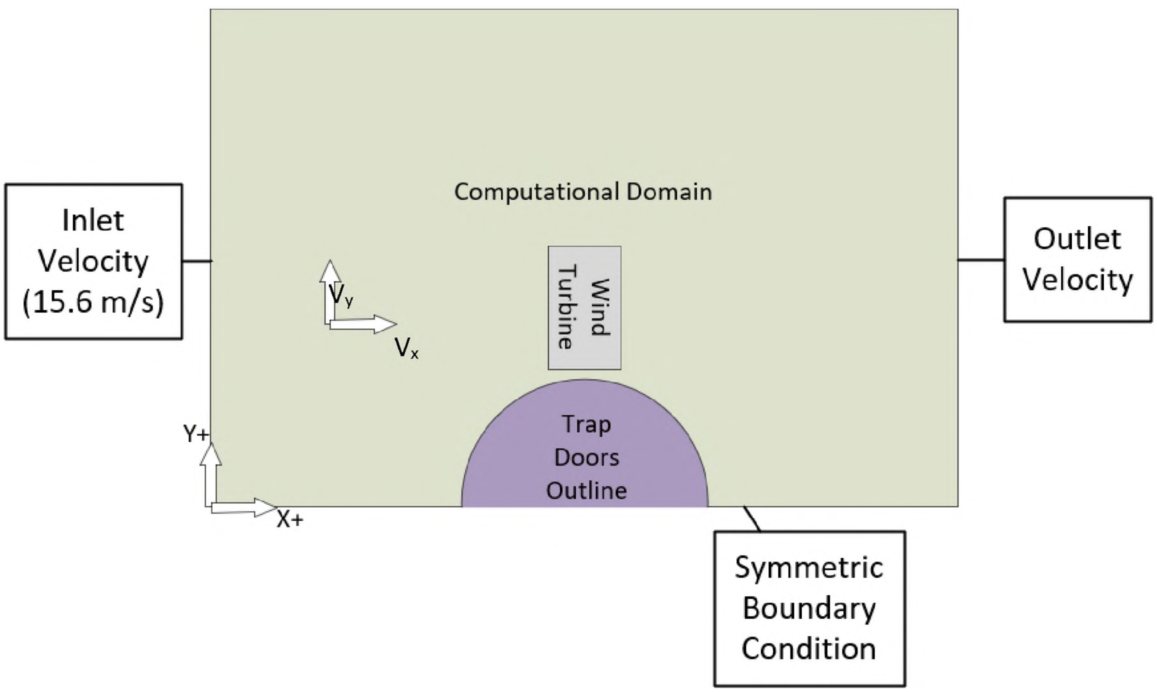


Figure 9: Computation Domain Setup of Fluid Dynamics Analysis.

The method employed for solving the stream function around the structure is the Gauss-Seidel method. When the stream function converges, the velocity is decomposed into the components for analysis. The "V_x" velocity is of interest because that is normal to the wind turbine. The velocity plot is used to determine the reduction in the free stream velocity of the air.

4.2 Scheme for Solving the Stream Function Around the Closed Trap Door Structure

The scheme used for analyzing the structure in the closed position is successive-over relaxation. The steps involved with solving the flow field include the following:

1. Set the stream function for the boundary.
2. Solve the flow field using Gauss-Seidel.
3. Calculate the error between the last time step and the current stream values.
4. When the error is less than a determined value the solution has converged.
5. Solve for the component velocities in the flow field with central difference method to determine the node values.
6. Plot the stream function and the "V_X" wind velocity at the center of the structure.

The parameters used for this simulation include the following radius of 0.5 meters, V_{free} of 15.6 m/s, and the computational domain of 3 meters.

4.3 Errors

The potential errors when using a computational method include discretization error, time step error, boundary layer error, and residual error. Each of these sources need to be analyzed prior to stating the results to determine the accuracy of the computational fluid dynamics analysis.

Time Step

The time step does not contribute to the error because this is a steady state analysis. The time is pseudo and used for tracking the number of iterations until the solution converges.

Residual Error

The residual error in Gauss-Seidel is set as a convergence criterion so the code does not converge unless the delta between iterations is under 5×10^{-8}. The sum of the error between the time steps divided by the number of nodes needs to be less than the convergence criteria. The delta between the stream function time steps needs to be less than 0.0005 which correlates to a velocity of 0.0495 meters per second. The residual error is acceptable for the analysis.

Discretization Error

The computational domain is 400 nodes by 400 nodes and the length of the computation domain is 3 meters. The distance between each node is 7.5 millimeters with this resolution and the results will not be any finer than this distance. The computational domain was doubled to 800 by 800 with the distance between the nodes being 3.75mm. The resulting stream function near the wall did not change so the computation domain of 400 by 400 is sufficient for capturing the fluid phenomenon around the passive trap door.

Boundary Layer Error

The boundary layer error is the thin fluid region near the walls of the trap door. The thickness of the boundary layer is determined by the wall function equation. The boundary layer was assumed to be minimal due to the highly turbulent flow in the field and the fact of the wind turbine being located outside of the boundary layer.

Solving component velocity error

The stream function is solved for going around the wind deflecting structure as shown in Figure 9. The wind velocity is then resolved to the components as shown in Figure 9.

4.4 Stream Function Around A Wind Deflecting Structure Results

The stream function in Figure 10 shows how the air will move around the wind deflecting structure. The stream function increases as it moves up vertically along the grid.

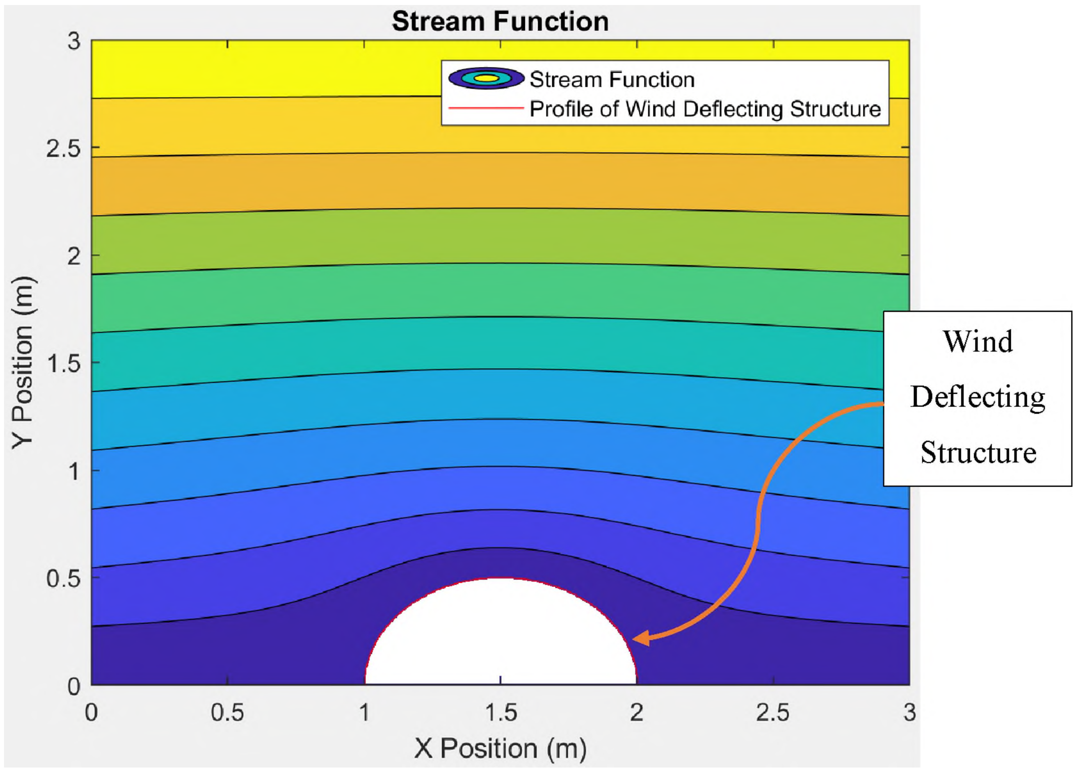


Figure 10: Stream function plot of the closed trap door configuration.

The wind turbine located outside of the wind deflecting structure at x position 1.5 meters and y position of 0.75 meters. The only velocity component that will generate wind in this position will be the V_x because the wind must be normal to the wind turbine. Figure 11: Velocity plot for the closed trap door position at the center of the cylinder, shows how the velocity change in the y direction. The velocity peaks at the surface of the wind deflecting structure and quickly tapers off to the free stream velocity. The maximin velocity is 30 m/s near the wall of the trap door.

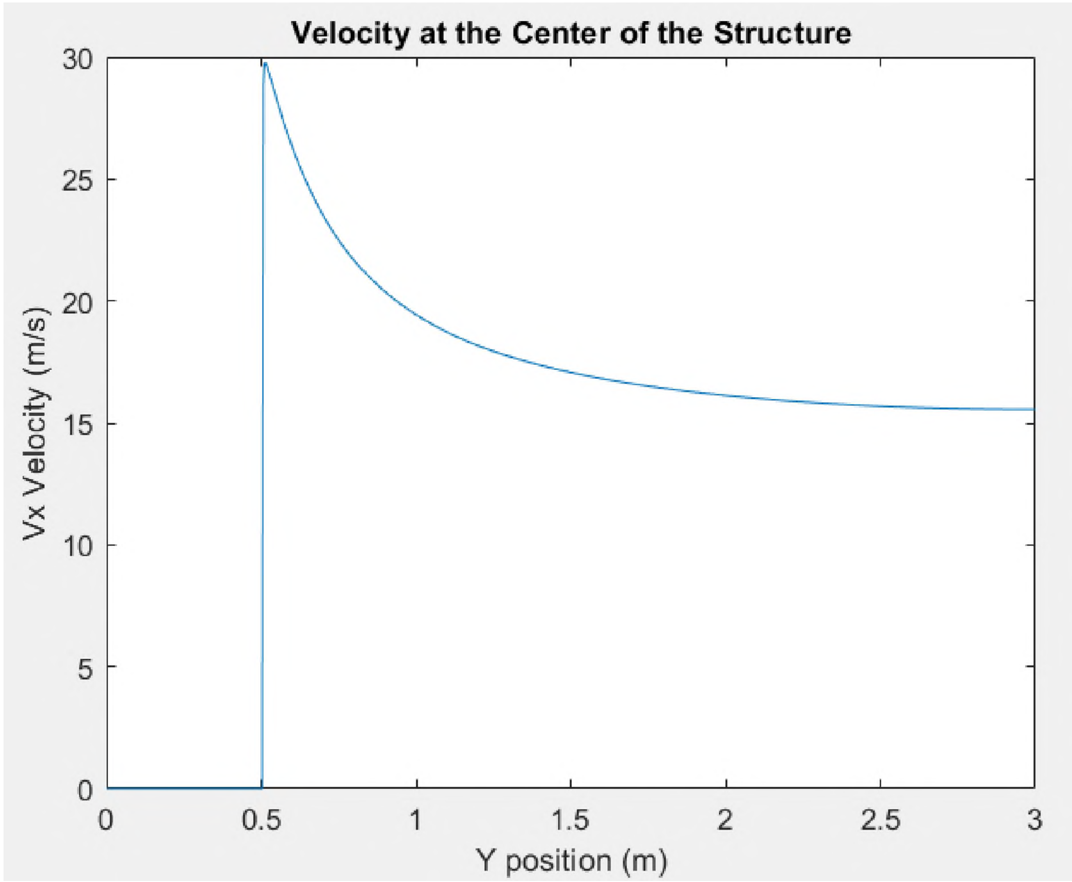


Figure 11: Velocity plot for the closed trap door position at the center of the cylinder.

