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Flettner Rotor Modification through Adding Ridges and Fins with Results Comparison to Base Model

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***Abstract*— Oceans are the most crucial factor in maintaining global environmental equilibrium. Researchers are looking into the possibility of capturing wind power for shipping. Ship builders and owners provide several solutions based on the use of electrical power, low-polluting fuels, solar energy, and wind energy. The goal of this research is to learn more about using Flettner rotors as alternate sources of power and to create a new operational model for the rotor that could generate more power output from the currently available base model. Due to the sluggish market and glut of tonnage, the global shipping industry is now having difficulties. Only a few ships have wind-assisted technologies to help them save money on fuel. For the research, we created a base model in the 3D program from the available data about the commercially used Flettner rotor, then we modified a number of variations for the model and compared the results we reached from the CFD software to find an outcome that is better than the current output of the base model, and the results have shown improvement for the lower wind speeds.**

Keywords— CAD, Flettner rotor, Maritime shipping, Renewable energy, Simulation, Wind energy.

I. INTRODUCTION

The European Union included the maritime industry in its "white paper on transport 2011" and shipping is expected to grow significantly until 2050. Perhaps it is time to consider alternate modes of propulsion to lessen this reliance, lower expenses for shipping corporations, and make the shipping industry more environmentally friendly. Oars and sails have powered vessels since ancient Mesopotamia until the industrial revolution when mechanical engines were introduced. The problem is to figure out how to integrate current technology with traditional sailing techniques to provide green energy capable of moving large modern ships and meeting the needs of the maritime [1].

The International Maritime Organization (IMO) has put in place necessary measures to minimize shipping's greenhouse gas (GHG) emissions. Wind propulsion technology adoption is currently quite low on the market. The IMO's governing capacities were examined, allowing policy proposals to be customized to the IMO. Across all three wind propulsion methods, function fulfillment is found to be low or mediocre at best. The development and dissemination of knowledge should be the focus of policy actions. The IM might set up a temporary fund for the same reason until MBMs are introduced[2].

International shipping transports over 90% of global trade and is critical to global trade and the global economy [3]. International shipping, on the other hand, plays a vital role in global environmental issues such as climate change. As a result, it is critical that the shipping industry reconsiders its current practices and commits to significant emission reductions.

The issue in the shipping industry is to reduce CO2 emissions from fossil fuel consumption. Low-carbon shipping technology is an important part of addressing this problem. The wind is a renewable energy source that is available on the high seas and has a long and illustrious history in transportation. It is necessary to develop a system for evaluating the prospective contribution of wind-power technologies on global maritime routes [4].

The goal of the study is to help shed the light on what might be the best alternative energy source available and easy to harness and use with the current technologies that are used in the shipping sector. Moreover, the research will present a computer-assisted design for the base Flettner rotor that will provide a reference for the study to create new working and more efficient variations of the technology. Nevertheless, in case the variations of the newly modified rotors present negative or unwanted results that will also help in uncovering the current limitations of the technology.

In the marine propulsion sector, renewable energy sources and technologies are being investigated. Fossil-based alternative fuels result in lower SOx, NOx, and particulate matter (PM) emissions, but they also pose considerable issues in terms of greenhouse gas (GHG) emissions. Wind-assisted propulsion has been employed as a potential way to lessen the shipping industry's environmental imprint. In light wind situations, Flettner rotors might give the ship significant propulsive power. The ship with Flettner towers has been shown to save fuel usage by up to 20%[5].

The most likely reduction level of fuel consumption has been identified as 10% to 15%. Interest in using kites to assist ships in operating as soon as possible. Given rising fuel costs and environmental concerns, the parafoil and

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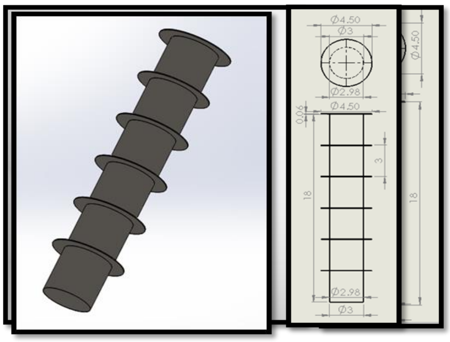


Figure 3 Flettner modified model 2 and dimensions [m].

