Ocean current energy harvesting system for Arctic monitoring

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Abstract

Arctic Ocean monitoring with near-real-time data transfer is urgently needed. The harsh and remote conditions constraining year-round observation sites present significant logistical challenges and energy needs for sustained Arctic observations. The Arctic project group is attempting to design a mechanical structure to harvest energy from low-speed current in the Arctic Ocean. An Arctic energy harvesting system that consists of a transverse flux generator, boosted by a nozzle-diffuser-duct, and an American multiblade turbine that drives the generator, are designed in this study. The transverse flux generator is then optimized based on its design parameters and the optimization successfully improves the torque performance of the generator while maintaining the largest power output. The American turbine fits the extreme low-speed current condition (<0.2m/s) well and could support the rotation of the generator. Finally, the article compares the energy harvesting system is compared with the existing ones in the market and demonstrates its superior performance.

Current energy harvesting system for Arctic

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General Audience Abstract

The article explores an energy harvesting system designed to convert fluid dynamic energy into electrical power. Specifically, the system contains a new type of multiblade water turbine and a brand-new type of transverse flux generator. The multiblade water turbine, which used to be popular in wind turbine field, is able to self-start from an extreme low speed current speed and is newly introduced to the water turbine field in this article, while the transverse flux generator is a new type of compact generator with a high efficiency. The transverse flux generator in article improves the low-speed torque performance comparing with other designs. Lastly, this system enhances energy provisioning for small-scale devices like sensors and communication systems, significantly improving their support capabilities.

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1. Introduction

1.1 Project Description

The Arctic is home to some four million people comprising a diverse range of cultures and an economy worth about $230 billion annually. With global concerns spanning climate change, energy resources, freshwater supplies, and sustainable economic growth, the Arctic has sparked intense research and public interest. Sustained Arctic observing systems become popular, and a near-real-time data transfer is needed to do the observing in Arctic area. One of the greatest challenges to the near-real-time data transfer system is the energy supplement to the system. The team's goal is to design a sustainable power supply system through energy harvesting from the Arctic current and the harvested energy will be used to support sensors and power a novel real-time communication system through the sea ice. Specifically, the project aims to develop novel techniques to harvest ultra-low-speed oceanic current energy using a two-level diffuser augmented turbine and a novel transverse flux generator. The system is able to self-start in harsh, low temperature conditions and generate 0.1W power to real-time communication system continuously.

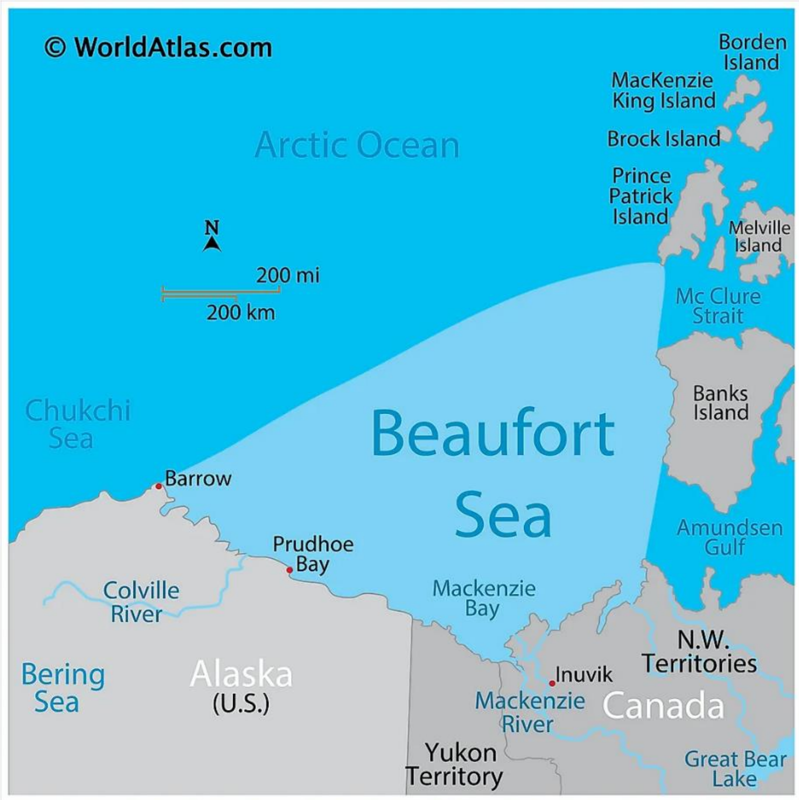


Figure 1.1: Arctic Study area [1]

1.2 Design Description

The energy system consists of three major parts: Transverse flux generator, American multiblade current turbine, flow augment Nozzle-diffuser part. The generator and turbine are primary study goals in our study.

1.3 Application

The American multiblade turbine fulfill the need for extreme low-speed horizontal water turbines and works in regions with slow-moving water currents, such as the Arctic, Alaska, and mountain streams. Its high torque enables efficient energy harvesting at very low water speeds, making it well-suited for challenging environments where conventional turbines struggle to perform. On the other hand, the transverse flux generator performs high-power density features compared with traditional generators. Its unique feature allows direct rotor drive, making it ideal for compact applications like vacuum cleaners. Moreover, the design can be adapted to function as a transverse flux motor, providing a significant advantage in terms of torque density.

1.4 Challenge

The major challenge of American Multiblade turbine is the conflict between high torque demand and the efficiency of the turbine. Particularly, in regions with slow currents like the Arctic, which peak speed is only 0.1m/s, the turbine is hard to generate sufficient torque for self-starting the generator. Increasing blade numbers, mounting twist angle of the blade enable the blades to block more water and generate more torques, however, this also leads to the power loss and reduced overall turbine efficiency, which reduces the harvested energy. Hence, it’s necessary to find a balance between torque and efficiency through adjusting the blade number and twist angle.

Another greatest problem in the generator design part of the project is to achieve an equilibrium among the cogging torque, starting torque and power. It is well known that the power of a generator is proportional to the flux density in its airgap. However, the stronger flux density, the greater cogging/starting torque the generator requires. Thus, the balance of cogging/starting torque and generator should be kept by adjusting magnet strength, poles number and the air gap distance of the generator to ensure the generator has a decent power output and self-start able from the static status.

One of the commercial designs that shown in Figure 1.3 has been tested under the certain flow condition. However, the design couldn't fulfill the need and only has the output of 0.009W.

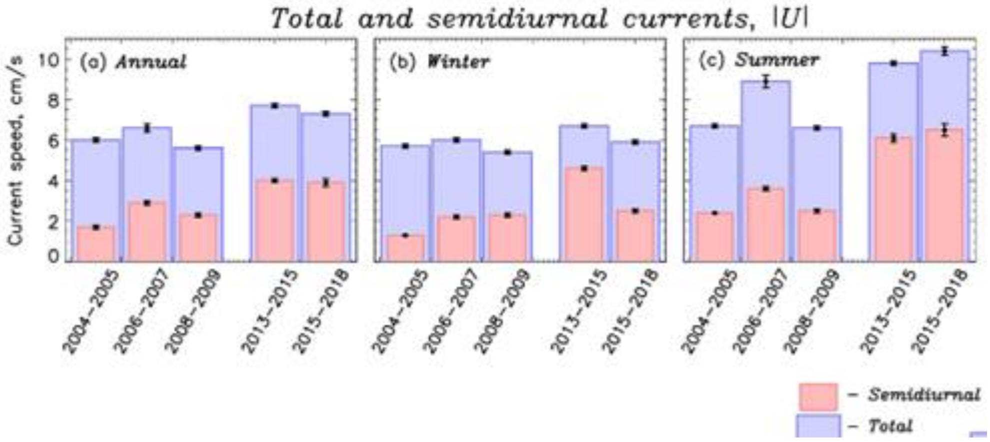


Figure 1.2: Arctic current speed distribution[2]

Figure 1.3 Commercial design

2. Design and optimization

The design consists of three parts: Nozzle-diffuser duct, American multiblade turbine, and the transverse flux generator.

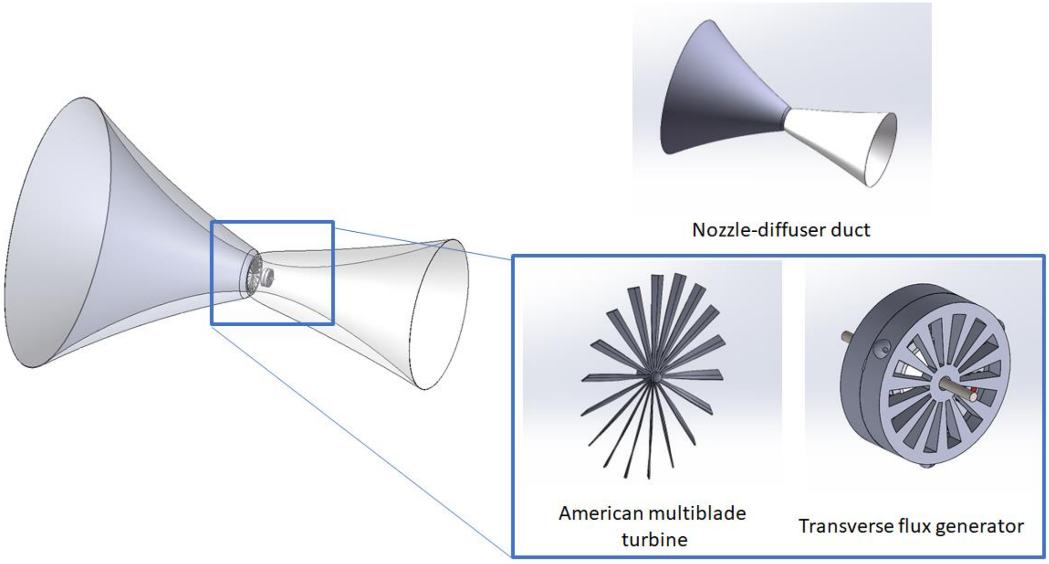


Figure 2.1: Components of the Design of the Arctic energy harvester

2.1 Generator model

The generator is redesigned and improved based on the study of Seyedmohsen Hosseini. [3] The transverse generator is composed of two stators and a rotor with alternate direction permanent magnets, as shown in Figure 2.2. The number of magnet pairs, p_m, is two times of the number of stators, which equals to the poles number of the generator, p. The stator C-shape iron core is made with laminated steel and has a good ability to transfer flux and avoid the eddy current loss inside the iron core. A single flux loop consists of a pair of permanent magnets, two iron cores, and two coils (windings) that are surrounded by iron cores, as shown in figure (a). In this flux loop, F_m shows the magnetomotive force (mmf) of permanent magnets. The magnet reluctance inside the loop consists of three major parts: the reluctance inside the magnet R_m, airgap magnet reluctance R_g, and iron core magnet reluctance R_c. Faraday's law of electromagnetic induction explains how it works: Rotor rotates and alternates the flux direction in each single flux loop, inducing an alternating current in the enclosed windings in the surrounding magnetic field.

The induced voltage, according to the faraday's law of electromagnetic induction, could be written as follow:

$$V(s) = N * \frac{d\emptyset}{dt} \tag{2-1}$$

Here, V(s) is the voltage induced by rotor rotation. N is the winding number of the generator, and dΦ/dt refers to the flux change rate over the time. The Φ, which is the effective flux within the flux loop, is written as:

$$\emptyset = B * S * p \tag{2-2}$$

Where B means the flux density in the air gap, S refers to the effective surface area of the magnets of a single pole within the flux loop, and p is the poles number. The flux density B varies as the rotor rotates in this design:

$$B = B_{max} * \sin(p\omega t) \tag{2-3}$$

B_{max} refers to the peak flux density during the rotation. The peak flux exists when all magnets exactly align with the stators. ω means the rotational speed of the rotor. Therefore, the flux change over time could be expressed as:

$$\emptyset(t) = B * \sin(p\omega t) * S * p \tag{2-4}$$

And the induced voltage expression is rewritten as:

$$V(s) = N * \frac{d\emptyset}{dt} = N * \omega * B * S * p^2 * cos(p\omega t) \tag{2-5}$$

The average voltage output of a generator could be estimated by root mean square voltage:

$$V_{rms} = \frac{V(s)_{peak}}{\sqrt{2}} = \frac{N * B * S * p^2 * \omega}{\sqrt{2}} \tag{2-6}$$

In the equations above, $B * S$ represent the flux that pass the airgap and enter a single iron tooth and could be simulated by Ansys Maxwell, a magnet simulation software. In this way, the output voltage of the generator design could be simulated by Ansys Maxwell. The simulation model in Ansys Maxwell is displayed in Figure 2.3 and Figure 2.5.