The velocity plot above shows how the "V_x" wind velocity changes as the horizontal distance (y) increases from the wind deflecting structure. The passively controlled trap door can only open 45 degrees and the resulting distance traveled is 0.36 meters (Equation 5). Figure 11 can be used to determine how much the velocity will drop by the distance between the trap door and the wind turbine. The wind velocity is 25 m/s at the wind turbine location and at the new position, when the door moves 0.36 meters, the wind velocity is predicted to be 19.9 m/s. The estimated wind speed amplification from 1.6 to 1.3 is a 36% reduction.

The angular displacement of the trap door decreases the wind amplification factor, so the wind turbine will be able to operate at a larger range of wind velocity. The lower wind amplification factor also means that the trap door doesn't have to be completely open at the free stream velocity of 15.6 m/s. Table 2 is a prediction based off the distance the wind turbine will be at various velocities and predicts the wind speed the trap door needs to fully open.

Free Stream Velocity (m/s)	Closed Position Velocity (m/s)	Open Position Velocity (m/s)
10	16.1	12.7
11	17.7	14.0
12	19.3	15.3
13	20.9	16.6
14	22.5	17.8
15	24.1	19.1
16	25.8	20.4
17	27.4	21.7
18	29.0	22.9
19	30.6	24.2
20	32.2	25.5

Table II: Free stream velocity vs turbine speed with the trap door open and closed.

Table 2 shows that the trap door does not have to open to the maximum position until the free stream velocity reaches 19 m/s due to the decreased wind speed amplification factor. The parametric study of gravitational hinge parameters will use a free stream velocity of 18 m/s for having the trap door in the open position which makes sure the trap doors are fully open before the amplified wind speed gets to 25 m/s.

CHAPTER V

FORCE ANALYSIS OF THE TRAP DOOR AND HINGE

The wind amplifying structure increases the free stream velocity of the air for the turbine to be effective at lower wind speeds. The amplification structure includes passive trap doors that open when the wind speed exceeds the turbines cut off speed. A force analysis is completed on the trap door system and the resulting moment on the gravity hinge is analyzed.

The drag force (Equation 1) is defined by the projected frontal area (Equation 8), drag coefficient (Table 1), and free stream velocity. The location of the drag force is shown in Figure 12: Approach velocity and the location of the drag force., where the drag force is acting on the center of the trap door located in middle of the height of the door.

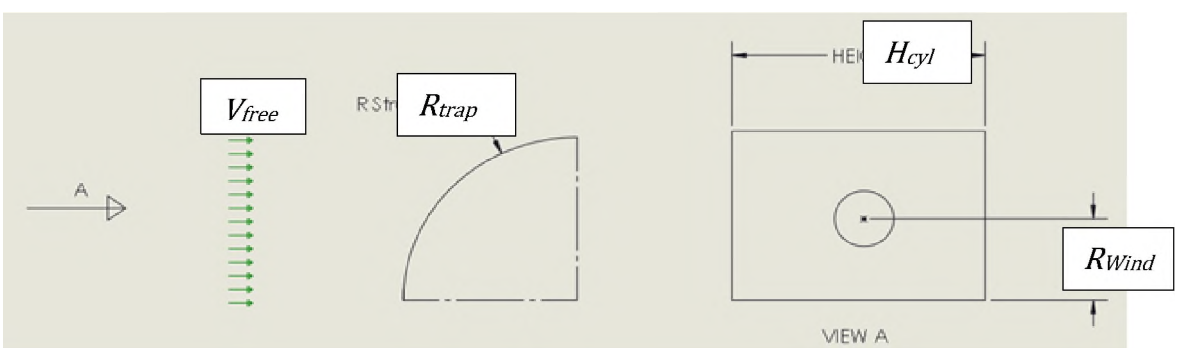


Figure 12: Approach velocity and the location of the drag force.

The free body diagram is shown in Figure 13 and Figure 14 shows the contact forces on the gravity hinge. The first one shows a top-down view of the trap door system and the second shows a detailed view of the gravity hinge.

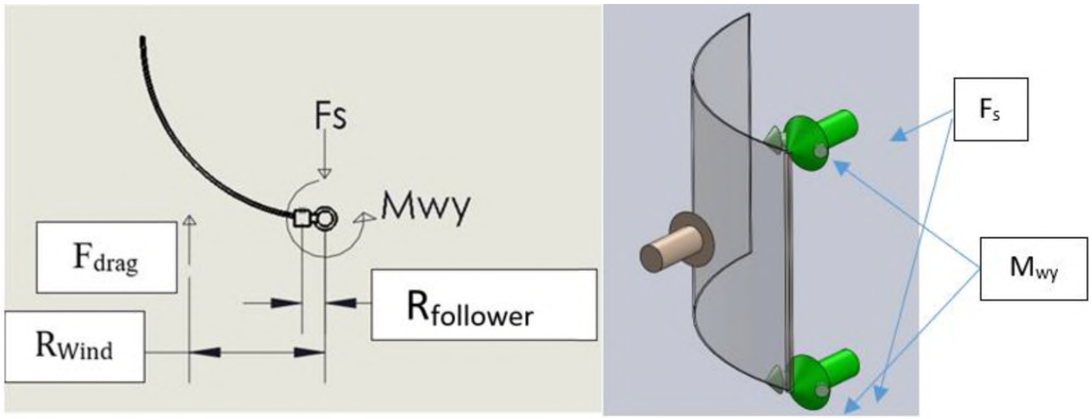


Figure 13: Free body diagram of the structure.

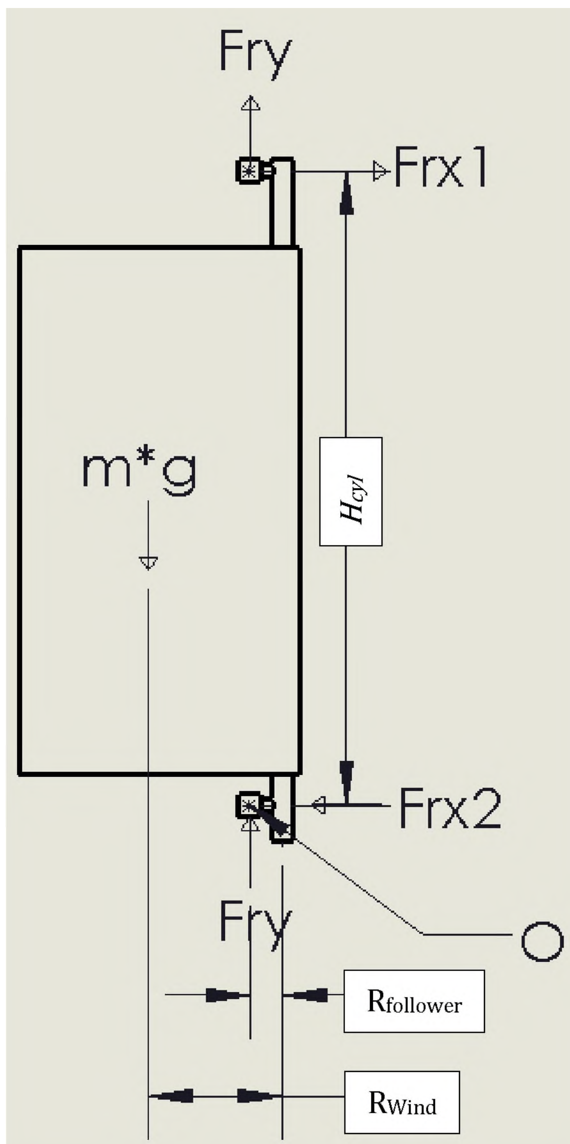


Figure 14: Frontal view of the trap door.

$$\sum M_0 = 0;\ F_{rx_1}H - mg(R_{Wind} - R_{follower})\ (11)$$

$$F_{rx_1}H\ =\ mg(R_{Wind} - R_{follower})\quad (12)$$

$$F_{rx_1} = \frac{mg(R_{Wind} - R_{follower})}{H}\quad (13)$$

$$\sum F_x = 0; F_{rx_1} - F_{rx_2}\ (14)$$

$$F_{rx_1}\ =\ F_{rx_2}\quad (15)$$

$$\sum F_y = 0;\ 2F_{ry} - mg\ (16)$$

$$2F_{ry} = mg\quad (17)$$

$$F_{ry} = \frac{mg}{2}\quad (18)$$

The drag force (F_{drag}) is acting on the center of the trap door's chord. The trap door's movement will cause F_{drag} to get closer towards the axis of rotation. Figure 15 and Equations 19-28 show the relationship between the angle displacement of the trap door and the location of R_{Wind}.

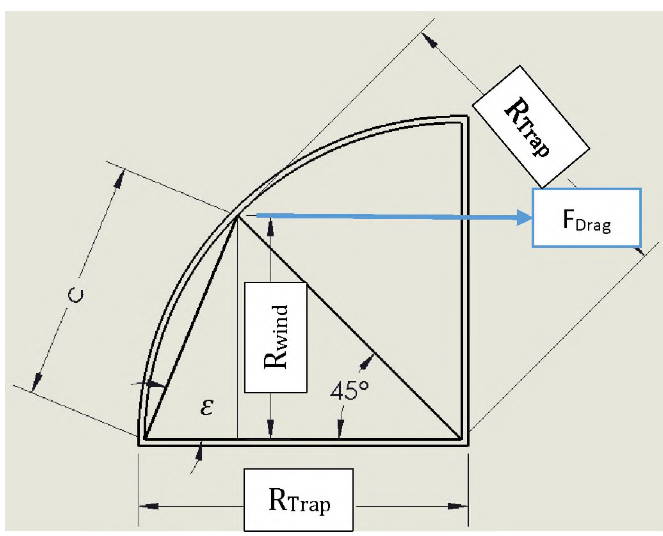


Figure 15: Location of the drag force.

$$c = \sqrt{a^2 + b^2 - 2abcos(\gamma)} \qquad (19)$$

$$c = \sqrt{2R^2 - 2R_{Trap}{}^2 cos(\gamma)} \qquad (20)$$

$$c = \sqrt{2R_{Trap}{}^2(1 - cos(\gamma))} \quad (21)$$

$$c = R_{Trap}\sqrt{2(1 - cos(\gamma))} \quad (22)$$

$$\gamma = 45; because\ a = b = R_{Trap}$$

$$c = R_{Trap}\sqrt{2(1 - cos\left(\frac{\pi}{4}\right))} \quad (23)$$

$$c = R_{Trap} \cdot 0.7653 \qquad (24)$$

Since a = b angles must be equal

$$\varepsilon = \frac{180-45}{2} = 67.5 \qquad (25)$$

$$sin(\varepsilon - \alpha) = R_{Wind}/c \qquad (26)$$

$$R_{Wind} = sin(\varepsilon - \alpha) \cdot c \qquad (27)$$

$$R_{Wind} = sin\ (67.5 - \alpha) \cdot R_{Trap} \qquad (28)$$

Equation 28 shows the relationship between the angular displacement (α) of the trap door and the location of R_{Wind}. The angular displacement can only be less than 45 degrees due to the mechanical limitations of the motion, so the magnitude of R_{Wind} will decrease as the angular displacement increases.