Flettner rotor were identified as possible alternative technologies.

1.1. Flettener Rotor

Flettner rotors are a type of wind-powered propulsion that makes use of the 'Magnus effect,' a phenomenon that occurs when a rotating body encounters a fluid flow. The curving flight path of a ball in various sports, or the deviation of a spinning artillery shell in a crosswind, are both due to this effect[6].

A Flettner rotor is often a cylinder with an endplate fastened to the top that is installed vertically on a ship's deck. The cylinder rotates in an air stream due to the action of a motor, creating a lift force that can assist the ship's propelling demands.

In the 1920s, a German physicist named Anton Flettner[7] installed the first Flettner rotors aboard a ship called the Buckau, seeing their potential for ship propulsion. High bunker prices have inspired investigations for retrofitting Flettner rotors onto existing ships, with a focus on energy-efficient design and fuel-saving technologies.

Flettner rotors were invented in the nineteenth century, but they couldn't compete with steam and diesel ships at the time. The 10,000 DWT cargo ship E-Ship 1 was launched in 2010, featuring four Flettner Rotors measuring 27 meters in height and 4 meters in diameter. The technology was demonstrated by taking up space and increasing the overall height of the ship, perhaps posing design challenges.

Flettner rotors take up deck space and will almost certainly raise the ship's total height, posing significant installation challenges depending on the ship's design and intended operational profile. When contemplating the use of Flettner rotors on a specific vessel, these assumptions and difficulties should be examined further. All of the results are based on a single rotor. Many factors, such as vessel specifications, would influence the optimal number of Flettner rotors, which are beyond the focus of this study. However, assumptions about the number of rotors must be taken into account when interpreting the results[8].

1.2. Numerical Performance Model

The amount of main engine power the rotor can replace is determined by the motor's power consumption and the lift and drag forces operating on the cylinder. The thrust generated by the rotor is computed by projecting the sum of the lift and drag forces onto the ship's course, respectively. The following equations indicate the magnitudes of the lift and drag forces, as well as the power delivered by the rotor and to the rotor, respectively:

$$l = \frac{1}{2}\rho A v_a^2 C_L \tag{1}$$

$$d = \frac{1}{2}\rho A v_a^2 C_D \tag{2}$$

$$p_{L\&D} = (L + D)\, V_{Ship}$$

$$p_{motor} = \frac{1}{2}\rho A V_{ship} C_M \alpha$$

The defining parameters are CL = 12.5, CD = 0, and CM = 0.2, the rotor is a plain cylinder without end plates, with a vertical cross-sectional area A equal to the height h = 35 m times the diameter d = 5 m, and the spin ratio a = 3.5. The ship's velocity vector is V_{Ship}, the apparent wind speed is Va, and the density of air is q. If the power contribution is less than the drag force alone, the rotor is believed to be shut off [8]. If the combined lift and drag force on the rotor surpasses 220 kN, equal to an apparent wind speed of 13 m/s, the rotor is throttled to maintain a consistently combined lift and drag force, as well as the power delivered into the rotor. The difference between the power produced by the Flettner rotor and the power consumed by the motor to rotate it is calculated as the power contribution p_{prop}.

$$p_{prop} = p_{L\&D} - p_{motor} \tag{3}$$

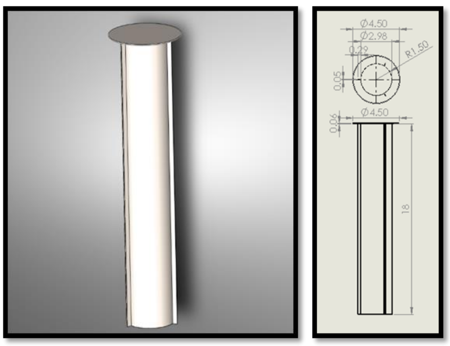


Figure 2 Flettner modified model1 and dimensions [m]

TABLE 1
OUTPUT COMPARISON TO MAIN ENGINE POWER FOR BASE MODEL.