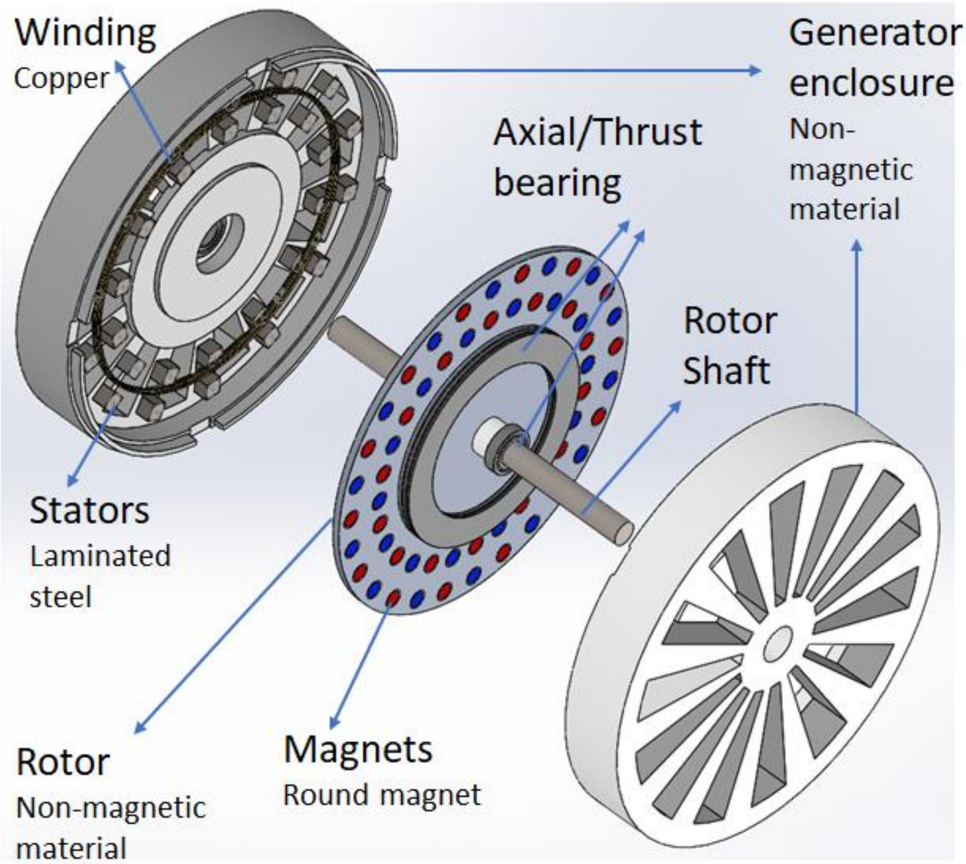


Figure 2.2: Components of the transverse flux generator

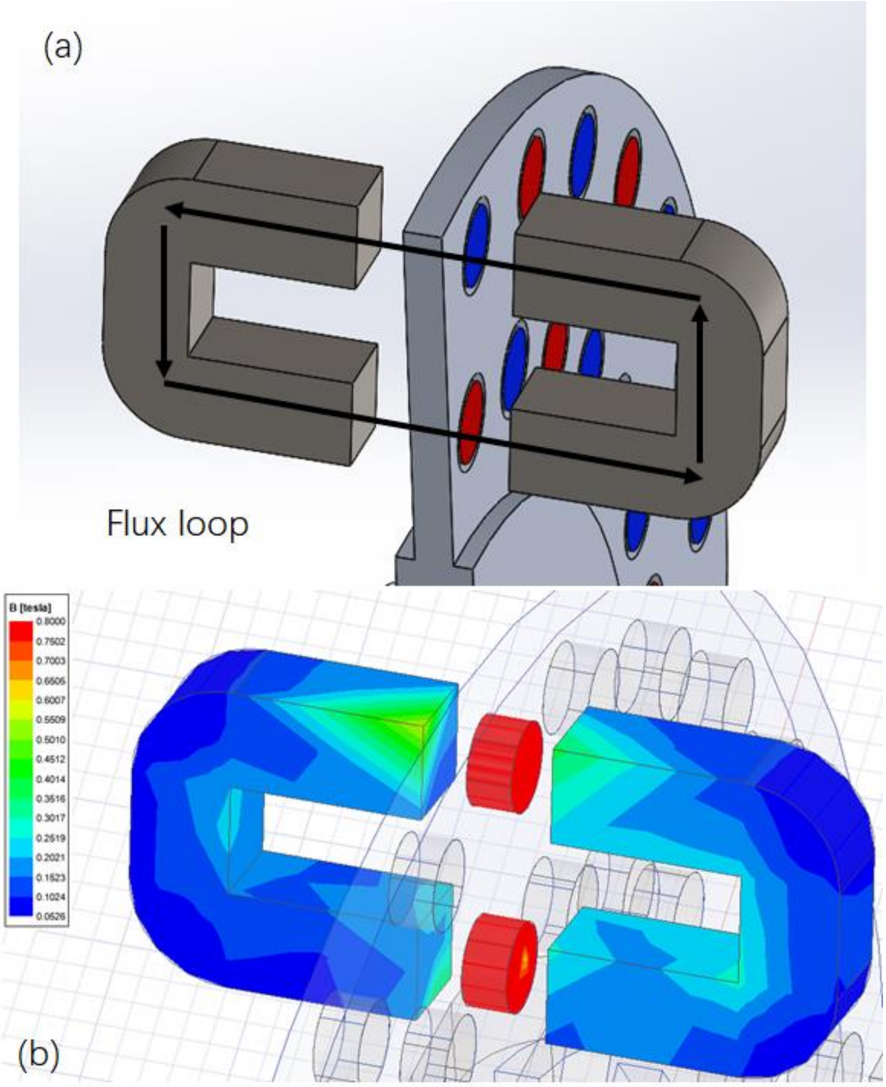


Figure 2.3: Flux path of a single pole and its Ansys Maxwell model

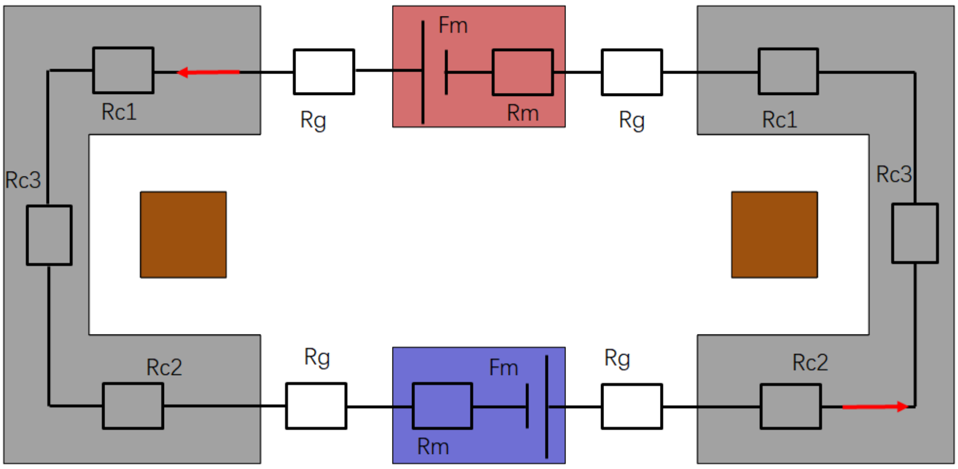


Figure 2.4: Magnetic equivalent circuit

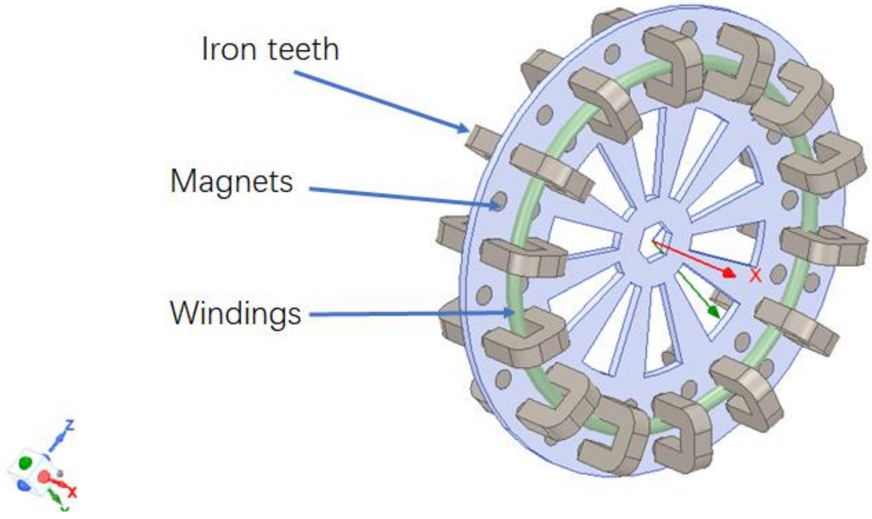


Figure 2.5: Ansys simulation model of whole TFM

2.2 Generator design parameters

The design parameters of the transverse flux generator determine the power output level, driving torque and the optimal rotational speed. From the front view of rotor, as shown in figure, the four magnets with opposite magnet poles form a unit pole of the generator, and the poles number p describe the total number of poles in the rotor. R_{in} and R_{out} are the radius of the inner layer of magnets and the outer layer of magnets. D_{mag} describes the diameter of each magnet on the rotor. After determining the poles number, R_{in}, R_{out}, and magnet diameter, the distance between the two adjacent magnets of inner magnet loop and outer magnet loop, d_{in} and d_{out} could be calculated because the magnets are evenly distributed as two circles on the rotor.

A single flux loop consists of two magnets and a pair of stators. The magnet thickness, which equals to the thickness of the rotor, is written as m_t. l_t, l_c, and l_c are the dimensions of the C-shape iron core stator. The airgap distance is written as g, and the winding number is expressed as N.

Table 1. Design parameters of the generator

Parameters	Item
D_mag	Magnet diameter
d_in	Inner magnet absolute distance
d_out	Outer magnet absolute distance
R_in	Inner magnet loop radius
R_out	Outer magnet loop radius
p	Poles number
m_t	Magnet thickness
g	Airgap distance
l_t	Side length of Iron teeth contact surface
l_h	Height of Iron teeth leg
l_c	Width of Iron teeth
N	Winding number

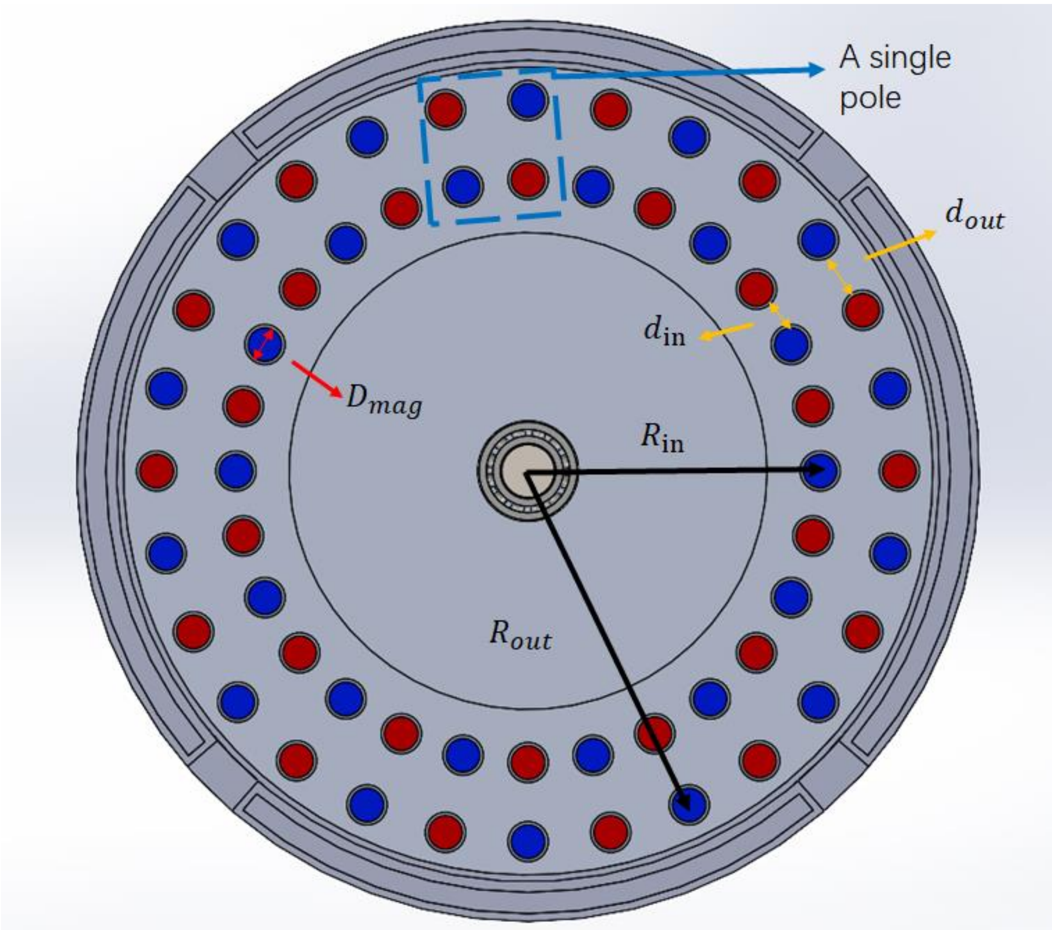


Figure 2.6: Design parameters in the rotor plate

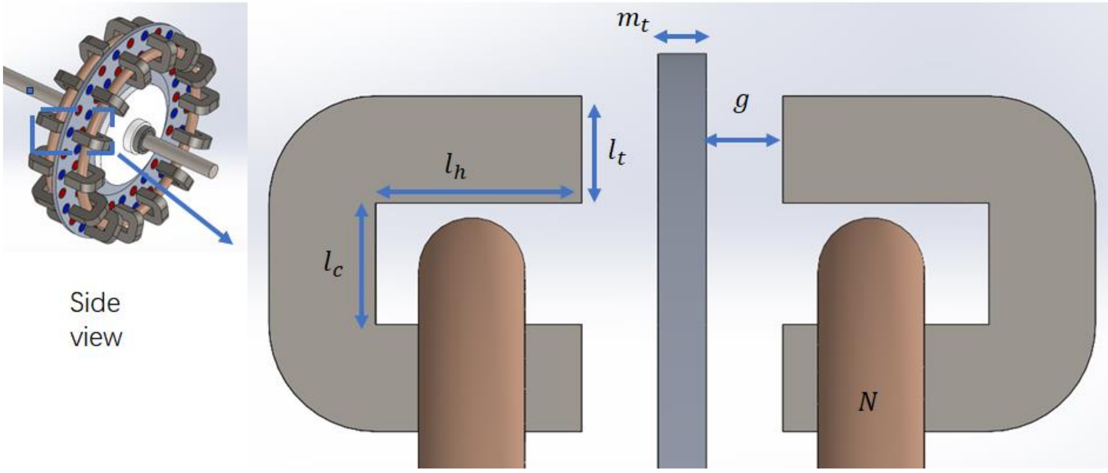


Figure 2.7: Design parameters in the stator-rotor interaction

2.3 Generator parameter study and optimization

2.3.1 Generator parameter study

The optimization is to find a balance point between the cogging torque and output power. Cogging torque is a phenomenon that occurs in certain types of electric generators. The cogging torque has a much greater effect on rotation during the low rotational speed condition because the low rotational inertia at this time. The existence of cogging torque prevents the generator to run smoothly and may stop the rotation when the flow speed getting low. Recall from previous chapter, the root mean square output voltage could be written as $\boldsymbol{V_{rms}}$. The mean power output of the generator could be written as $\boldsymbol{P}$. The flux density, $\boldsymbol{B}$, could be simulated by Ansys Maxwell. Moreover, the cogging torque $\boldsymbol{T_{cog}}$ during the rotation could also be simulated with Ansys Maxwell.