The sum of force is in the horizontal direction where Equation 29, shows the reaction force of the hinge to counter the applied drag force. Equation 30 is the sum of moments at the hinge to prevent the system from rotating because the trap door is in static equilibrium.

$$\Sigma F_y = 0; F_w - F_s = 0 \text{ (29)}$$

$$\Sigma M = 0;\ F_w R_{wind} - M_{wy} * Qty \qquad (30)$$

The moment related to the hinge is counteracted by the force being applied through the gravity hinge mechanism. The reaction force at the hinge could potentially be a force system as shown in Figure 16.

Figure 16: Detail of simplified forces.

This configuration would give the largest moment reaction around the cam surface. The problem is the downward force on the hinge inner radius means that the pinon will have lost contact with the V cam which is not possible. The next configuration analyzed was an inclined ramped force as shown in Figure 17.

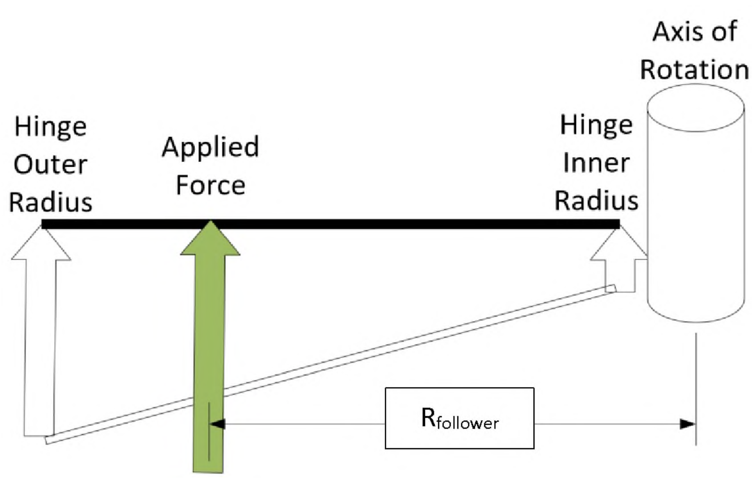


Figure 17: Detail of hinge reaction forces.

The applied force location would be two thirds of the distance between the inner and outer radius of the hinge. That would make $R_{follower} = 2/3\,(R_{outer\ hinge} - R_{inner\ hinge}) + R_{inner\ hinge}$

$$M_{wy} = F_p R_{follower} \quad (31)$$

$$F_p = M_{wy}/R_{follower} \quad (32)$$

The reaction of the forces of the gravity hinge are resolved by Figure 18 below. The figure shows the reaction force at the hinges decomposed into each component. F_p is broken into the parallel force up the hinge and the normal force into the inclination. The weight of the system is broken into the normal force of the hinge and the parallel sliding force.

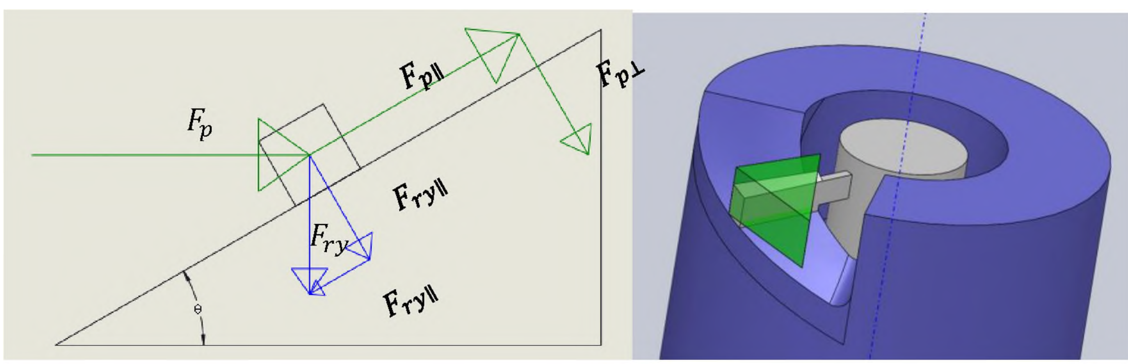
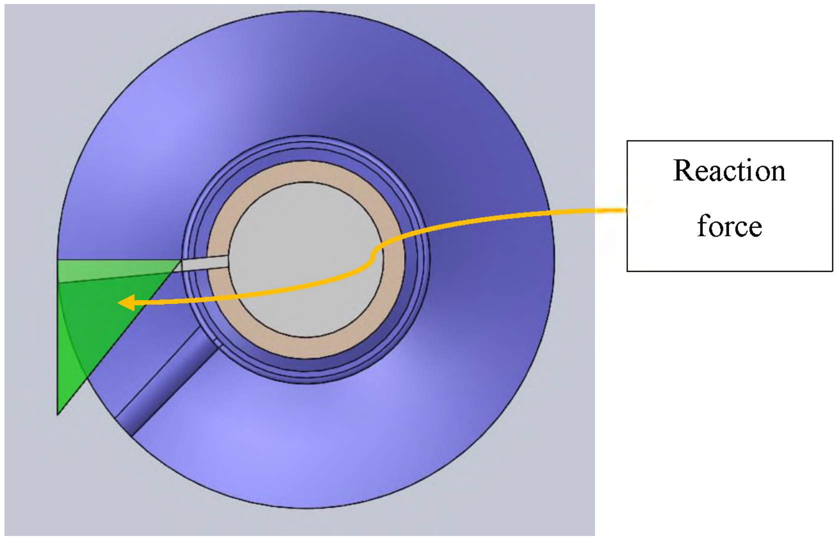


Figure 18: Force analysis of the rise of the hinge.



The wind and gravity forces are broken into the component's perpendicular forces and parallel forces of the hinge in Equations 33-37

$$F_{p\perp} = -sin\ (\theta)F_p \qquad (33)$$

$$F_{g\perp} = -cos\ (\theta)F_g \qquad (34)$$

$$F_{n\perp} = F_{g\perp} + F_{p\perp} \qquad (35)$$

$$F_{g\parallel} = -sin\ (\theta)F_g \qquad (36)$$

$$F_{p\parallel} = cos\ (\theta)F_p \qquad (37)$$

$$F_{f\parallel} = \mu\ F_{n\perp} \qquad (38)$$

$$F_{\parallel} = F_{p\parallel} - F_{g\parallel} - F_{f\parallel} \quad (39)$$

The perpendicular forces are combined to determine the force that will determine how much the frictional force will be for preventing the hinge from rotating in Equation 38. The resulting forces in the parallel direction of the incline will determine if the trap door's angular position will change based off the frictional force and applied forces at the hinge in Equation 39.

The free body diagram is shown in Figure 13: Free body diagram of the structure and Figure 18: Force Analysis of the rise of the hinge. These figures were used to calculate the component forces in the hinges. The component forces were then calculated to determine if the hinge opens or closes based off the component values. The equations listed above are used in the MATLAB code to determine the effect of each individual parameter. The MATLAB code is used to determine how each parameter affects the angular position of the trap door.

CHAPTER VI

PARAMETRIC STUDIES

The problem has multiple parameters that can influence the trap door's angular position. These parameters include the trap door's weight, trap door's height, trap doors projected diameter, coefficient of friction, hinge radius, angle of inclination, trap door angle opening, and wind velocity. The key criteria include the trap doors are open at the desired amplified wind speed of 25 m/s and return to the closed position when the free stream wind speed is 0 m/s. The gravity hinge mechanism has multiple parameters that need to be analyzed for understanding how each component influences the passive trap door's angular position.

A program written in MATLAB was used to analyze how each parameter effects the position of the trap doors under various loading conditions. The code performs an initial evaluation of the parameters to determine if the set satisfies the criteria of the trap door opening and closing at the desired wind speeds. The loop of the MATLAB code runs in the following order:

1. Generate a variation list of the parameters
    a. Each parameter is varied independently
2. Calculate the drag force on the trap door in the closed position

3. Perform a force analysis to determine if the trap door starts to open given the drag force.

4. The drag force is re-calculated at the new position if the trap door changed location and step 3 is repeated until the trap door is stable or in the max open position. The code documents the parameters of the system and the angle of opening.

6. The code sets the drag force to 0 Newtons for simulating when the free stream velocity is 0 m/s.

7. The force analysis is completed and determined if the trap door moves down the v-cam on the gravity hinge.

8. When the trap door reaches the end position (0°) or the door stable.

9. The code saves the angular position of the trap door, when the zero-drag force is applied to the system.

10. The MATLAB code saves all the configurations that the system opens at the desired speed and returns to the starting position when the drag force is removed.

11. These parameters are then filled into making detailed variation plots where one parameter is varied when the others are held constant. This determines the effect of each parameter on the system.

The initial parameter set included the following:

R_{Trap} = 0.5 meters

H_{Cyl}= 1 meters

V_{Free}= 10 m/s and 18 m/s

Angle of inclination = 5°, 10°, 20°, 30°, 40°, and 45°

$R_{follower}$ = 10 mm, 35 mm, and 60 mm

Coefficient of Friction = 0.01 ,0.1, 0.325, 0.55, 0.78, and 1

The gravity hinge parameters need to be analyzed to determine if it's a possible solution for having the trap door open by the drag force and close due to the gravitational force. Despite having 300 possible iterations only 50 of them are applicable because the trap door is actuated, and the trap door returns when the drag force is removed. The potential configurations are then saved and further analyzed with varying a single parameter varied. For instance, the wind speed, trap door mass, cylinder height, trap door radius, angle of inclination, and hinge radius are held constant while the friction coefficient is varied between 0 and 1. The graph below shows the effect of varying the coefficient of friction with a certain parameter set:

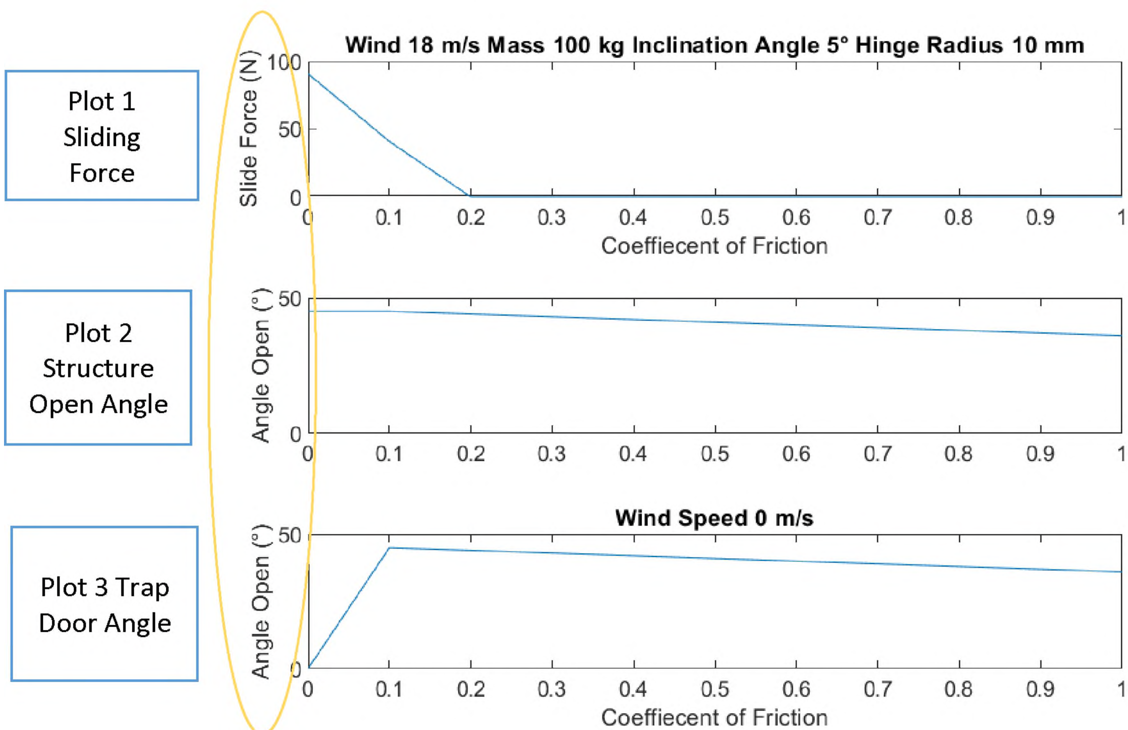


Figure 19: Interpreting the MATLAB Plots.