Base Model							
Wind speed [m/s]	Output Comparison to Main Engine Power					AVERAGE	
	50 [rpm]	100 [rpm]	150 [rpm]	200 [rpm]	250 [rpm]	Wind speed	Rotor speed
10	0.60%	1.46%	2.38%	4.46%	8.61%	3.50%	1.87%
20	1.31%	4.45%	7.66%	16.66%	22.67%	10.55%	5.60%
30	2.62%	7.13%	9.58%	20.08%	38.71%	15.62%	7.68%
35	2.95%	9.35%	11.11%	23.06%	54.51%	20.20%	16.07%
							31.12%

1.3. The Magnus Effect

Flettner rotors take advantage of a force called the Magnus Effect, named after physicist Heinrich Gustav Magnus who first identified it in 1851 and which develops when air rushes past a revolving body [9] [10] [11]. The effect is well-known in a variety of sports, including baseball and table tennis, in which balls with applied spin travel through the air on curved trajectories.

The Flettner rotor, invented by Anton Flettner in 1922, used a vertically rotating, deck-mounted cylinder to harness the Magnus effect and create propulsion [9]. Flettner, a self-taught engineer who had studied mathematics, was inspired to create a ship-powering rotor after learning about Professor Ludwig Prandtl's study at the Aerodynamic Research Institute [12].

Flettner called the wind fuel he had captured "blue coal" and stated that billions of horsepower were readily available at low cost [13]. He was a prolific inventor who also received patents for the motorless ventilator, which is used globally on cars, caravans, and motor homes, and the trim-tab steering system, which is still widely used by both ships and planes today (Martin, 1926; Gilmore, 1984). As one of the pioneers of the modern helicopter, Flettner is also widely credited for advancing German and American helicopter technology both during and after World War II [14].

II. METHOD

The research methodology will be split into multiple steps, at the beginning, a base model date will be chosen from the commercially available rotors in the market, the Norsepower company rotor model has a 3m Diameter and 18m Length, and it’s selected reference model for the study.

After choosing the Rotor, a 3D model will be created for the study using the 3D modeling program, moreover, the performance of the basic model will be verified through simulation to collect RPM data, through different wind speeds. Afterward, if the model performance is validated and works like the rotor, we calculate the lift and drag for the basic model.

Nevertheless, modifications and variations of the model will be introduced, the modified model will have fins added on the circumference of the rotor perpendicular to the horizon, with a length of 18m matching the rotor length, and a width and depth of 0.2m each.

2.1. Base Model

The base model is built using the 3D program following the manufacturer’s dimensions and specifications, with a height of 18 m, a diameter of 3 m, a total weight of 20 tons, and Material consisting of ASTM A36 Steel for the welded steel structure.

Once the model is completed, it is exported from 3D as an XT file to run the next step and start the simulation using Numeca Fine Marine software, after importing to Numeca, we open the Hexpress tool and choose the Parasolid XT file to import and check after the program shows that the part is good for next steps, we start creating the test box for the wind simulation.

2.2. Modified Model #1

The first modified version of the rotor is based on the original design, and it is built using the 3D program following the dimensions and specifications with a height of 18 m, a diameter of 3 m, and the modification adds 3 fins positioned on a 120 degree from each other, fin thickness is 0.01 m, and fin width is 0.30 m, and the fin spans over the length of the rotor.