$$V_{rms} = \frac{N * B * S * p^2 * \omega}{\sqrt{2}} \tag{2-7}$$

$$P = \frac{V_{rms}^2}{R_w} \tag{2-8}$$

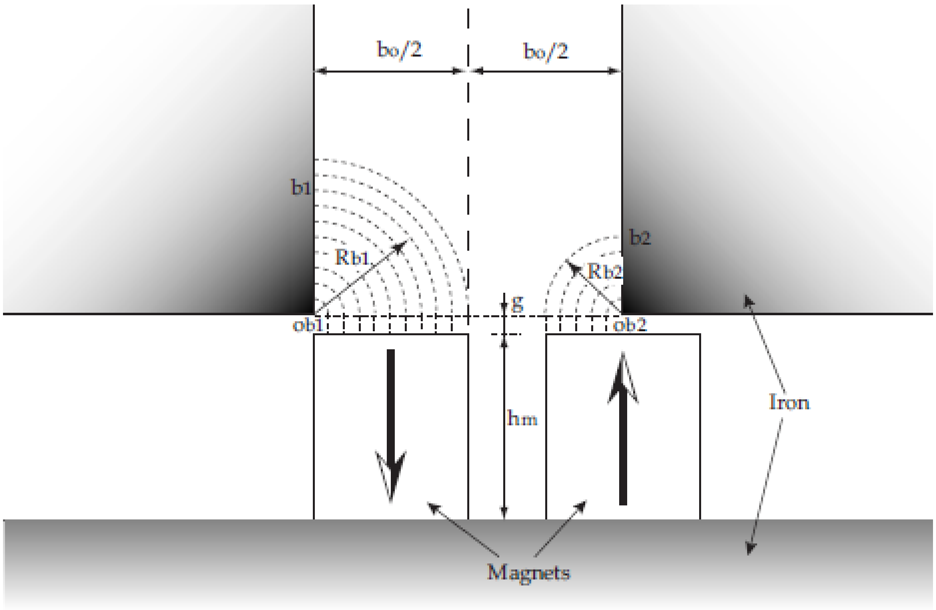


Figure 2.8: Theory of how cogging torque generate [4]

The design parameters in Table 1 have impact on either cogging torque or the power output. D_{mag} and m_t are diameter and thickness of the magnets, respectively. In this study, $m_t = 0.125in$ and keep constant because the rotor board has a requirement of elastic modulus and weight. If we give D_{mag} a certain starting value and simulate the flux density B and cogging torque, T_{cog} we could get the relationship shown in Figure. Let the initial D_{mag} to be the smallest value, take down the flux density and cogging torque at this time, then increase the D_{mag} by different times, and then compare the flux density and cogging torque result under each magnet surface area. The increase of D_{mag} boosts the surface area of the magnets and increase the flux density B, but the trend is slow down and follows a logarithmic trend. Meanwhile, the cogging torque T_{cog} rises with the surface area of the magnets and has a power trend up.

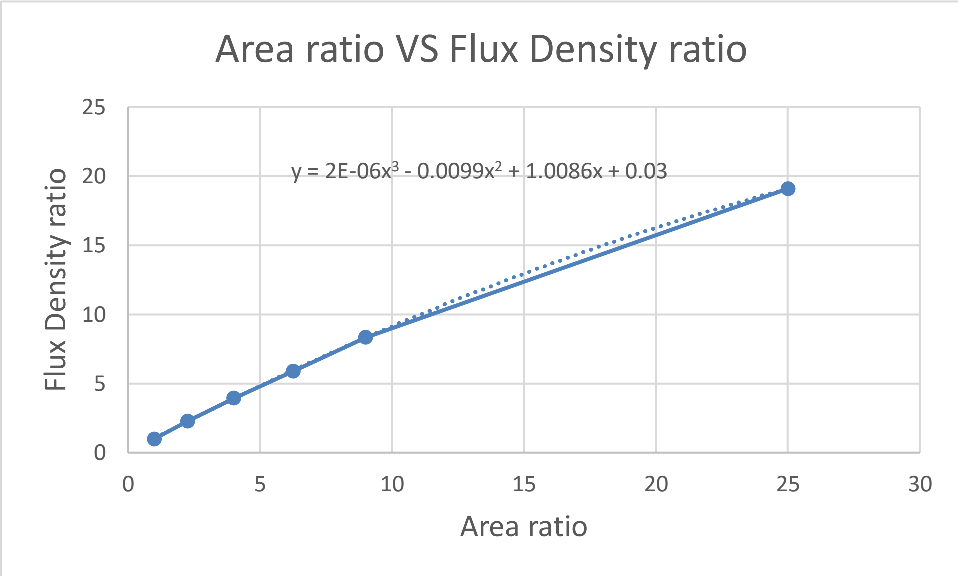


Figure 2.9: Flux density VS magnet area trend

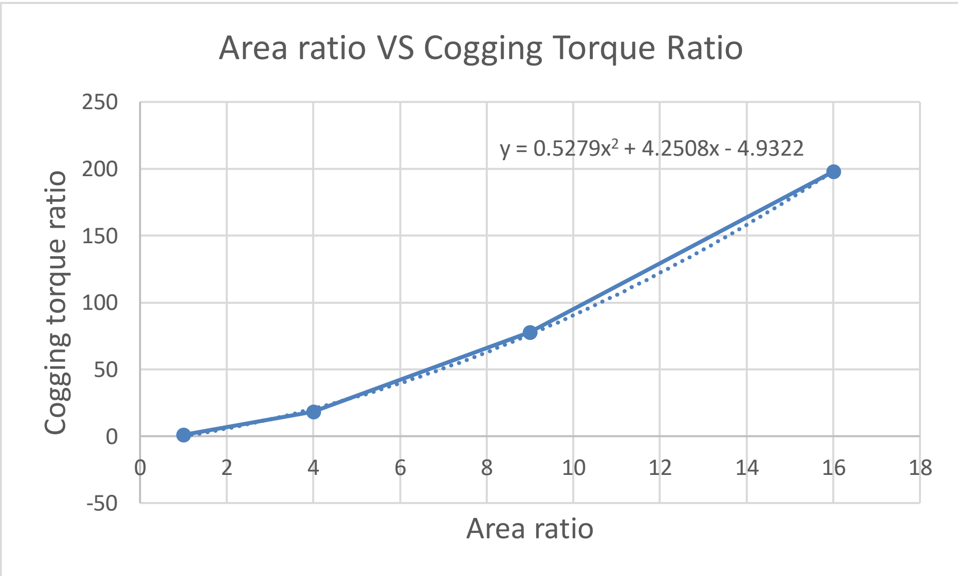


Figure 2.10: Cogging torque VS magnet area trend

Poles number p describe the quantity of magnet pairs. The output voltage is proportional to the square of p and the increment of p greatly benefit the output voltage. Meanwhile, a large p greatly increase the starting torque and the cogging torque and would stop the self-starting of the generator. To study p, we need assume the d_{in} and d_{out} keep constant to avoid the effect of magnet absolute distance. From the power trend we could indicate that if the p getting larger and larger, the generator would not be able to either self-start or run smoothly. Moreover, the mechanical structure complexity of the generator also boosts with p , which is not good for the reliability under Arctic harsh weather conditions.

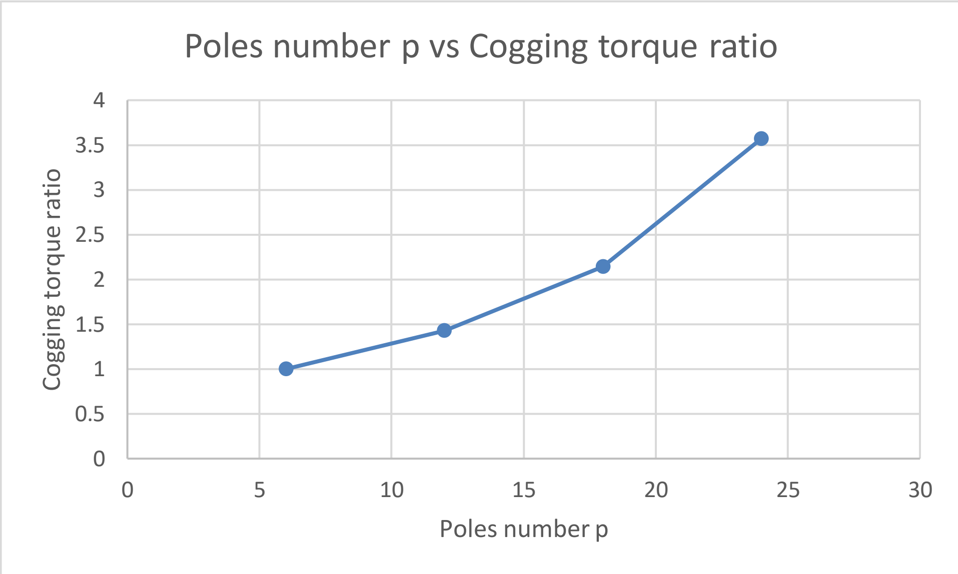


Figure 2.11: Cogging torque VS poles number trend

Airgap distance g play a significant role in adjusting the cogging torque T_{cog}, starting torque and flux density B. As the airgap distance becomes larger, the T_{cog} reduce following a negative logarithm trend line, and the flux density also reduce along the increment of airgap distance. However, the flux density B seems to have a slower reduction slope than the T_{cog} during the study range, which indicate increasing the airgap distance properly could benefit the balancing of cogging torque and flux density in this study.

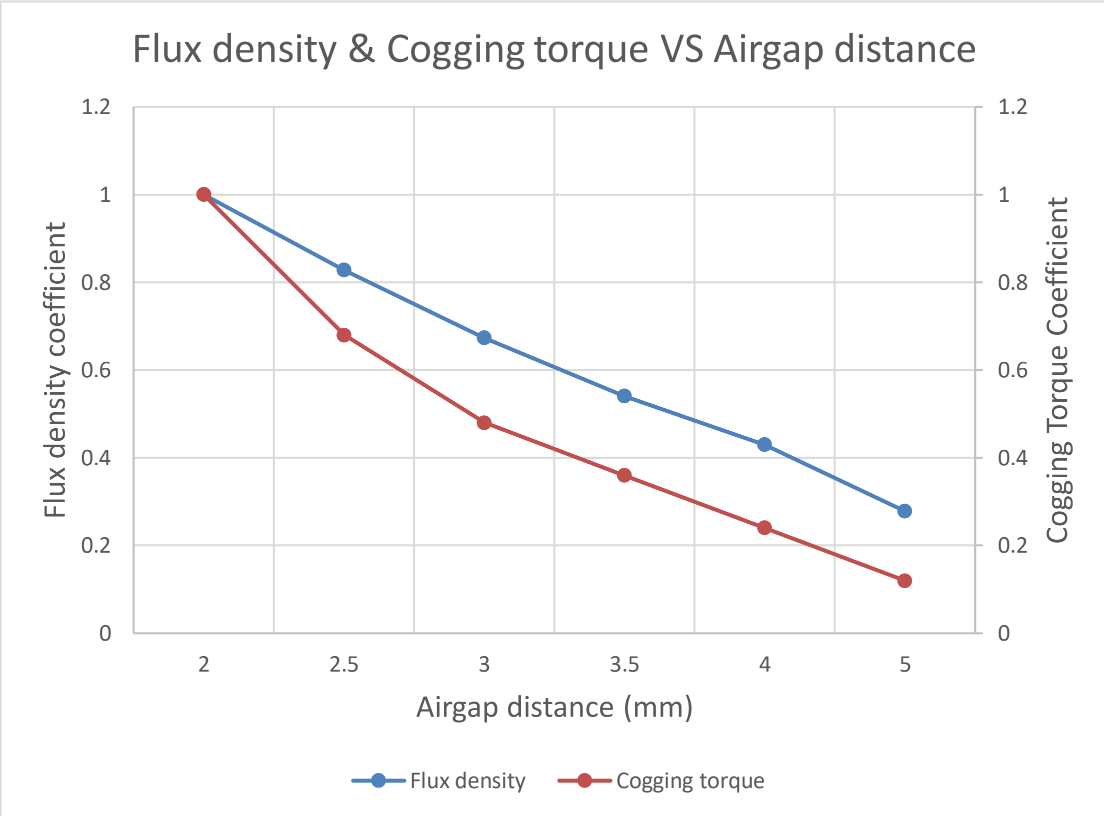


Figure 2.12: Flux density & Cogging torque VS Airgap distance trend

d_{in} and d_{out} are dependent design parameters that decided by R_{in}, R_{out}, and poles number p. The study starts when d_{in} and d_{out} are very small, that is, the magnet are very close to each other. Then d_{in} and d_{out} are adjusted according to different times value of the magnitude magnet diameter, D_{mag}. When the magnet absolute distance is at least 0.5 times of D_{mag}, the flux density is close to the original magnet flux density of the magnet, which is 1 time of that. As the absolute distance getting smaller, the flux density in the airgap becomes only around 0.8 times of the original flux density. The ratio would be less than 0.7 times if the absolute distance is less than 0.2 times of D_{mag}.