The details in Figure 19: Interpreting the MATLAB Plots. gives a high-level overview of how changing the coefficient of friction will affect the angular position of the trap door. Each one of the MATLAB plot figures provides the parameters that are held constant for the run, in this case wind speed is 18m/s, mass of the trap door is 100 kilograms, angle of inclination is 5 degrees, and the hinge radius is 10 millimeters. Plot 1 in Figure 19 shows how the sliding force changes based off various coefficients of friction. Plot 2 shows the corresponding angular displacement of the trap door due to the changing coefficient of friction. Plot 3 shows what the angle of the trap door will be at when the wind speed subsides to 0m/s after being opened to the angle in plot 2. For example, a coefficient of friction of 0.01 will have an angular opening of 45 degrees when the wind speed is 18m/s but when the wind changes to 0 m/s the wind trap door will close. The second example is a coefficient of friction of 0.1 where the trap door will fully open at a wind speed of 18m/s, but it will stay open when the wind speed changes to 0 m/s. The frictional force of the trap door is too high for the gravitational force of the system to return the trap door back to the closed position. This system will only be feasible when the coefficient of friction of the hinge is less than 0.05 because the frictional force is too large in comparison with the gravity force for returning the trap door. This combination of parameters is not ideal because the trap door opens regardless of what the coefficient of friction, which means the structure will have opened before the wind speed reached 18m/s. The low opening speed will result in a lower wind speed amplification, but the turbine will be able to operate at higher free stream velocities vs without having the gravitational hinge.

6.1 Coefficient of Friction

The friction force of the gravity hinge impedes the trap door movement. The two components that influence the frictional force include the normal force to the surface and the coefficient of friction. The higher frictional forces will impede the ability for the trap door to return to the closed position when the wind subsides. Opening of the trap door is prevented by the normal force of the trap door onto the gravity hinge and the coefficient of friction. The higher the frictional force will require a greater drag force and gravitational force to move the system to the open or closed position.

Figure 20: The effect of the changing the gravity hinge's friction coefficient below shows a potential solution for the trap door and the gravity hinge parameters.

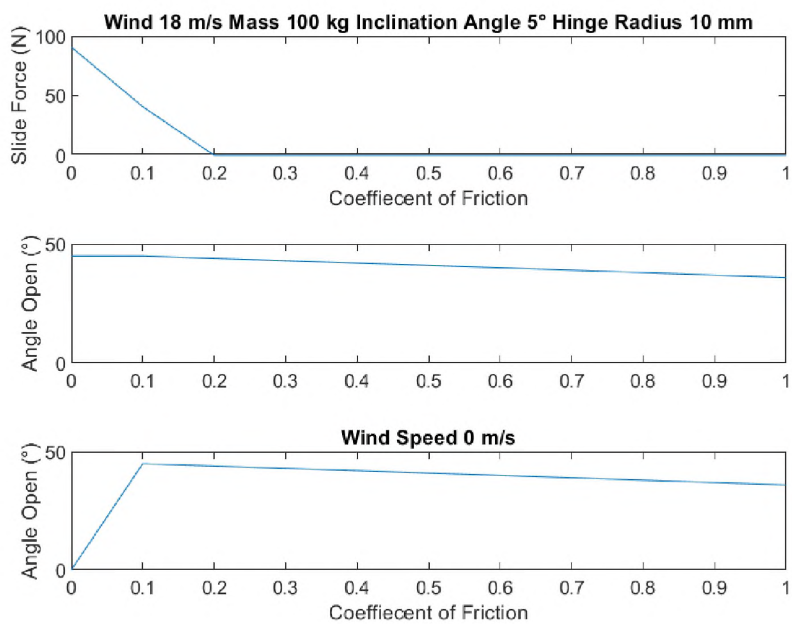


Figure 20: The effect of the changing the gravity hinge's friction coefficient.

Only a range of coefficient of friction between 0.01 and 0.1 are possible solutions given the set of parameters because with the higher friction coefficient the trap door will not return to the closed position. This is due to the return gravity force not being sufficient to return the trap door when the wind subsides.

6.2 Hinge Radius

The hinge radius supports the trap door of the system. This analysis will look at the $R_{follower}$ because it directly relates to various inner and outer hinge radii. The size of the hinge radius will change the reaction force applied to the hinge for resisting the moment caused by the drag force. The larger the hinge radius the smaller the sliding force of the trap door.

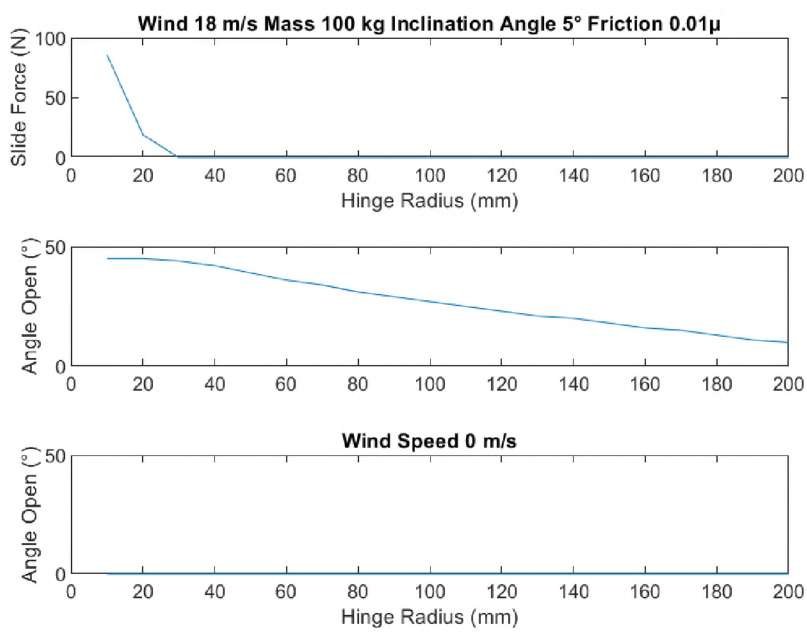


Figure 21: The effect of the changing the gravity hinge's radius.

Figure 21 The effect of the changing the gravity hinge's radius, shows how changing the radius of the hinge will affect the trap door's angular displacement. The sliding force of the trap door is an exponential decay between 10 mm and 100 mm. This sharp decay is caused by the reaction force of the hinge being further away from the pivot point. A hinge radius of greater than 20 mm will start limiting the angle of the trap door that will open due to the lower reaction forces on the hinge. The hinge radius does not have a significant effect on the return angle of the trap door after the wind speed is 0 m/s. Increasing the size of the hinge radius has a great effect on decreasing the sliding force at the gravity hinge.

6.3 Trap Door Mass

The mass of the trap door will impact the frictional force that the drag force will need to require to overcome. The inclination angle and the door mass will cause a closing force on the system to make sure the trap door closes when the wind velocity subsides.

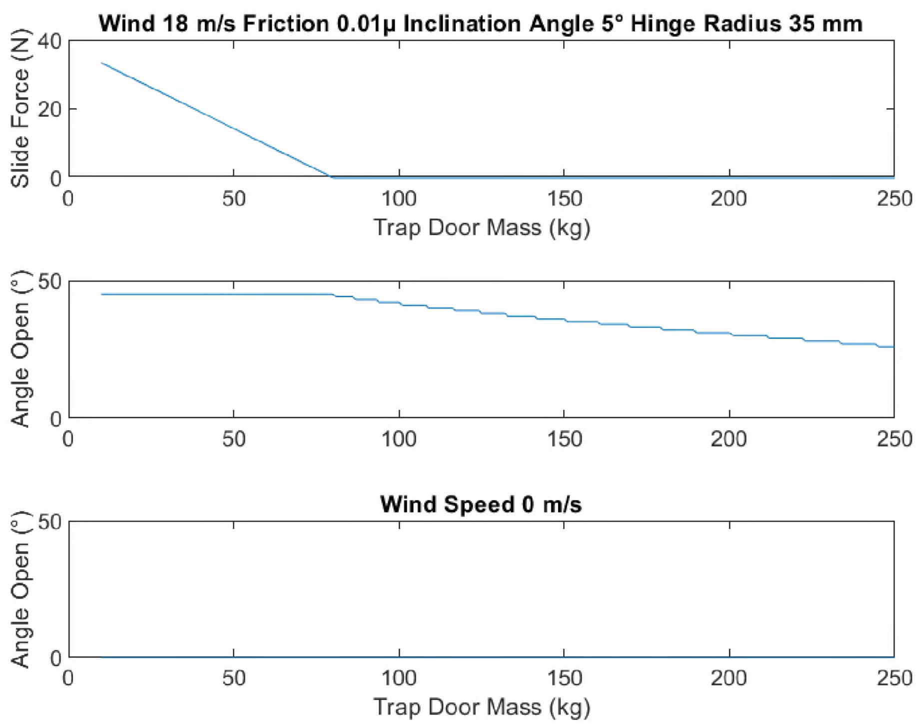


Figure 22: The effect of varying the trap door's mass.

The trap door's mass does not have a significant factor in opening of the trap door. However, adjusting the weight can be a significant factor for fine tuning the return position of the trap door when the wind velocity subsides as shown in Figure 22: The effect of varying the trap door's mass.

6.4 Angle of Inclination

The angle of inclination of the gravity hinge will have a drastic effect on the force required for opening the trap door. The angle of inclination changes the normal force and sliding force applied at the gradational hinge.

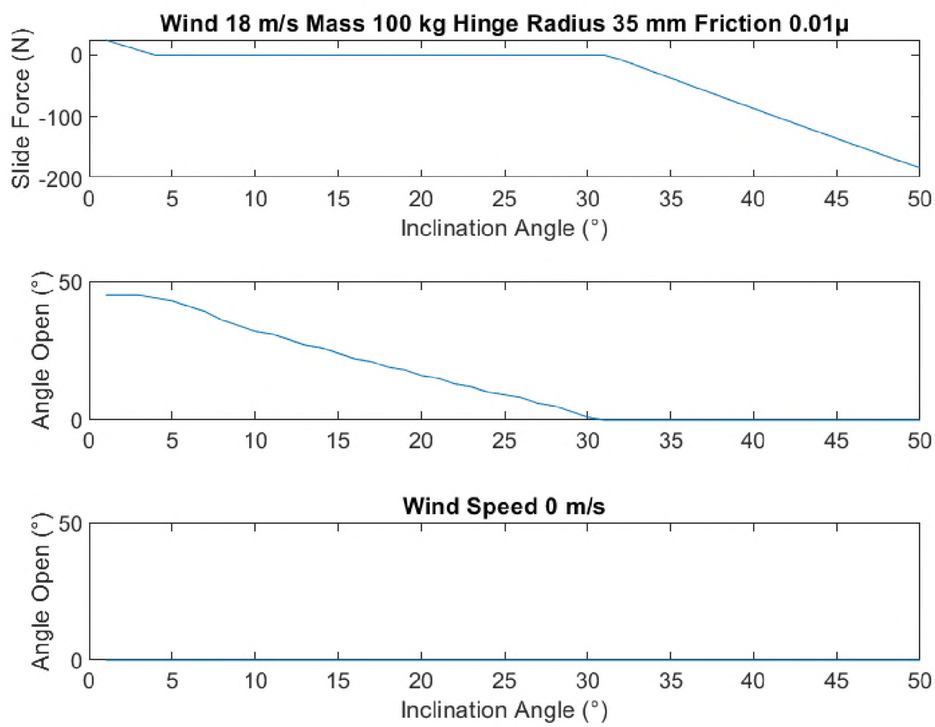


Figure 23: Gravity hinge with varying the angle of inclination.