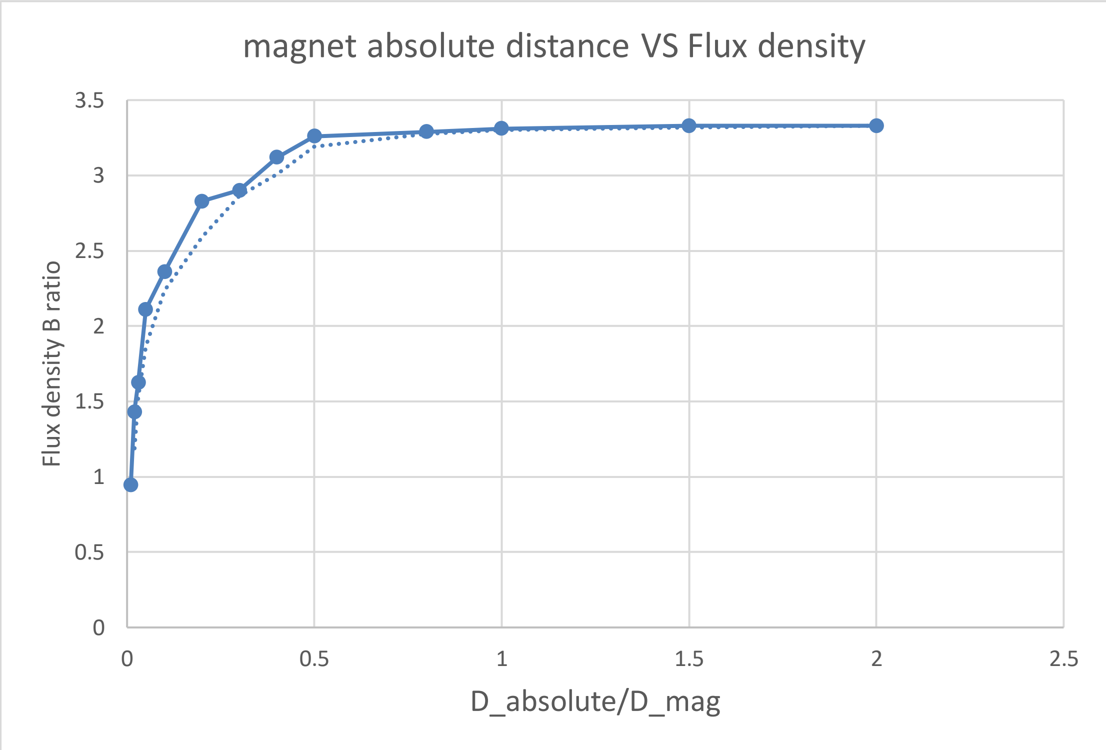


Figure 2.13: Flux density VS Magnet absolute distance over D_mag

2.3.2 Generator Optimization

The Gradient-based method is a common optimization approach that is widely used in engineering and scientific applications. This method involves iteratively adjusting the design variables based on the gradient of the objective function, which represents the rate of change of the function with respect to the variables. The Sequential Quadratic Programming (SQP) problem is a type of gradient-based method that solves nonlinear programming problems by iteratively solving quadratic subproblems, subject to constraints.

There are two goals in the optimization: maximize the voltage output V_{rms} and reduce the cogging torque T_{cog}. The rules of the optimization are the R_{out}, R_{in} should be limited within 0.2m because of the size limit of the generator. From the generator parameter study, the airgap distance g, magnet diameter D_{mag}, and poles number p has greater impact on the optimization goals and are going to be optimized. Thus, we could get the constraints written by magnet diameter D_{mag}, poles number p and the airgap distance g and express the V_{rms} and T_{cog} with these parameters. The procedure of the optimization is shown in Figure.

Table 2. Optimization parameters of the generator

Optimization Parameters	Item	
g	Airgap distance	As g boost Decrease both T_{cog} and B T_{cog} faster
D_mag	Magnet diameter	As D_mag boost Increase both T_{cog} and B T_{cog} much faster
p	Poles number	As p boost Increase both T_{cog} and B T_{cog} faster

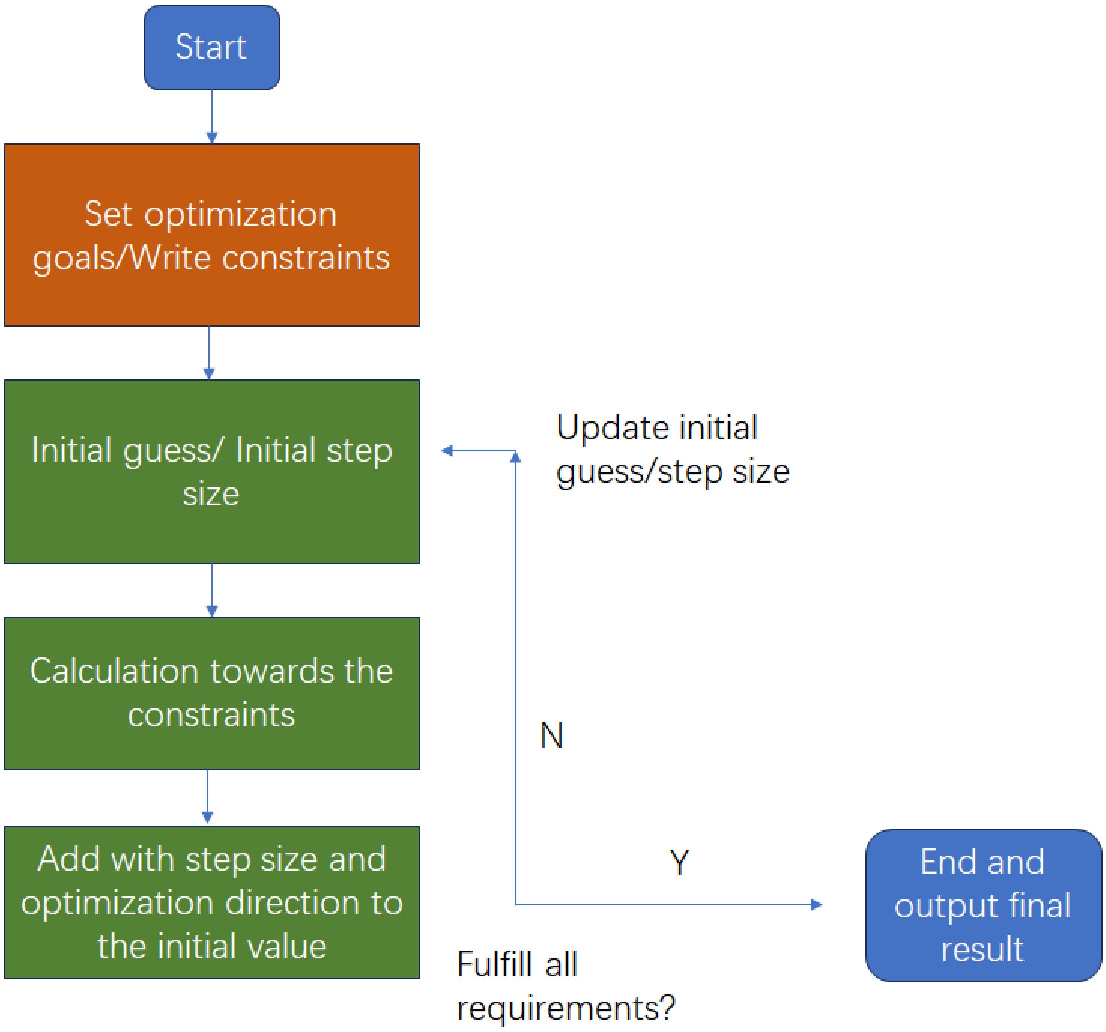


Figure 2.14: Optimization procedure

After optimization, the optimization result shows the best design locates at $D_{mag} = 6.4mm$, $p = 24$, and $g = 3mm$. The D_{mag} would be set to 0.25 in diameter instead since the 0.25 in magnets are the closest available magnet for purchase.

2.3.3 Teeth shape optimization

A new H shape teeth is introduced to substitute the original C shape iron teeth design. The H teeth improve the generator's cogging torque interpoles (when the stator teeth is not right face to the magnets) performance by creating a small airgap distance between left and right part of the teeth. It can be seen by comparing Figure 2.16 and Figure 2.17 from simulation that after changing from C shape teeth to H shape teeth, the attraction force angle between iron teeth and rotor board at the interpoles position reduce from almost 90 deg (the force direction perpendicular to the teeth and parallel to the rotational direction) to around 45 deg, and the attraction force in vertical direction reduced. The cogging torque at this time halved to 0.2 N*m, while the peak flux density only reduces by 8%, which are shown in Figure 2.18 and 2.19.

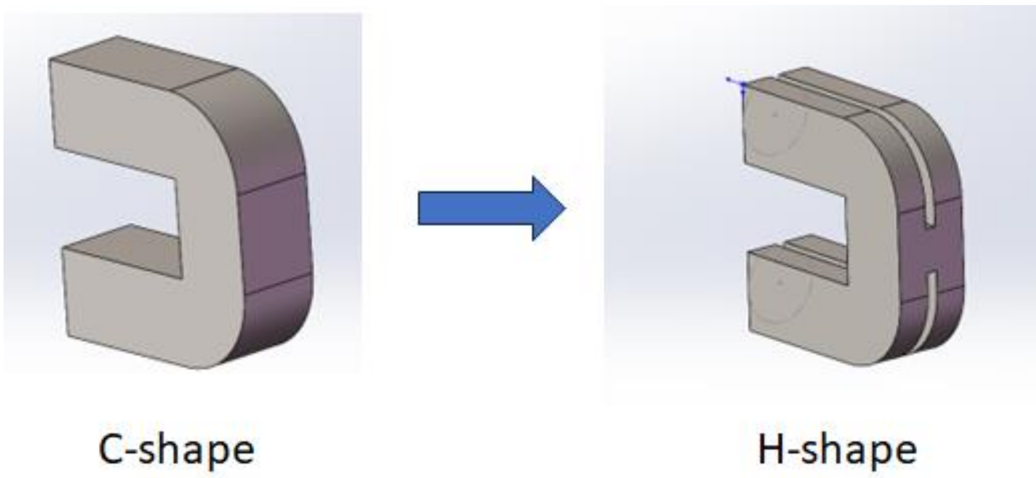


Figure 2.15: Teeth shape optimization

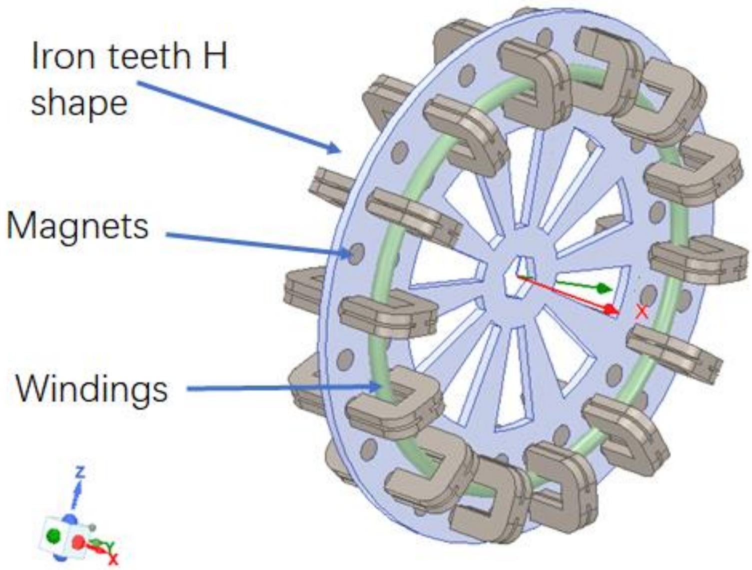


Figure 2.16: Ansys modeling of new H-shape iron teeth

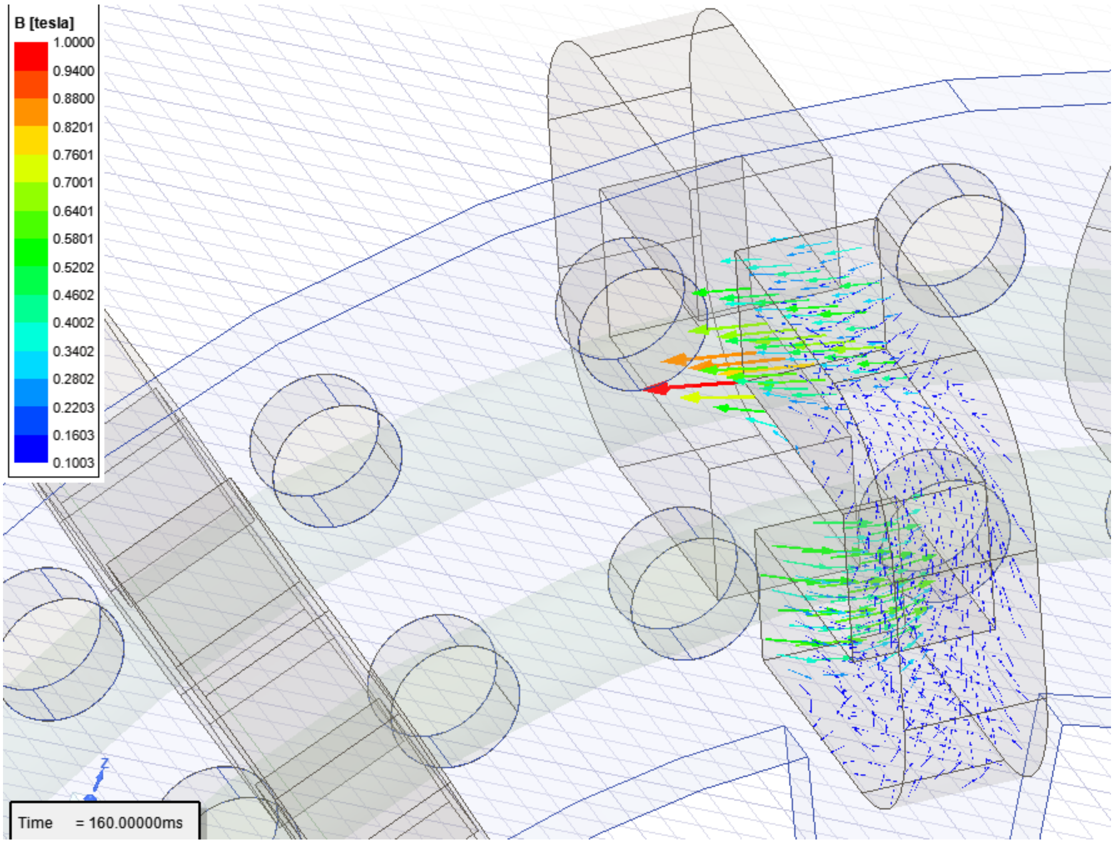


Figure 2.17: Flux distribution of C-shape iron teeth at interpole

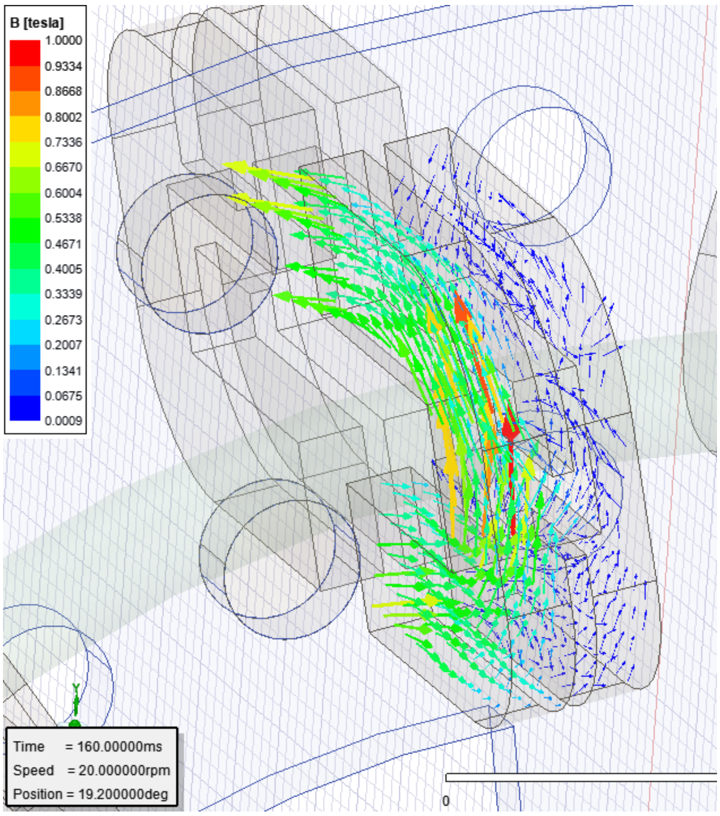


Figure 2.18: Flux distribution of H-shape iron teeth at interpole

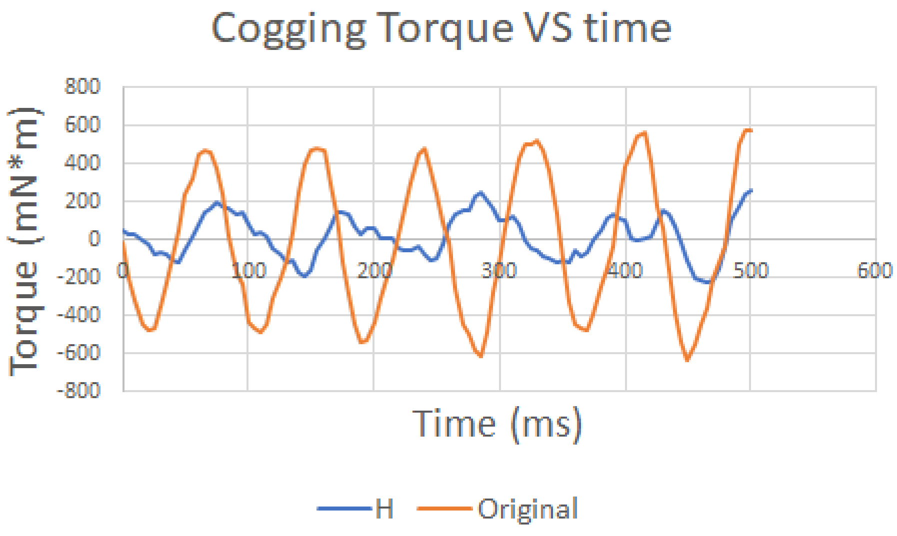


Figure 2.19: Cogging torque performance comparison of H shape teeth and Orignal C-iron teeth

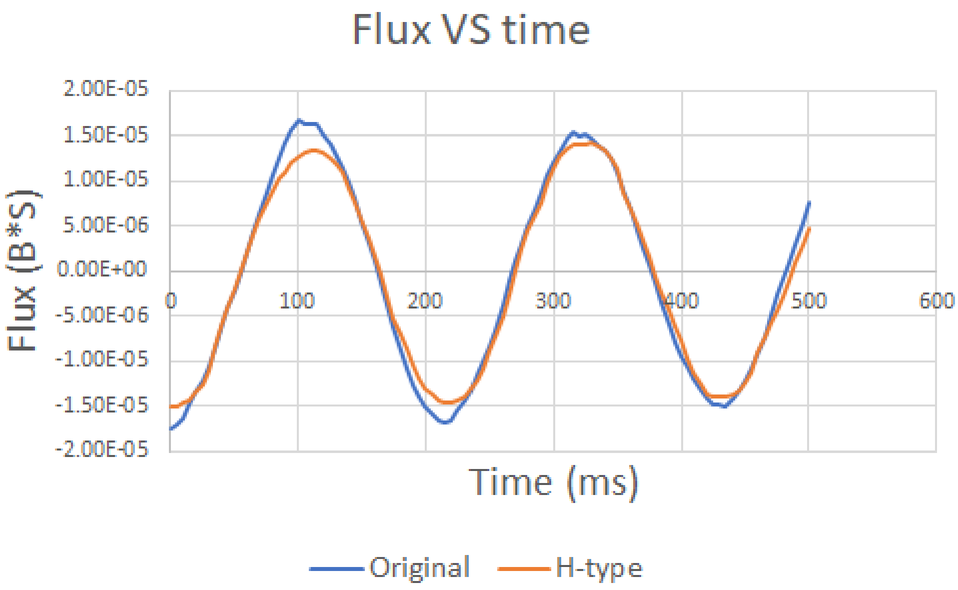


Figure 2.20: Flux comparison of H shape teeth and Original C-iron teeth

2.4 Nozzle-diffuser duct

The nozzle-diffuser duct (NDD) is a structural configuration that enhances fluid flow velocity while simultaneously improving the efficiency of the centrally positioned turbine. The nozzle part increases the flow that enters the nozzle, due to the principle of conservation of mass, and the diffuser decreases the outlet flow speed, while increases the pressure of the outlet flow. The nozzle regains some of the pressure lost in the nozzle and improves the efficiency of the turbine. The NDD greatly improves the performance of turbine-generator system at the low flow speed environment. The nozzle part is formed by the rotation of Airfoil NACA 2408, which forms a 21° angle with the horizontal axis. The diffuser part is generated by rotating Airfoil NACA 4480, with a 16° angle with the horizontal axis. The designed duct model is then built and simulated with Ansys Fluent. The greatest speed at the center of the nozzle-diffuser duct could reach 1.8m/s under an inlet flow of 1m/s, and the speed up ratio is 1.8 times.