The parameter set in Figure 23: Gravity hinge with varying the angle of inclination, needs a gravity hinge with an inclination angle of less than 3 degrees so the drag force applied to the trap door will overcome the gravitational force. Any angle of inclination between 3 degrees and 32 degrees will result in the trap door not reaching the maximum angle of opening of the trap door. The angle of inclination does not have a significant impact on if the system returns to the closed position due to the low frictional forces.

6.5 Free Stream Velocity

The geometrical parameters of the gravity hinge directly influence when the trap doors will open. A few geometric parameter sets have been identified for fully opening when the wind speed reaches the critical velocity of 18 m/s. The goal is to make sure the trap doors stay in the closed position until they reach the desired opening speed since premature opening will start limiting the velocity at the wind turbine.

The goal is to determine a set of parameters that the trap doors will open at 18 m/s and will close the trap doors when the wind speed is 0 m/s. Figures 24 and 25 below shows how the trap door's position with only varying the velocity between 0 m/s and 18 m/s.

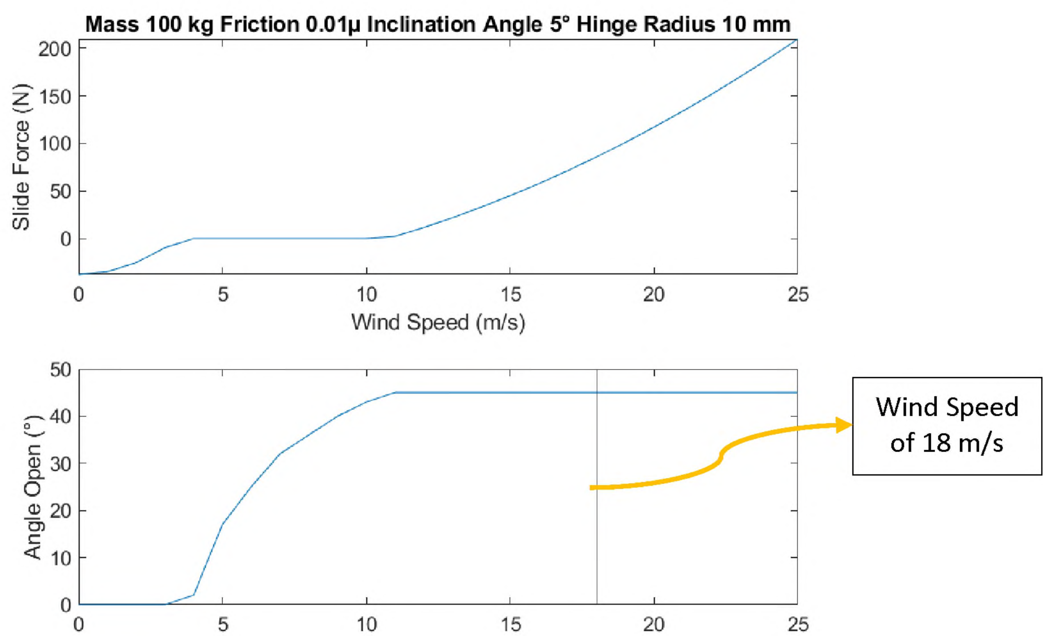


Figure 24: Trap door's reaction to varying the wind speed with 10mm hinge radius.

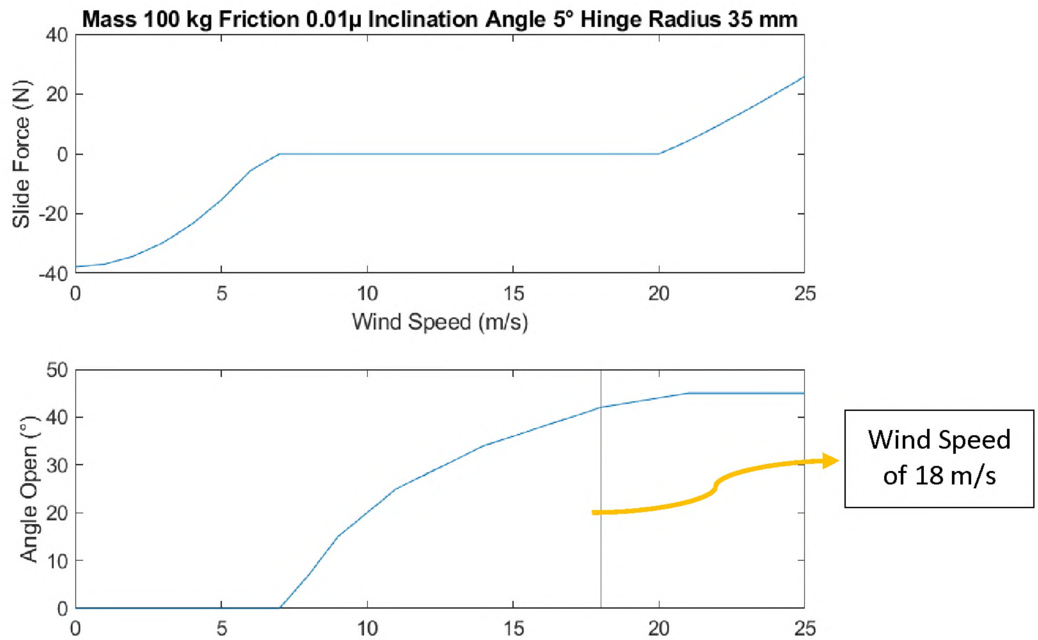


Figure 25: Trap door's reaction to varying the wind speed with 35mm hinge radius.

Figures 24 and 25 show that we can fine tune the hinge radius to make sure the trap door fully opens at 18 m/s. The ideal hinge radius for this system was determined to be 26 mm because that is the point where further increasing the hinge radius would make the system not fully open. The final analysis of the system is shown in the figure below.

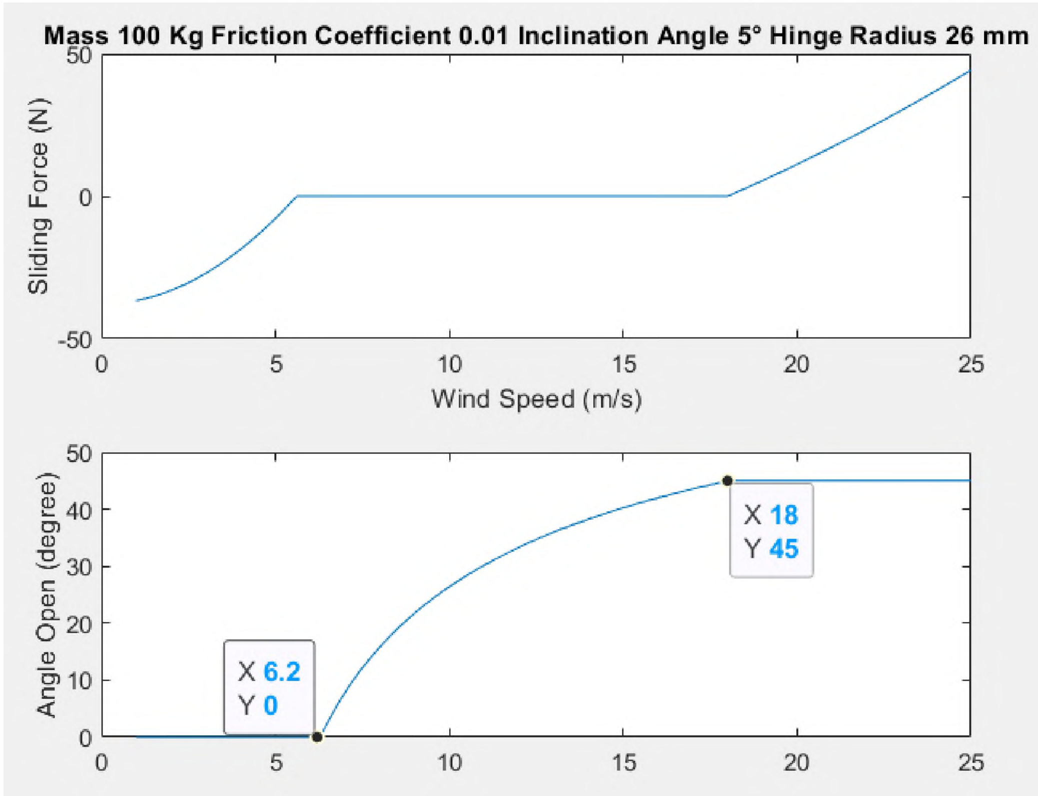


Figure 26: Trap door's angular opening due to the wind speed with 26mm hinge radius

The system consisting of a trap door mass of 100 kilograms, coefficient of friction of 0.01, angle of inclination of 5 degrees, and a hinge radius of 26 mm will have the trap door to start opening when the wind reaches 6.2 m/s, and the door will be completely open at 18 m/s to ensure safe wind turbine operation.

CHAPTER VII

DYNAMIC RESPONSE OF THE SYSTEM

The atmospheric conditions are ever changing, and the passively controlled trap door is designed to maximize the wind amplification without damaging the wind turbine. The gravity hinge mechanism is designed to passively control the wind amplification factor between 1.28 and 1.6 when the trap door is at various positions. The wind will randomly fluctuate during a storm with gusts being a short burst of higher wind speed. The trap doors will respond to the gusts with different angles of opening based off the initial conditions and wind speeds applied. The dynamic response of the system was derived using Lagrange Multiplier Technique.

The dynamic inputs to the trap door are the wind gusts, with an instantaneous wind speed lasting at least three seconds over a sample period of ten minutes (Guide to Meterological Instruments and Methods of Observation, 2008). A wind gust is defined as a brief increase in the speed of the wind due to transient conditions. A squall is a strong wind characterized by a sudden onset in which the wind speed increases at least 16 knots (8.2 meters per second) and is sustained at 22 knots (11.3 meters per second) for at least one minute. The passively controlled trap door needs to be analyzed with using a squall and wind gusts to determine the how these environmental conditions affect the angular displacement of the trap doors.

7.1 Lagrange Method Analysis

The Lagrange Method uses the potential and kinetic energy of the system to solve for the total energy of the system. The total energy of the system is then integrated to solve of the position of the system at any point in time. This method is helpful because the energy of the system can be resolved into one coordinate system for analyzing the effects of the applied forces on the trap doors.

The system is decomposed into two setups where Figure 27: Lagrange top-down view shows how the trap door rotates around the hinge and Figure 28: Lagrange inclined ramp. Figure 27 shows the green line as the trap door in the closed position during the time of low wind speeds where the light green line shows the trap door slightly opened by α which is the trap door's angular position. ω is the angular velocity that the door is rotating at this instance.