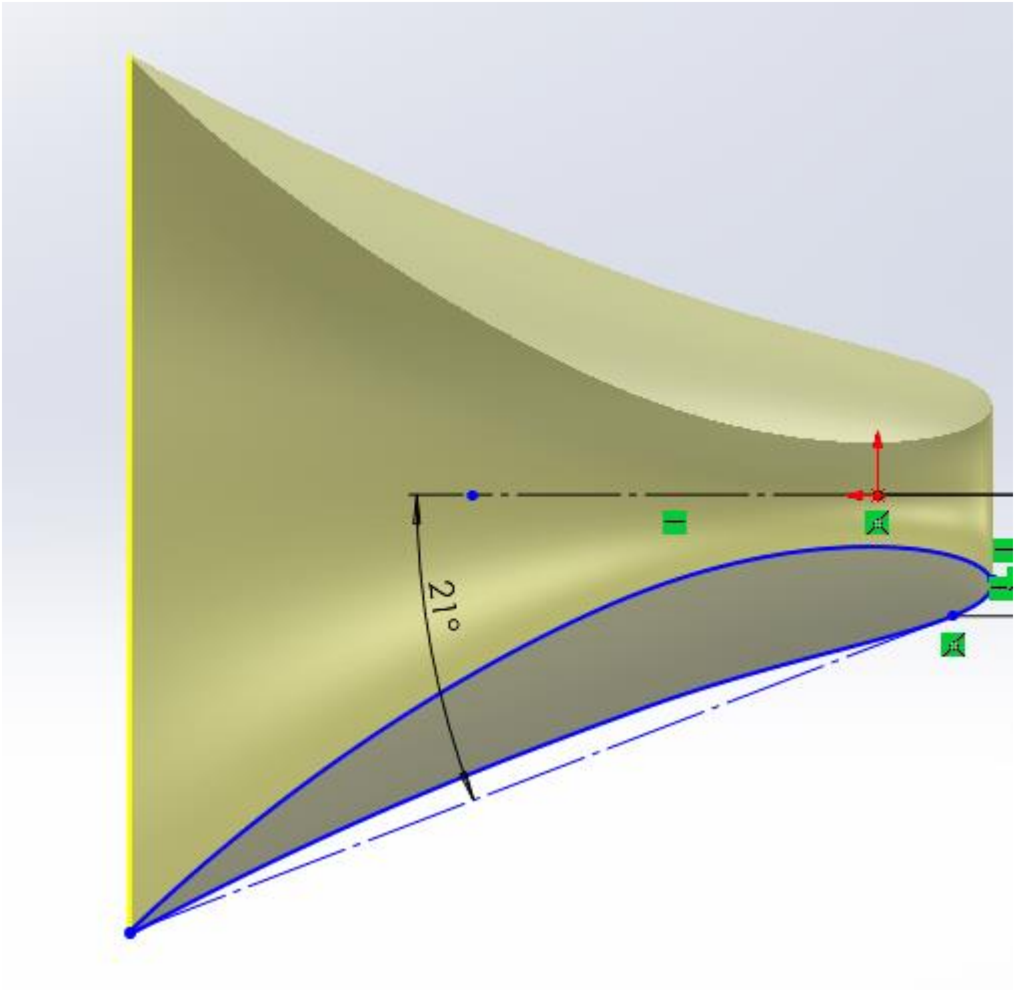


Figure 2.21: Airfoil design and angle of Nozzle

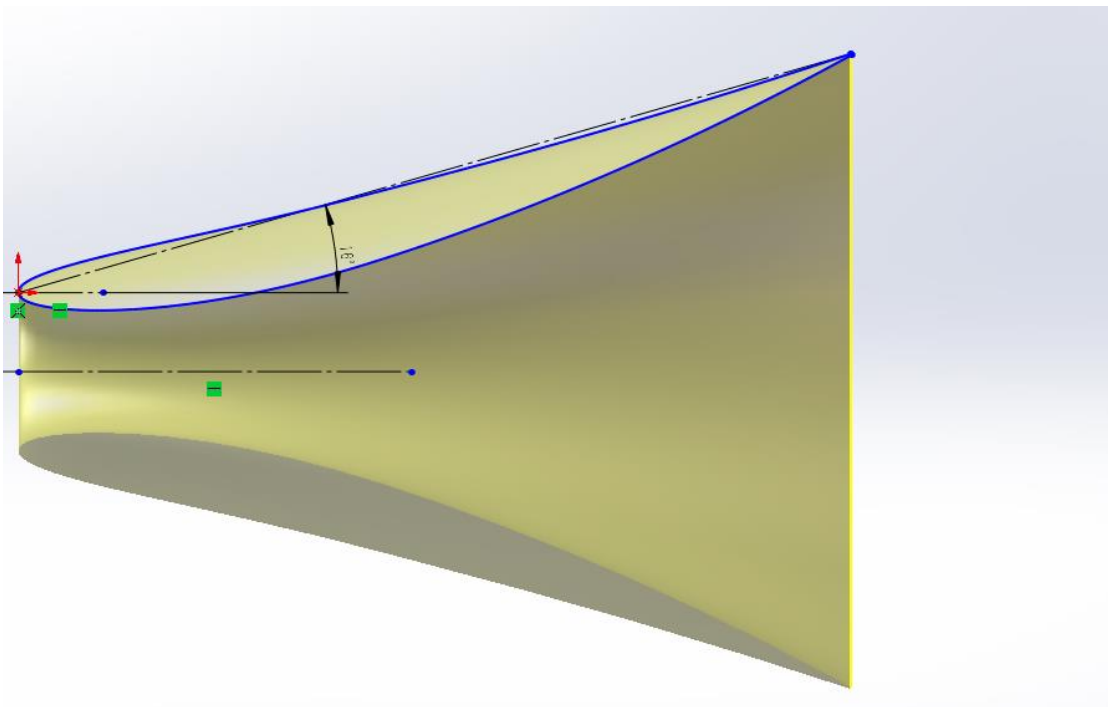


Figure 2.22: Airfoil design and angle of Diffuser

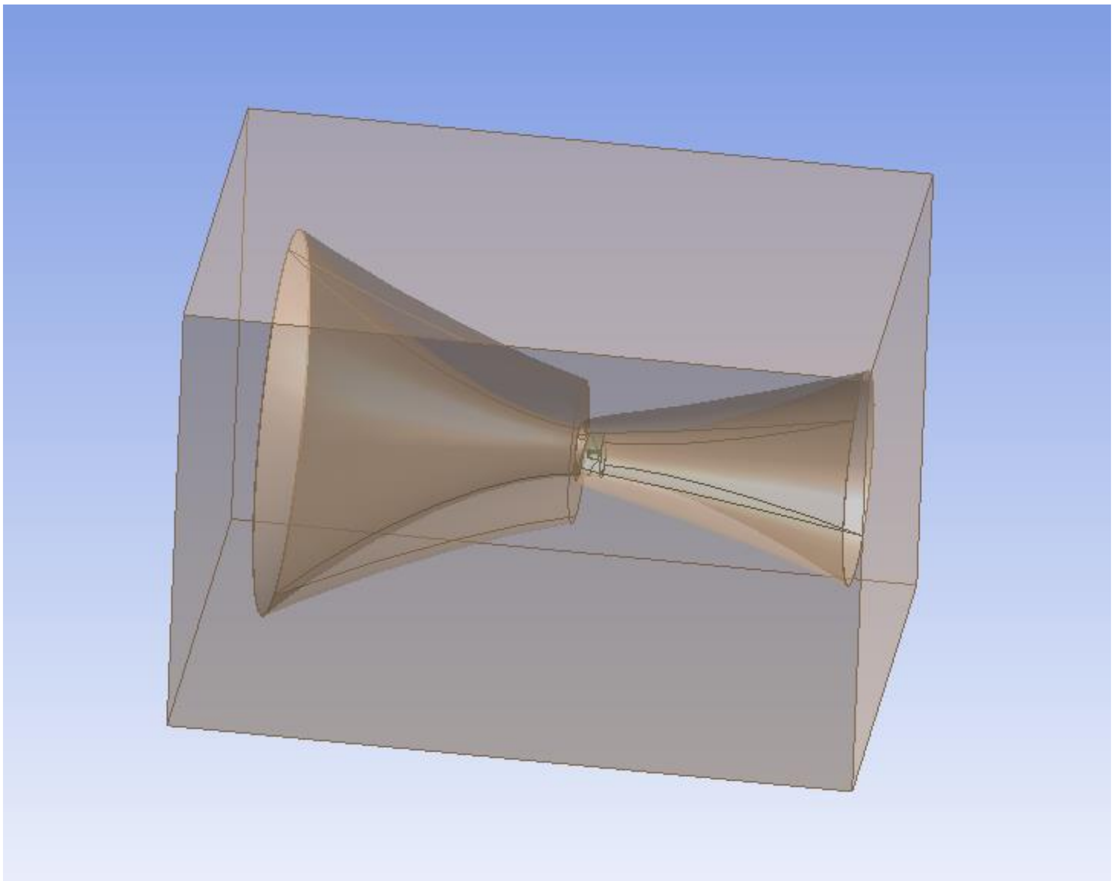


Figure 2.23: Ansys fluent model of Nozzle-diffuser duct

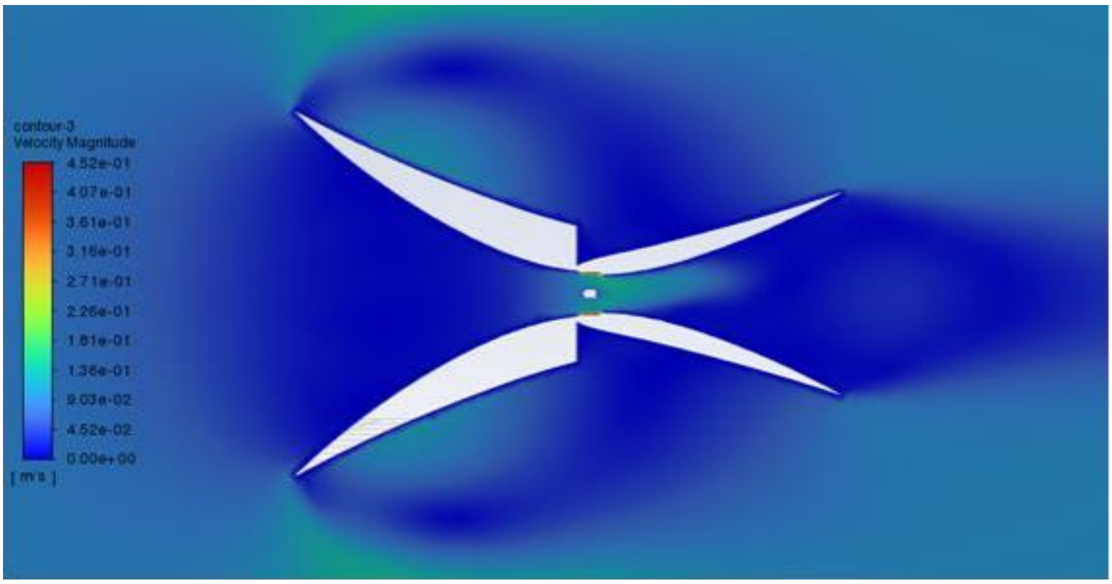


Figure 2.24: Flow velocity of cross-section from Ansys Fluent

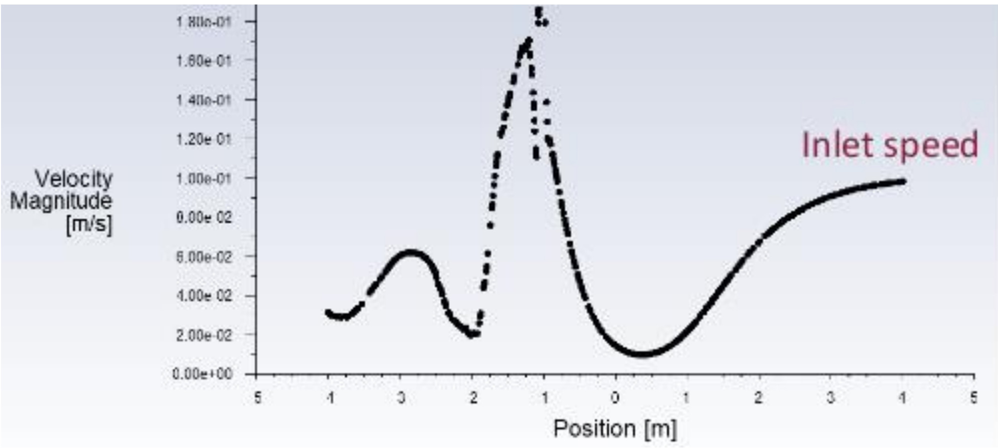


Figure 2.25: Flow velocity along inlet axis from Ansys

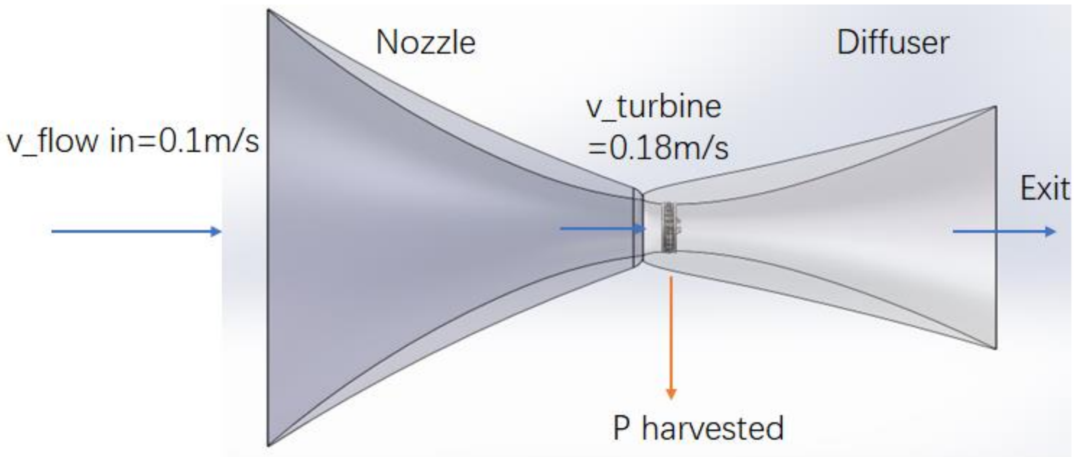


Figure 2.26: Nozzle-diffuser duct acceleration effect

2.5 Turbine model

American multiblade turbine is a kind of turbine which has great performance under low flow speed condition and could generate great torque under low flow speed condition. It is widely used in wind flow energy harvesting, but also could be utilized in low-speed water flow. The design principle of this American Turbine is modified based on article 'THE AMERICAN WIND TURBINE' by R.H.Nilberg. [5]