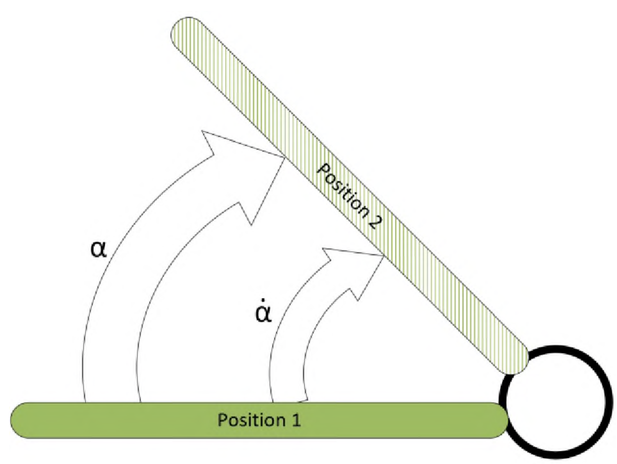


Figure 27: Lagrange top-down view.

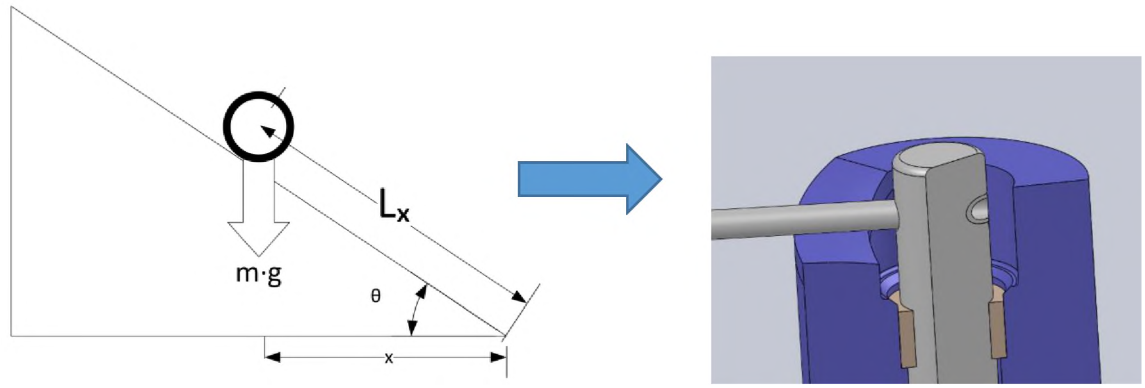


Figure 28: Lagrange inclined ramp.

Figure 27 shows the position of the trap door at a specified angle opening (α) where the trap door has moved up the gravity hinge by θ increasing the gravitational potential energy. θ is the angle of inclination of the gravity hinge where L_x is the length traveled along the cam surface. The "x" component is the horizontal distance traveled of the trap door and h_x is the vertical distance the trap door has risen above the lowest point in the system.

The Lagrange of the system is defined by$L = KE - PE$ Equation 40 where KE is the kinetic energy and PE is the potential energy of the system.

$$L = KE - PE \quad (40)$$

The only kinetic energy of the system is the trap doors rotational energy defined by Equation 41. The potential energy of the system is the height that the trap door has risen on the gravity hinge which is shown in Equation 42.

$$KE = \frac{1}{2} I \omega^2 = \frac{1}{2} I (\dot{\alpha})^2 \qquad (41)$$

$$PE = mgh_x \qquad (42)$$

The system is constrained by Equation 7 because the angle of inclination must be less than 45°. If the angle of inclination is greater than 45° and the drag force was removed the pinon would loose contact with the cam which is impossible. Equation 43 is a coorindate transformation to determine how far the trap door has traveled in the x-cooridnate system.

$$tan(\theta) = \frac{h_x}{x} \ ; \theta \leq 45^0 \qquad (43)$$

$$\text{From Figure 27 } x = r \cdot \alpha \qquad (44)$$

$$tan\,\theta = \frac{h_x}{r \cdot \alpha} \qquad (45)$$

Equation 45 is the combination of Equation 43 and Equation 44 to relate how the two different coordinate systems translate into each other. This is simplified to solve for h_x in Equation 46.

$$h_x = tan(\theta) \cdot r \cdot \alpha \qquad (46)$$

$$PE = m \cdot g \cdot tan(\theta) \cdot r \cdot \alpha \qquad (47)$$

$$L = {}^{1}\!/_{2}\, I(\dot{\alpha})^2 - m \cdot g \cdot tan(\theta) \cdot r \cdot \alpha \qquad (48)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\alpha}}\right) - \frac{\partial L}{\partial \alpha} = \tau_{Wind} \qquad (49)$$

$$\frac{\partial L}{\partial \alpha} = -m \cdot g \cdot tan(\theta) \cdot r \qquad (50)$$

$$\frac{\partial L}{\partial \dot{\alpha}} = I\dot{\alpha} \qquad (51)$$

$$\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{\alpha}}\right) = I\ddot{\alpha} \qquad (52)$$

$$\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{\alpha}}\right) - \frac{\partial L}{\partial \alpha} = I\ddot{\alpha} + m \cdot g \cdot tan(\theta) \cdot r = \tau_{Wind} \qquad (53)$$

The equation of motion is described by Equation 53. The torque applied to the hinge due to the drag force applied to the trap door and the distance from the center of the trap door to the hinge. The following simulations are for a trap door with a moment of inertia of 600 kg·m^2, r_{hinge} of 26 mm, D_{cyl} of 1 m, H_{cyl} of 1 m, trap door mass of 100 kg with an ode45 equation solver in MATLAB.

The first case the trap door is closed with a prevailing wind speed of 15 m/s. The angular response of the system is shown in Figure 29: Dynamic Response of a Closed Trap Door to a 15 m/s Prevailing Wind Speed. The door quickly starts to open when the wind reaches the trap door on the structure. The trap door opens to 41.4 degrees at 10 seconds which is the peak angular displacement. The trap door settles at an angular position of 40.4 degrees.

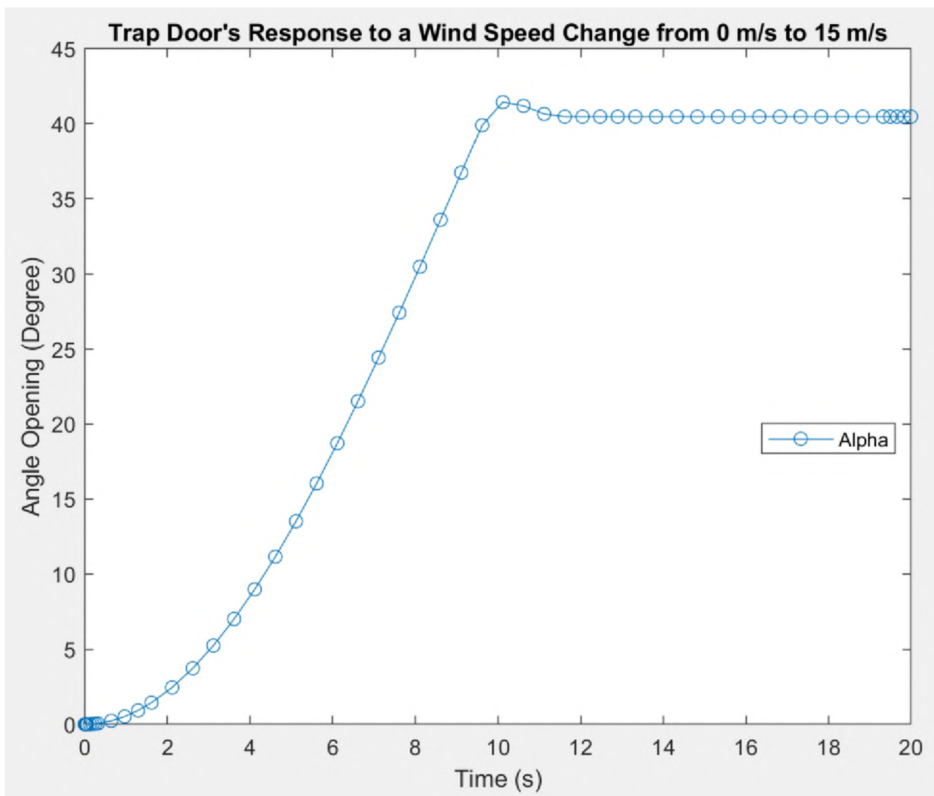


Figure 29: Dynamic Response of a Closed Trap Door to a 15 m/s Prevailing Wind Speed.

The second case shows the trap door fully open when the wind speed changes from 15 m/s to 6.2 m/s and is shown in Figure 30: Trap Door's Response to a Wind Speed Change from 15m/s to 6 m/s.

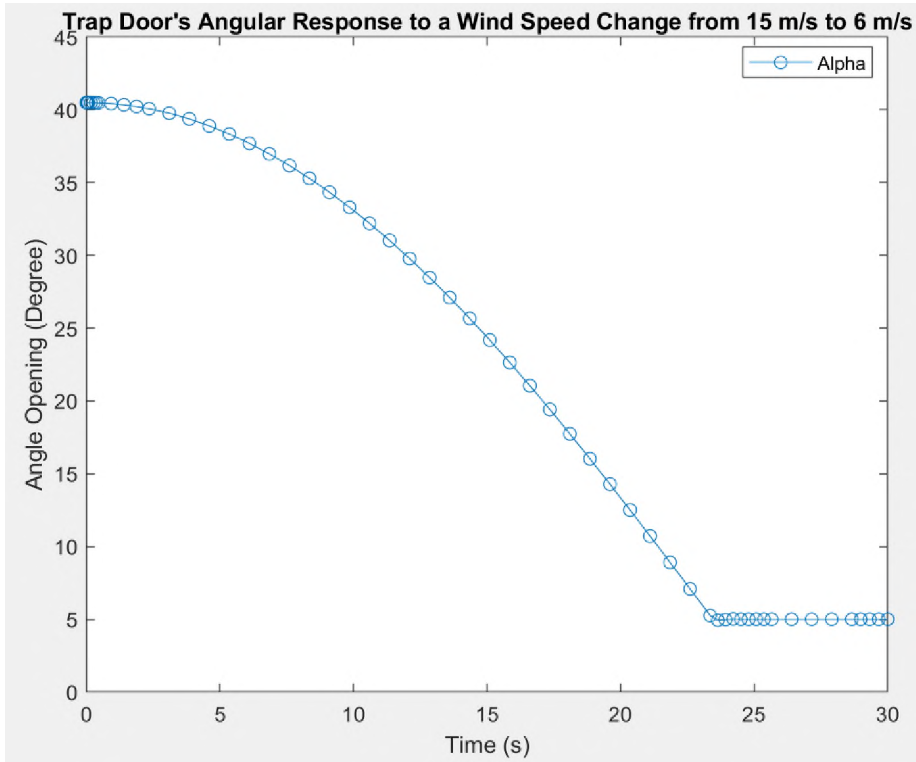


Figure 30: Trap Door's Response to a Wind Speed Change from 15m/s to 6 m/s.

The trap door slows closes due to the decreased applied torque to the gravity hinges. The angle of the trap door due to the decreased wind speed is 5 degrees from the fully closed position. The almost closed position of the trap door will result in a higher amplified wind speed for the wind turbine. The gravity hinge will be able to passively control the angular deflection of the trap during high wind gusts and still allow for the door to close when the wind speed decreases.

7.2 Parametric Study of the Trap Door equation of motion

The atmospheric conditions constantly change, and the passively controlled doors' response needed to be analyzed. An equation of motion has been developed in this work using Lagrange Technique for the trap doors for the gravitational hinge geometry. The equation of motion can be used to determine the response of the system due to an applied input during a transient load. The first case showed that the trap door's angular position is 40 degrees when a sustain wind speed of 15 m/s occurs for a period of longer than 12 seconds. The second case demonstrated that the trap door's angular position will decrease from 40 degrees to 5 degrees when the wind speed subsides from 15 m/s to 6 m/s. The gravity hinge system can passively control the angular position of the trap door during transient wind speeds.