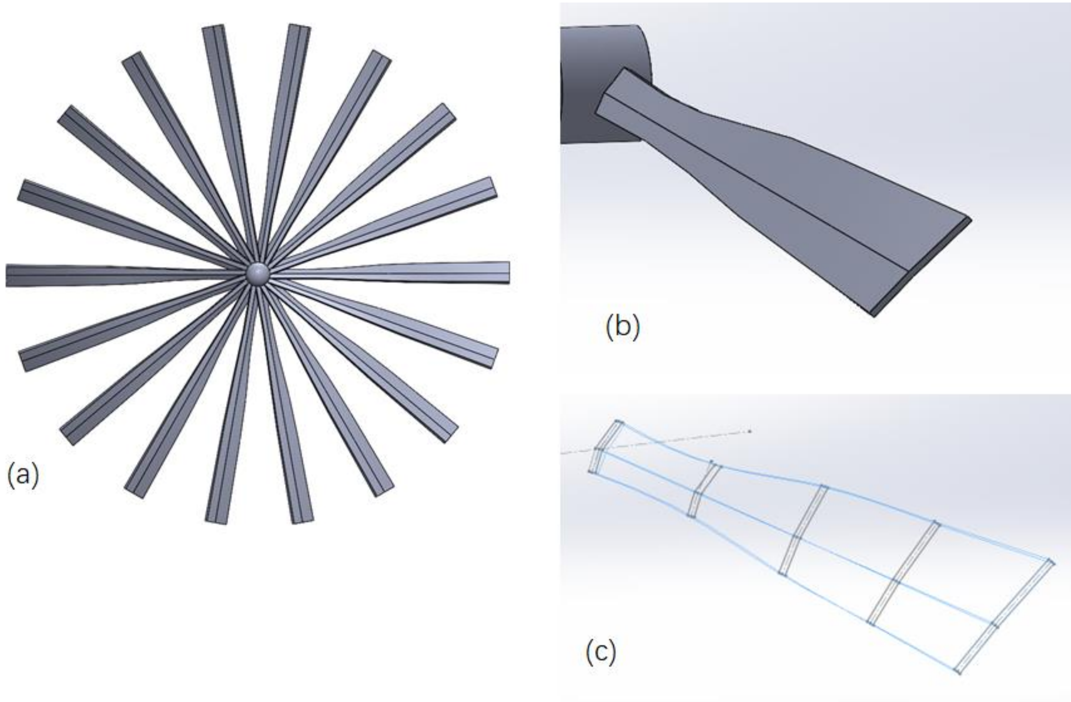


Figure 2.27: Turbine blade design

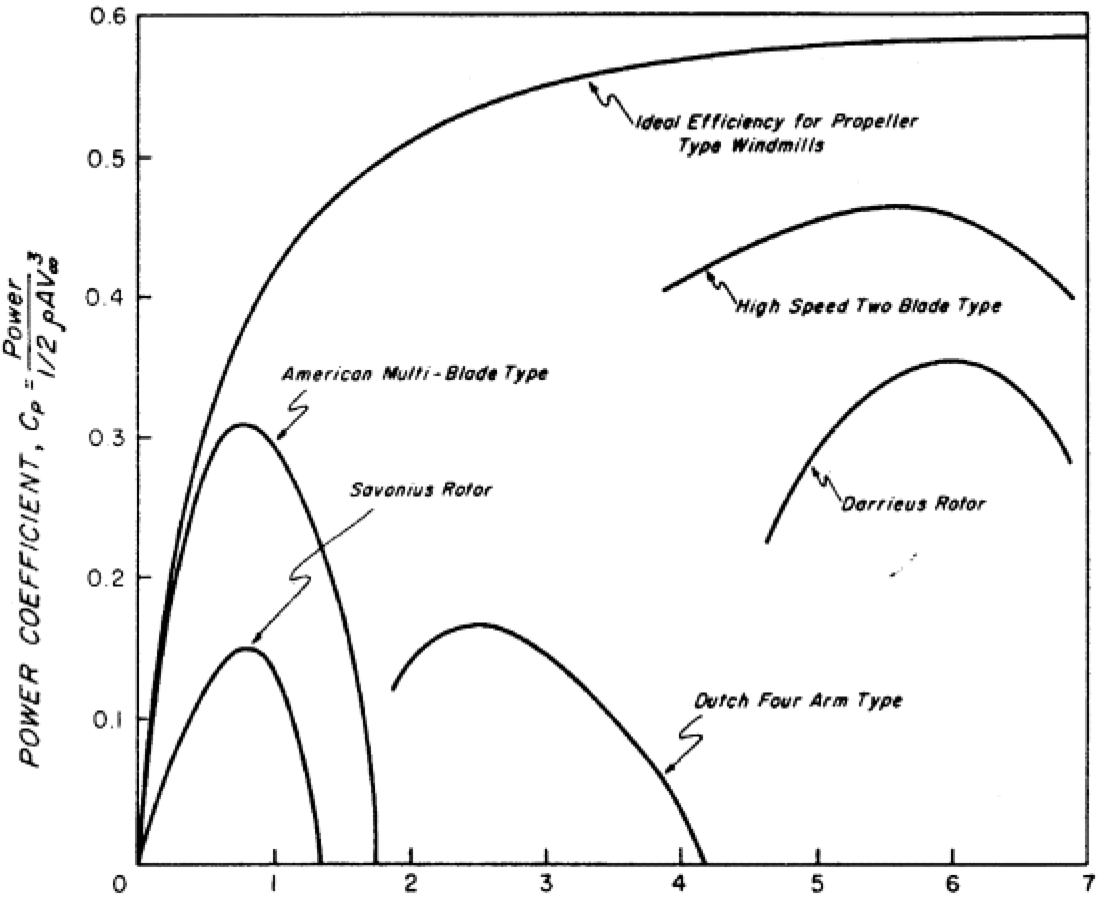


Figure 2.28: Power coefficient VS Tip speed ratio distribution [6]

The designed turbine has a 1m diameter and is design to work in 0.2m/s flow speed condition. The flow speed of the turbine, v_r', could be written as:

$$v_r' = 0.2m/s \tag{2-9}$$

And the radius of turbine equals to:

$$R = 0.5m \tag{2-10}$$

American multiblade turbine consists typically more than 8 blades to ensure the turbine could block enough water and convert the energy to the torque. After testing the performance of 12, 18 and 24 blades flat plate turbine, 18 blade has a better balance of torque and turbine efficiency. Thus, 18 blade number is picked for the primary design.

The design of a single blade is composed of five cross sections. Let the radius of a single blade equals to R, and the five cross sections are pick at r=0, r=0.25R, r=0.5R, r=0.75R and r=R. The section from r=0 to r=0.25R compose the root zone of the turbine blade and has the greatest twist angle, while the section from r=0.75R to r=R is called as the tip of the turbine blade and has the smallest twist angle. The tip speed ratio λ is defined as:

$$\lambda = \frac{u_r}{v_r'} \tag{2-11}$$

Where u_r refers to the tip speed of the turbine, in m/s.

$$u_r = \omega * r \tag{2-12}$$

Here ω is the rotational speed is rad/s and r is the radius in meter. u_r varies at the five cross sections because the r varies at different sections. American turbine has the great efficiency at λ =0.75 to λ =1. To maximum the efficiency, the section from r=0.75R designed to have λ =0.75, and the section to r=R has λ =1. The shape of each cross section is a bar shape with a twist at center, divide the blade shape into two parts. Let B be the center point of the cross section and draw a horizontal dot line that pass B. The first part is display as line AB, while the second part is shown as line BC. The line AB and the horizontal dot line form angle θ_r, while the line BC and the horizontal dot line form angle θ_r'. The angle θ_r is defined as:

$$\tan(\theta_r) = \frac{v_r'}{u_r} \tag{2-13}$$

With given v_r' and u_r, the angle θ_r of five cross sections could be calculated and displayed in the Table 1. The two cross sections of the root part (r=0, r=0.25R) are the same. O_r refer to the rotational velocity of the wind behind the turbine and is defined as:

$$o_r = u_r + (u_r^2 + v_1^2 - v_r^2)^{0.5} \tag{2-14}$$

Where v_r refer to the flow speed exit the nozzle-diffuser duct, and v_1 is the flow speed enter the nozzle-diffuser duct. With the help of Ansys simulation, it could be found that v_1=0.1m/s and v_r=0.04m/s. The angle θ_r' is defined as:

$$\tan(\theta_r') = \frac{v_r'}{o_r - u_r} \tag{2-15}$$

The angle θ_r' of cross sections is displayed in Table 2.

Next, the length of the part AB and part BC needs to be determined. Connect AC and draw an extension line of BC. Line AB and the extension line of BC form angle γ. Line AB and Line AC form angle α, while the angle between Line BC and Line AC is called angle β. Let the length of AC equals to l_r, and l_r is defined as:

$$l_r = a_r * \frac{2\pi r}{z} \tag{2-16}$$

Where a_r relates to the C_L and C_D, the lift and drag coefficient. z is the blade number and equal to 18 according to the primary design.

$$a_r^2 = \frac{{v_r'}^2 * 4 * o_r^2 + (v_1^2 - v_r^2)^2}{U_r^4(C_L^2 + C_D^2)} \tag{2-17}$$

Where U_r is the sum speed of v_r' and u_r. The length of line AB and BC is defined as:

$$AB = l_r * \sin(\beta)/\sin(\gamma) \tag{2-18}$$

$$BC = l_r * \sin(\alpha)/\sin(\gamma) \tag{2-19}$$

And from the definition of angle γ,

$$\gamma = \theta_r - \theta_r' \tag{2-20}$$

From Table 3 and Table 4, the angle of γ, α, β are calculated, and the length of part AB and part BC of different sections are displayed in Table 5. With the help of Ansys Fluent, the 1m diameter turbine could generate 2.6 N*m torque under the flow speed of 0.2m/s. The rotational speed under this torque is 0.2rad/s and the efficiency could be calculated by：

$$P_{out} = T * \omega = 0.52W \tag{2-21}$$

$$P_{in} = \frac{\frac{1}{2}mv^2}{t} = \frac{1}{2}(\rho\pi R^2 * v)v^2 = 3.15W \tag{2-22}$$

$$\eta = \frac{P_{out}}{P_{in}} = 16.5\% \tag{2-23}$$

However, it is hard to build a 1m diameter American turbine in the lab. A scaled 0.3-meter diameter turbine model is designed to prove the theory and work with the generator. The root angle of the scaled turbine is adjusted to match the need of building protype. The adjusted angle is shown in Table 6.

The scaled turbine has a diameter of 0.3m. Under the same 0.2m/s flow, the rotational speed could reach 1.5rad/s and has a higher efficiency of 26%.

$$R\_s = 0.1m \tag{2-24}$$

$$P_{out\_s} = T\_s * \omega\_s = 0.0327W \tag{2-25}$$

$$P_{in} = \frac{\frac{1}{2}mv^2}{t} = \frac{1}{2}(\rho\pi R\_s^2 * v)v^2 = 0.1257W \tag{2-26}$$

$$\eta\_s = \frac{P_{out}}{P_{in}} = 26\% \quad (2\text{-}27)$$

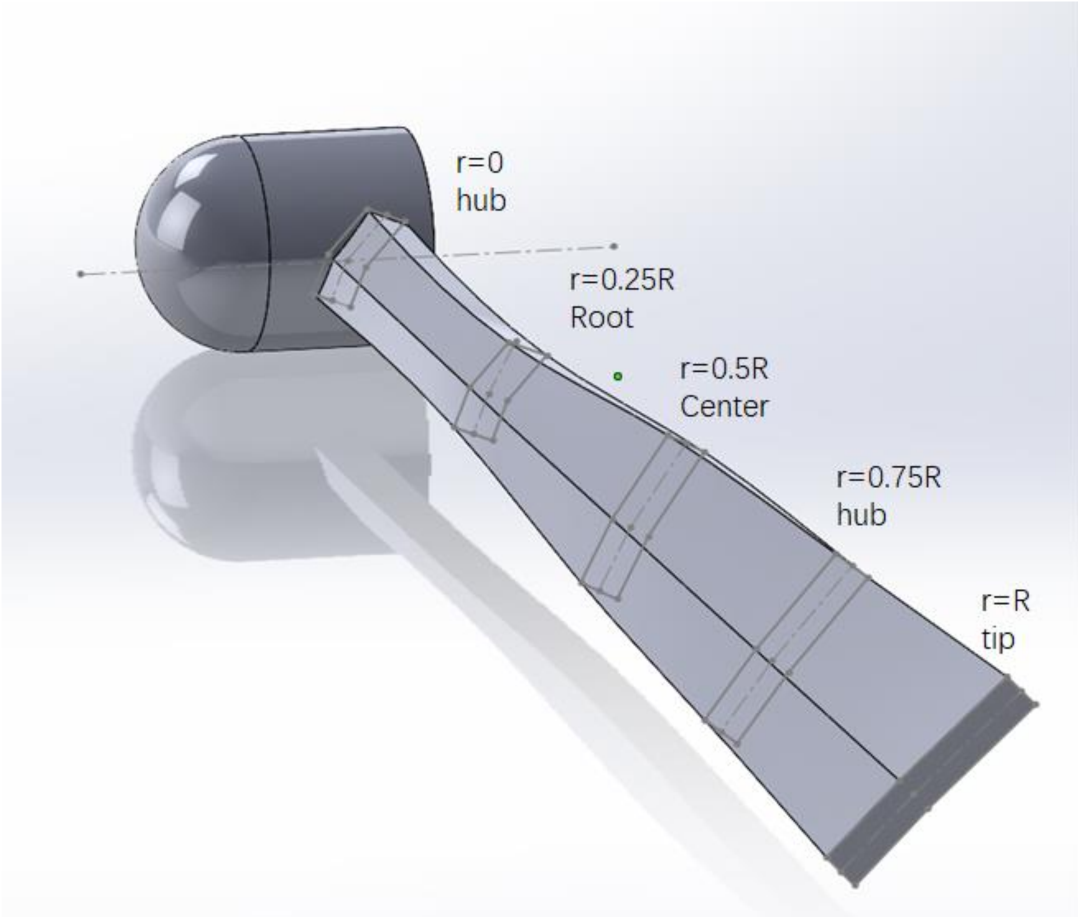


Figure 2.29: Cross section and shape along radius

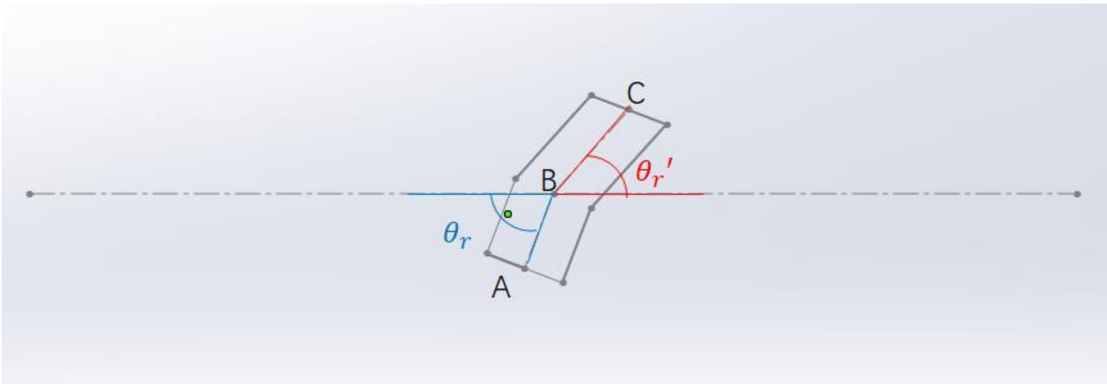


Figure 2.30: Inclination angles in cross section

Table 3. Twist angle θ_r of different cross sections

Radius(r)	TSR(λ)	v_r' (Flow speed)	u_r (tip speed)	v_r'/u_r	θ_r (deg)
0.25R	0.25	0.2m/s	0.05m/s	4	76
0.5R	0.5	0.2m/s	0.1m/s	2	63.4