CHAPTER VIII

WIND TURBINE POWER OUTPUT

The goal is to increase the wind turbine power output while maintaining the safety and operation of the turbine. The comparison will be made between three cases including "Free Stream Velocity", "Wind Amplification System", and "Gravity Hinge". The wind turbine and air deflecting system will be held constant. The free stream wind velocity will be varied to see the power output of the wind turbine of each of the cases.

The power output of the wind turbine is governed by the Equation 54 as shown below.

$$P = \frac{1}{2}\rho \cdot A_{swept} \cdot C_{OP} \cdot v_{free}{}^{3} \cdot \eta_g \cdot \eta_b \qquad (54)$$

Where is ρ air density (1.23 kg/m^3 at 20 C and 1 atm), A_{swept} is swept area of the turbine (0.79 m^2 for one-meter diameter), is C_{OP} coefficient of performance (turbine specific), η_g is generator efficiency (assume 90%), and η_b is gearbox/bearing efficiency (assume 90%).

The coefficient of performance is the turbine's ability to convert the wind energy to rotational mechanical energy for the system. The Cop is dependent on the turbine and specifically the blade geometer. Figure 31: Example of a coefficient of performance of wind turbine, shows how the coefficient of performance changes based off the wind speed. The wind turbine cut-in speed is 3 m/s, and the cut-out speed is 25 m/s and coefficient of performance varies with the wind speed as shown below:

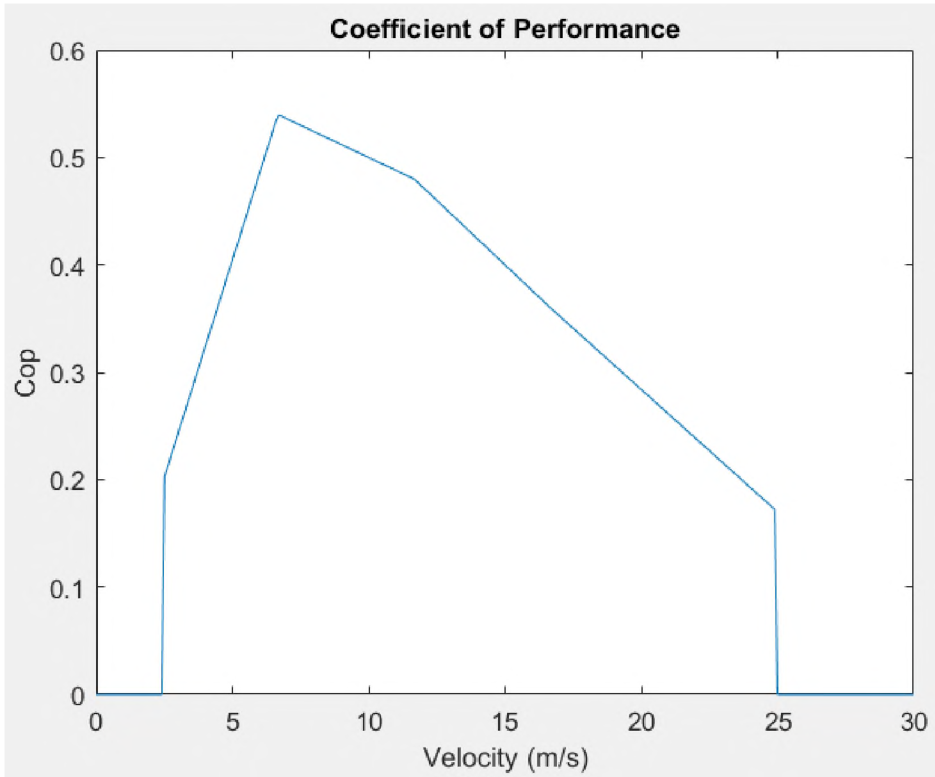


Figure 31: Example of a coefficient of performance of wind turbine.

The wind turbine can be placed in any of the following locations including No Wind Amplification, Wind Amplification, and Wind Amplification with Gravity Hinge. The system that will be held constant for the comparison is the wind turbine that has a diameter of 1.1 meters and coefficient of performance as shown in Figure 29. The wind speed will be varied between 0 m/s and 25 m/s. The parameters for gravity hinge include trap door mass 100 kg, hinge radius 26 mm, trap door diameter 1 meter, trap door height of 1 meter, and inclination angle of 5 degrees.

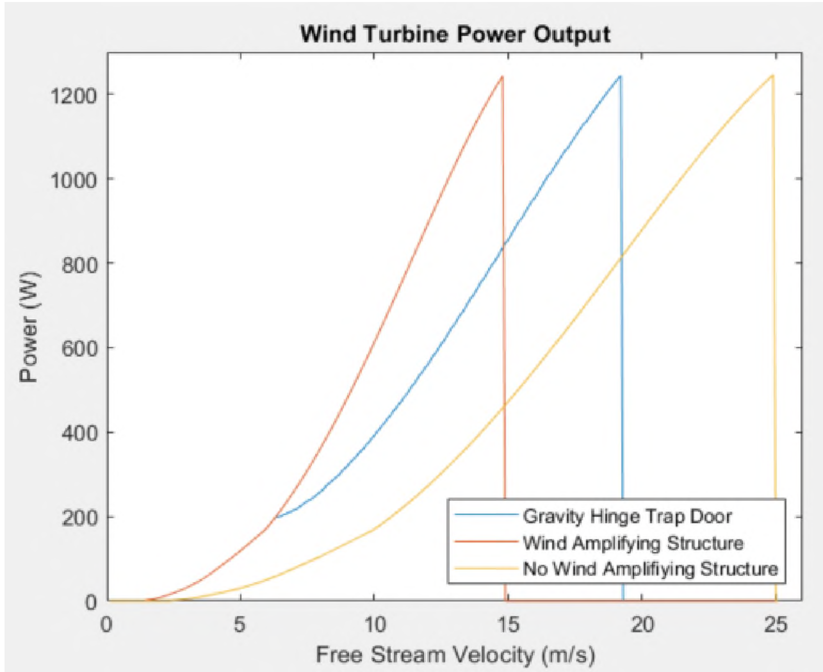


Figure 32: Wind turbine power output with each of the case.

Figure 32: Wind turbine power output with each of the case, shows the power outputs of all the scenarios with how the wind amplification structure and gravity hinge mechanism effect the power output of the wind turbine vs the free stream velocity. The gravity hinge and amplifying structure is the same between 0 m/s and 6.2 m/s because the trap door has not started to open. The wind amplification structure has to cutout after 15 m/s free stream velocity because the amplified velocity is above the cutout speed of the turbine. The gravity hinge system can still safely produce electricity until 19 m/s. Once this wind speed is met, the wind turbine must shut down due to reaching the cut-off speed. The power output between the cases is shown the table below.

	Power Output (Watts)		
Wind Speed (m/s)	No Wind Amplification	Wind Amplifying Structure	Gravity Hinge Trap Door
6.2	50	200	200
15	460	1250	840
19	810	0	1250
25	1250	0	0

Table III: Power output of the same wind turbine in different settings.

The inclusion of a gravity hinge trap door mechanism can expand the operational window of the wind turbine due to decreasing the free stream velocity. The gravity hinge has the same power output of the wind amplifying structure between the cut-in speed and the critical speed that the passively controlled trap doors start to open. The turbine installation that is a free installation will be able to produce power during higher wind velocities due to the fact the opened structure doesn’t completely mitigate the wind amplification factor. The installation of a wind amplification system is beneficial due to the lower cut-in speed of the wind turbine and the inclusion of a gravity hinge expands the window of operation of the wind turbine.

CHAPTER IX

SUMMARY AND FUTURE WORK

Wind energy is a major driving force in renewable energy. The major challenge with wind turbines is the cut-in speed required for starting the system and the cut-off speed where the turbine can't produce any more energy safely. The wind deflecting structure in conjunction with a gravitational hinge significantly improves the cut-in speed and the cut-off speed of with wind turbine by passively controlling the angular position of the trap doors.

A fluid dynamic analysis was conducted for predicting the amplified wind speed the turbine captures. This allows the wind amplification system can be fine-tuned to maximize the power output. A force analysis was conducted for analyzing if the passive trap doors would move under the applied loading conditions. The coefficient of friction, hinge radius (inner and outer), trap door mass, inclination angle, and wind velocity were calculated to determine the angular position of the trap doors. The system was analyzed to see if the trap doors would return to the closed position when the applied drag force was removed.

The wind turbine power output was determined for 3 cases including the wind amplifying structure, the passively controlled trap doors, and the free stream velocity.

The system that produced the most power out of the wind turbine was the wind amplifying structure alone, but it had a much lower cut-out speed. The passively controlled trap door was able to be operated over a larger range of wind speeds due to reducing the wind amplification factor.

The passively controlled system explored is the gravity hinge and this compares to the spring-loaded hinge in the following areas. The gravity hinge is beneficial over the spring hinge mechanism because the spring experiences fatigue where the spring coefficient can creep essentially losing the force over time. The gravity hinge uses gravity as the restoring force so it will not change over time for the system. One concern regarding the gravity hinge is ensuring the coefficient of friction stays constant over time. The surfaces of the gravitation hinge could corrode or oxidize and change the friction coefficient. The spring-loaded hinge will be a lower cost due to the simpler construction and not having to control the surface finish of the contacting surface. The benefit of using a spring hinge mechanism is the ability to fine tune the spring force to make sure the door stays closed.

The areas for future work include building a prototype system and instrumenting for validating the response of the wind deflecting structure. The fluid flow analysis can be completed for when the wind deflecting trap doors are in the fully open position. The transient scenarios can be conducted to validate the response of the structure to a wind gust.

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APPENDIX A

MATLAB Code Drag Force

```
function  [Fdrag,Re,D_Project] = DragForce(Vfree,alpha_deg,D_cyl,H_cyl)

Temp_C = 25;    % Temperature of fluid (Celsuis)

% Calculate density of air from function
[rho, nu] = AIR_PROP(Temp_C);

alpha_rads = (180- alpha_deg)*pi/180;
D_Project = (D_cyl/2)*(1-sin(alpha_rads)); % Cord Length for drag force

Re = Vfree*D_cyl/nu;        % Reynolds Number

ratio = H_cyl./D_Project;

if Re <= 10^4
    if ratio <= 1 && ratio >= 0
        Cd = 0.6;
    elseif ratio <= 2 && ratio > 1
        Cd = .1*ratio + 0.5;
    elseif ratio <= 5 && ratio > 2
        Cd = .1*ratio/3 + 0.633;
```

```
    elseif ratio > 5
        Cd = 0.9;
    end

else
    Cd = .3; %Turbulent flow
end

SA = D_Project*H_cyl;           % Front surface area (meters)



Fdrag = Cd*rho.*Vfree.^2.*SA;    % Drag force newtons


end
```

APPENDIX B

MATLAB Code Sliding Analysis

```
function [alpha_deg,stability,Fnperp,Fnet,Ffrict] =
Force_Analysis(Fdrag,alpha_deg,theta,D_cyl,friccoef,rhinge,qty,Mass)


% theta = 10;          % Angle of inclination
da = 1;               % Increment of door Angle
% D_cyl = 3;           % Diameter of cylinder
% friccoef = .16;      % Friction coefficient
% rhinge = .1;         % Radius of hinge (Meter)
% qty = 2;             % Quantity of hinges
% Weight = 3000;       % Mass of the door (Newtons)


R = D_cyl/2;    %Radius of the trap door
c = R*((2*(1-cos(pi/4)))^.5); %Length of the triangle that making up the center point of
the trap door that the drag force is acting
R_wind = sind(67.5-alpha_deg)*c;



Hinges_Torque = Fdrag .* R_wind;  % (Newton Meter)


Fwr = Hinges_Torque/rhinge*(1/qty); % Horizontal force

```

```
Fwperp = -sind(theta)*Fwr;  % Wind Force perpendicular (normal force)

Fwparr = cosd(theta)*Fwr;   % Wind Force parrel (sliding force)


Fg = Mass*9.8;            % Weight of the trap door (Newtons)

Fwg = Fg/qty;           % Weight of the door (Per hinge)

Fgperp = -cosd(theta)*Fwg;  % Weight perpendicular (normal force)

Fgparr = sind(theta)*Fwg;   % Weight parrel (sliding force)


Fnperp = abs(Fwperp + Fgperp);   % Normal force


Ffrict = friccoef*Fnperp;   % Friction force (sliding force)


Fslide = Fwparr - Fgparr;   % Sliding force (Wind and gravity)



Fs2 = abs(Fslide);           % why is this squared?

Ff2 = abs(Ffrict);           % why is this squared?


if Fs2 > Ff2 && Fslide < 0

    alpha_deg = alpha_deg - da;

    stability = -1;

    Fnet = Fslide + Ffrict;

elseif Fs2 > Ff2 && Fslide > 0
```

```
 alpha_deg = alpha_deg + da;
     stability = 1;
     Fnet = Fslide - Ffrict;
else
     stability = 0;
     Fnet = 0;

end
```

APPENDIX C

MATLAB Code Inviscid Flow

```
% Stream function for Inviscid Flow with incoming velocity and half circle
% at top
function  [PSI,y,uc_center,vc_center] = Open_Inviscid_Flow(uleft,Stream)


L = 3;                  % Length of cavity (m)
rcylinder = .5;         % Radius of cylinder (m)
nodex = 400;            % Number of nodes in x direction
nodey = nodex;          % Number of nodes in y direction
hx = L/(nodex-1);       % Delta x distance between nodes
hy = L/(nodey-1);       % Delta y distance between nodes
h = (hx^2+hy^2)^.5;     % Approximate delta discretization error
nodes = nodex*nodey;    % Total number of nodes


ratio = .105;           % Ratio for stability


t = 0;                  % Start time
dt = ratio*h^2;         % Change in time steps
cmax = 50000;           % Max number of time steps



lbm = 1:nodey;    % Set left boundary
```

```
PSIl = (lbm)';          % Left stream function
PSItop = lbm(1);        % Upper stream function value
PSIb = lbm(end);   % Bottom stream function value
PSIr = PSIl;            % Right stream function equals the left

%Use the old stream function for the new iteration
tf = isempty(Stream);   % Test to see if stream function is empty if empty fill matrix
if tf == 1
   PSI = ones(nodex,nodey);   % Initial Empty Stream Function Matrix
   PSI = PSIl.*PSI;           % Set the whole function so it is even across the field
   PSI = PSI/max(lbm);        % Scale down the stream function
else
   PSI = Stream;
end


PSI = uleft.*PSI./max(PSI);   % Scale inlet stream function


PSIcyl = PSI(1,1);        % Stream function around the cylinder


ram = 1.5;           % Constant for moving convergence forward
beta = 5e-7;        % Residual error
```

```
p0 = 0;            % Set initial stream function

% Generate cylinder wall for inviscid flow
% Find the nodes related to the cylinder wall

Rnodes = rcylinder/hx;  % Radius of cylinder in nodes

a(1) = 0;
dx = (2*Rnodes^2)^.5/2;
dy = dx;
xcyl = round(nodex/2);      % X Coordinate of the cylinder center

% Set the left boundary to the new inlet condition

for n = 1:1:180
   a(n) = round(xcyl + cosd(n)*Rnodes);    % X Wall of cylinder
   ba = round(sind(n)*Rnodes-dy);          % Y Wall of cylinder

   if ba<= 0
      b(n) = 1;
   else
      b(n) = ba;
   end
```

```
    PSI(b(n),a(n)) = 0;
end



% Solve for Stream function using SOR
for c = 1:cmax
    t = t+dt;

    for i= 2:nodex-1
        for j = 2:nodey-1
            PSI(i,j) = (PSI(i+1,j)+PSI(i-1,j)+PSI(i,j+1)+PSI(i,j-1))*ram/4 + (1-ram)*PSI(i,j);
        end
    end

    PSI(1,:) = PSI(1,1);    %check me later

    for n = 1:1:180
        a(n) = round(xcyl + cosd(n)*Rnodes);    % X Wall of cylinder
        b(n) = round(sind(n)*Rnodes);           % Y Wall of cylinder

        if b(n) >= 2
            PSI(b(n),a(n)) = PSIcyl;
```

```
        end

        PSI(b(n)+1,a(n)) = PSIcyl;
    end

%       PSI(:,nodex) = PSI(:,nodex-1);

    E = abs(PSI-p0);        % Calculate the error from last time step
    Eavg = sum(sum(E))/nodes;

    if Eavg < beta
        fprintf('Convergence Reached')
        break
    end

    p0 = PSI;       % Store new stream function for next iteration

end

PSIp = flipud(PSI);     % Flip y axis to match plot
x = 0:hx:L;             % Range of x for plot
y = 0:hy:L;             % Range of y for plot
```

```
% Scale wall input so its a function of distance instead of nodes
ax = a*hx;  % X coordinate of the cylinder
by = b*hy;  % Y coordinate of the cylinder



figure(1)
contourf(x,y,PSI,10)
hold on
plot(ax,by,'r') % Plot the profile of the wind deflecting structure
title('Stream Function')
xlabel('X Position (m)')
ylabel('Y Position (m)')
legend('Stream Function', 'Profile of Wind Deflecting Structure')

u = zeros (nodex, nodey);
v = zeros (nodex, nodey);

% Solve for componet velocities
for i = 2:nodex-1
  for j = 2: nodey-1
    u(i,j)= L*(PSI(i+1,j)-PSI(i-1,j))/(2*hx);
    v(i,j)= L*(-PSI(i,j+1)+PSI(i,j-1))/(2*hy);
  end
```

```
end


v(:,1) = (-PSI(:,1)+PSI(:,2))/(hx);

v(:,nodex) = (-PSI(:,nodex)+PSI(:,nodex-1))/(hx);


for i = 2:nodex-1

    u(i,1)= L*(PSI(i+1,1)-PSI(i,1))/(hx);

end


u(:,nodex) = u(:,nodex-1);

u(1,:) = u(2,:);    % Set the first row to the second row

u(nodey,:) = u(nodey-1,:);

uc = flipud(u);   % Coordinate transformation of u velocity

vc = flipud(v);   % Coordinate transformation of v velocity


uc_center = u(:,xcyl);

vc_center = v(:,xcyl);



figure(2)

plot(y,uc(:,nodex-1))

title('Velocity at Exit')

xlabel('Y position (m)')
```

```
ylabel('Vx Velocity (m/s)')


uvelocity = flipud(uc_center);

figure(3)

plot(y,flipud(uvelocity))%c(:,xcyl))

title('Velocity at the Center of the Structure')

xlabel('Y position (m)')

ylabel('Vx Velocity (m/s)')

xlim([0 3])

ylim([0 35])


figure(4)

plot(a,b)

ylim([0 nodey])

xlim([0 nodex])

end
```

APPENDIX D

MATLAB Code Gravity Hinge Dynamics

```
% Gravity Hinge Dynamic Analysis


function YP = Gravity_Hinge_Dynamics(t,y)


Mass = 100;     % Mass of Trap door (kg)

J = 600;        % Moment of inertia of the door (kgm^2)

thetad = 5;     % Angle of inclination(Degrees)

rhinge = 0.026; % Hinge Radius (Meters)

mu = 0.01;      % Friction Coefficient (~)

D_cyl = 1;      % Diameter of the trap door (m)

H_cyl = 1;      % Height of the trap door (m)


% Wind velocity information

frequency = (pi)/4;     % Frequency of the squall

Squall = 0;             % Velocity of the wind squall increase

Vfree = 15;             % Initial velocity of the storm


g = 9.81;   % Gravity Constant (m/s^2)


alpha = y(1);     % Angle of door open (Radians)

adot = y(2);      % Angular velocity of the door (radians/second
```

```
%Lagrange function with respect to da
dLda = Mass*g*tand(thetad)*rhinge;


%Part for solve the applied torque due to the wind varying
alpha_deg = alpha*180/pi;


% Determine the torque applied to the hinge
Vt = Vfree + Squall.*sin(frequency*t);     % Free Stream velocity at time t
Fdrag = DragForce(Vt,alpha_deg,D_cyl,H_cyl);


R = D_cyl/2;    %Radius of the trap door
R_wind = sind(67.5-alpha_deg)*R*0.7653;    % Distance from the pivot point to the drag
force(meters)


Torque = Fdrag * R_wind;                  % Applied torque to the hinge


% Input the friction at the hinge
Fp = Torque/rhinge;
Fpp = -sind(thetad)*Fp;
Fgp = -cosd(thetad)*Mass*g;
Fnp = Fpp + Fgp;
```

```
Ffric_parallel = mu*Fnp;
Torque_Friction =  abs(Ffric_parallel*rhinge);


Tapplied = Torque -dLda;
Taabs = abs(Tapplied);


% Determine if the door moves and subtract the friction
if Torque_Friction >= Taabs
    Torque_total = 0;
else
    if Tapplied >0
        Torque_total = Tapplied -Torque_Friction;
    else
        Torque_total = Tapplied +Torque_Friction;
    end
end


line1 = adot;               % Angular velocity
line2 = (Torque_total)/J;   % Angular acceleration


%Ensure that if the acceleration doesn't match the velocity it slows down
if line2<=0 && line1>0
    line1 = adot/-10;
```

```
end


%Calculate if the door will continue to open if wind is at steady state
Fdrag = DragForce(Vt,alpha_deg,D_cyl,H_cyl);
Force_Analysis(Fdrag,alpha_deg,thetad,D_cyl,mu,rhinge,2,Mass);
[ideal_open_ang,~,~,~] =
Force_Analysis(Fdrag,alpha_deg,thetad,D_cyl,mu,rhinge,2,Mass);



if Torque_total > 0
   %Force the door to stay open or slow down due to the equilibrium point
   if alpha_deg >= ideal_open_ang
      line1 = 0;
      line2 = 0;
   end
else
   if alpha_deg <= ideal_open_ang
      line1 = 0;
      line2 = 0;
   end
end
```

```
YP = [line1; line2];

end
```

APPENDIX E

MATLAB CODE Air Properties

The following function solves for the properties of air including density, dynamic, and kinematic viscosity.

```
function [rho, nu] = AIR_PROP(Temp_C)


% Calculate density of air
Temp_K = Temp_C + 273.15;   % Temperature in Kelvin
R = 287.05;                 % Specific gas constant for dry air (J/(kg*K))
P_stp = 101.325e3;          % Pressure at sea level (Pa);


rho = P_stp/(R*Temp_K);     % Density of air at the temperature
https://wahiduddin.net/calc/density_altitude.htm



% Calculate viscosity of air
S = 110.4;                  % Constant
C1 = 1.458e-6;              % K/(m*s*(K)^.5)


mu = C1*(Temp_K)^1.5/(Temp_K+S);   % Dynamic Viscosity
nu = mu/rho;                % Kinematic Viscosity
end
```