0.75R	0.75	0.2m/s	0.15m/s	1.33	53.1
R	1	0.2m/s	0.2m/s	1	45

Table 4. Twist angle θ_r' of different cross section

Radius(r)	TSR(λ)	v_r' (Flow speed)	u_r (Rotational speed)	o_r	$v_r'/(o_r - u_r)$	θ_r' (deg)
0.25R	0.25	0.2m/s	0.05m/s	0.154m/s	1.923	62.52
0.5R	0.5	0.2m/s	0.1m/s	0.236m/s	1.47	55.77
0.75R	0.75	0.2m/s	0.15m/s	0.325m/s	1.142	48.79
R	1	0.2m/s	0.2m/s	0.42m/s	0.909	42.27

Table 5. Angle γ of different cross sections

Radius	TSR	θ_r (deg)	θ_r' (deg)	γ(deg)
0.25R	0.25	76	62.52	13.48
0.5R	0.5	63.4	55.77	7.63
0.75R	0.75	53.1	48.79	4.31
R	1	45	42.27	2.73

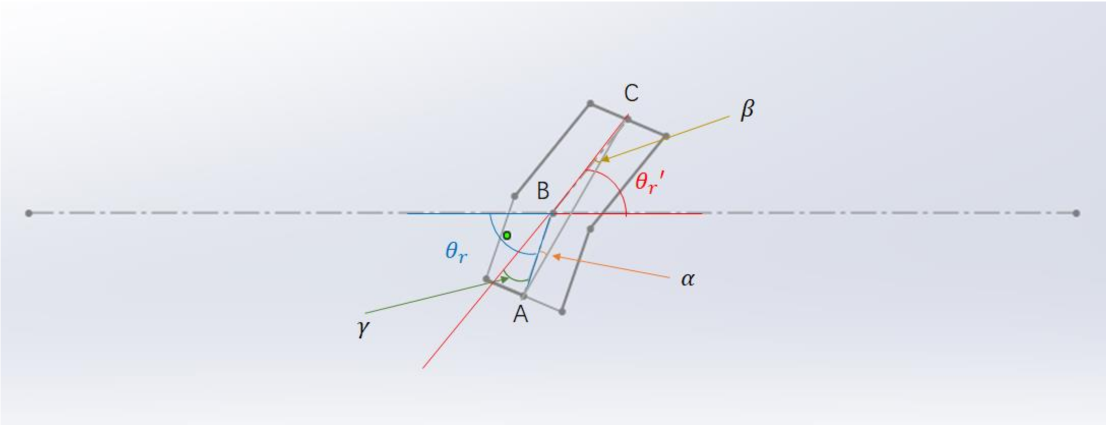


Figure 2.31: Inclination angles in cross section

Table 6. Angle α, β of different cross sections

γ(deg)	α(deg)	β(deg)
13.48	7.9	5.58
7.63	4.5	3.13
4.31	2.54	1.77
2.73	1.6	1.13

Table 7. Length of turbine section AB, BC of different cross sections

Radius	AC	AB	BC
R	0.059m	0.0246m	0.0348m
0.75R	0.049m	0.02015m	0.02895m

0.5R	0.0398m	0.01636m	0.02347m
0.25R	0.0238m	0.0099m	0.01395m

Table 8. Twist angle θ_r, θ_r' of the scaled turbine

Radius	TSR	θ_r (deg)	$\theta_r{}'$ (deg)
0.25R	0.25	69	48
0.5R	0.5	63.4	55.77
0.75R	0.75	53.1	48.79
R	1	45	42.27

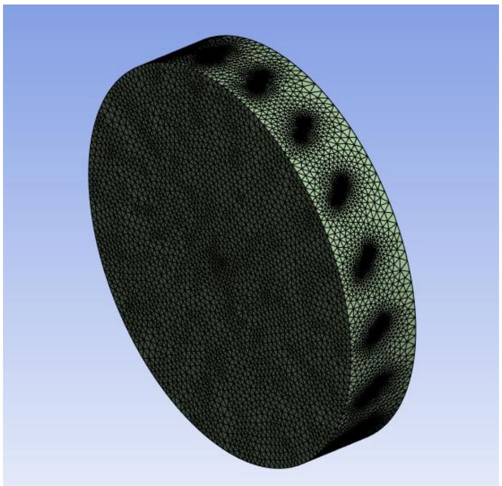


Figure 2.32: Meshing of American multiblade turbine

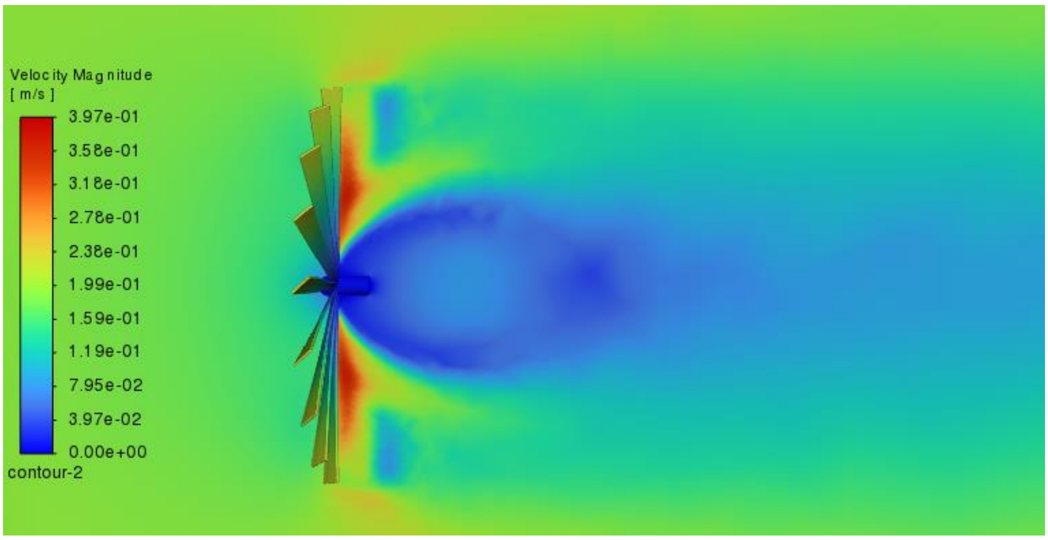


Figure 2.33: Flow velocity simulation of American multiblade turbine

```
Moments - Moment Center (0 0 0) Moment Axis (0 1 0)
                                 Moments [N m]
Zone                             Pressure         Viscous          Total
turbine                          0.10812703       0.00015607008    0.1082831
-------------------------------- ---------------- ---------------- -----------
Net                              0.10812703       0.00015607008    0.1082831
```

Figure 2.34: Torque output of American multiblade turbine

3. Generator system and comparison

The transverse flux generator harvesting system is compared with the commercial Energy harvesting system and show its superiority. The generator and turbine are compared separately since the generator have lathe test result, while the turbine only have the performance simulation. The Transverse flux generator (TFG) and the Axial flux coreless generator from low-speed energy harvesting system are set to work at 50 rpm, which is a typical achievable rotation speed under 0.2m/s current flow. The TFG generates 0.08W power output, with a 0.4 N*m cogging torque, while the Axial flux coreless generator harvest only 0.009W and with neglectable torque resistance. The designed TFG has much better performance than the axial coreless if the starting torque could be overcome and the cogging torque is bearable for the system.

The 0.3m diameter American turbine compete the 0.31m/s fan blade turbine from the commercial Energy harvesting system. Given a 0.2m/s cross flow condition, the American turbine could generate 0.108 N*m torque and rotates at 1.34 rad/s, and the efficiency of the turbine at this time. Meanwhile, the fan blade turbine only has 0.095 N*m torque and rotational speed is 0.5 rad/s. The American multiblade turbine has a better performance than fan blade under this flow speed. Overall, both the turbine and generator perform better than ones of the commercial energy harvesting system.

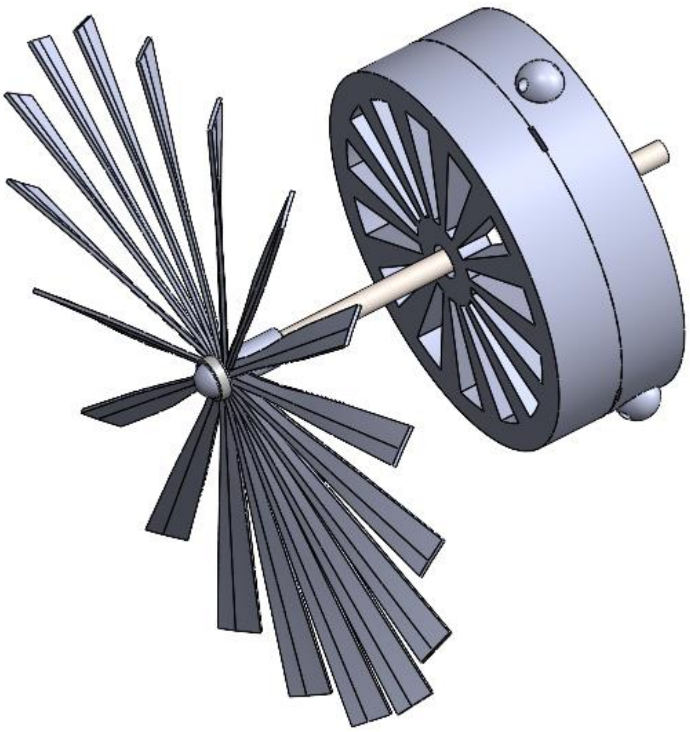
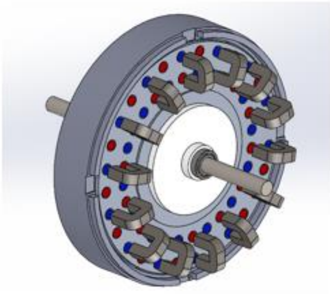


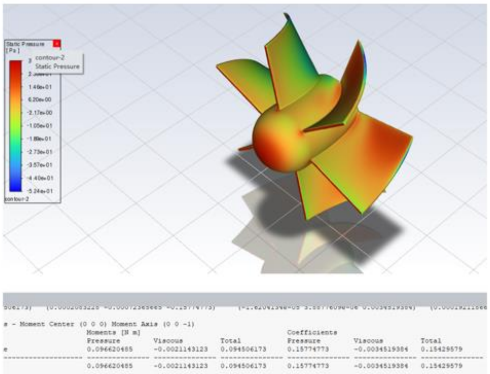
Figure 3.1: Proposed energy harvesting system

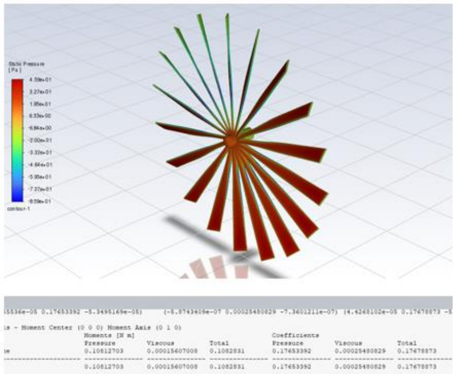
Figure 3.2: Commercial energy harvesting system



TFG **Axial flux coreless generator**

Figure 3.3: Generator comparison: TFG VS Axial flux





Fan blade **American multiblade**

Figure 3.4: Turbine comparison: American multiblade VS Fan blade

4. Prototype

The prototype of the transverse flux generator and the American multiblade turbine is displaced below. A 0.2m diameter transverse flux generator prototype and 0.3 m American multiblade turbine are built for the future test and study.

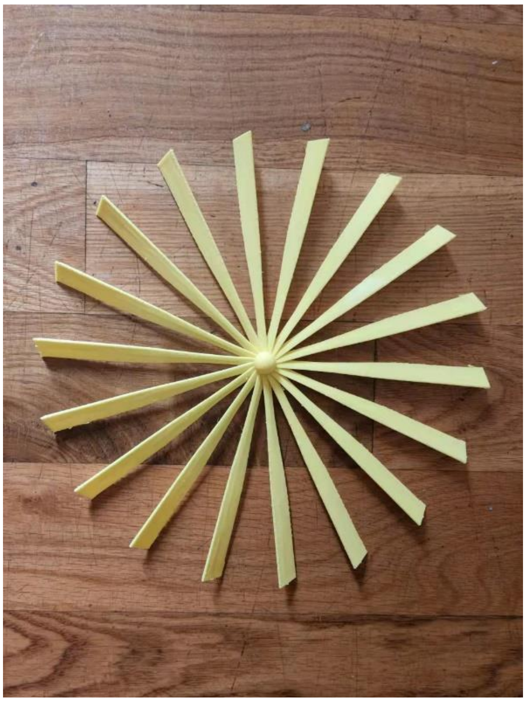


Figure 4.1: American multiblade prototype

Figure 4.2: TFG prototype

5. Conclusion

A mechanical energy harvesting structure for Arctic Ocean monitoring with near-real-time data transfer is designed in the article. The designed nozzle-diffuser duct could speed up the 0.1m/s Arctic current by 1.8 times and then enter the American multiblade turbine, which is popular in wind energy harvesting and firstly introduced in extreme low speed water current flow. The turbine has 26% efficiency, provides great torque, and supports the generator to rotate. The transverse flux generator, which has the advantage of compact structure and high flux density, is designed, and then optimized with the Gradient-based method. After that, the article compares the energy harvesting system is compared with the commercial ones in the market and reveals its superiority. Finally, the prototypes of the major parts are constructed and displayed.

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