The fins are expected to add wind force to the existing Magnus effect, thus resulting in more power output and better performance and overall efficiency. Once the model is completed, it is exported from 3D to use in Numeca

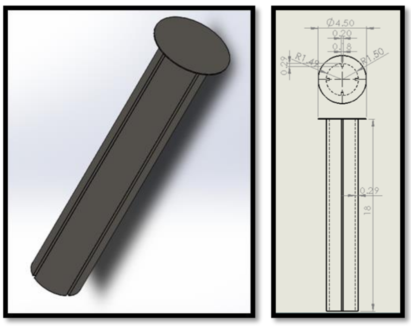


Figure 4 Flettner modified model 3 and dimensions [m].

program following the same steps used for the base model.

2.3. Modified Model #2

The second modified version of the rotor is based on the original design, and it is built using the 3D program following the dimensions and specifications with a height of 18 m, and a diameter of 3 m, and the modification adds 5 body plates to the rotor with a diameter of 4.5 m and thickness of 0.05 m. The plates are equally distanced from each other with 3 m increments.

The plates are expected to increase the Magnus force generated by increasing the surface area affected by the wind force on the rotor. Once the model is completed, it is exported from 3D to use in Numeca program following the same steps used for the base model.

2.4. Modified Model #3

The third modified version of the rotor is based on the original design, and it is built using the 3D program following the dimensions and specifications with a height of 18 m, a diameter of 3 m, and the modification adds 4 ridges positioned on a 90 degree from each other, ridge depth is 0.30 m, and ridge width is 0.20 m, and the ridge spans over the length of the rotor.

The ridges are expected to add more wind force to the existing Magnus effect compared to the fins, as the ridges have a bigger area to collect the wind and will work better collecting the wind energy alongside keeping the Magnus effect uninterrupted, thus resulting in more power output and better performance and overall efficiency. Number of time steps calculated is 1000 time step, the time step is uniform, and the time step value is 0.0015 [s].

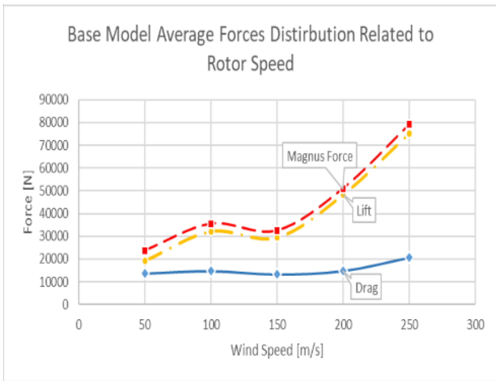
The mesh quality is then tested to ensure the reliability of the setup before the simulation starts, and when testing the mesh quality we must get a return value of zero Negative Cells, zero Twisted Cells, and zero Concave cells, to make sure of the setup process quality. Moreover, for the Base Model, we find out the total number of cells is (881,297), and the total number of vertices is (957,292). For Model 2 we find out the total number of cells is (1,038,859), and the total number of vertices is (1,190,804), and for Model 3 the total number of cells is (1,526,450), and the total number of vertices is (1,797,749).

TABLE 3
OUTPUT COMPARISON TO MAIN ENGINE POWER FOR MODEL 2.

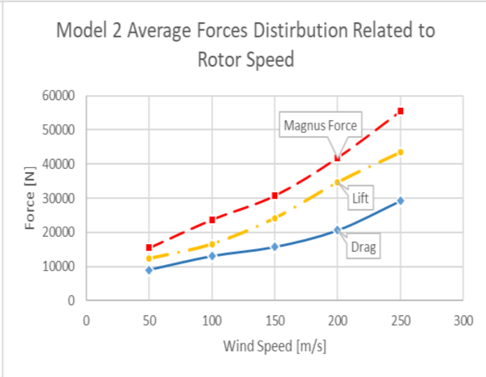
Model 2							
Wind speed [m/s]	Output Comparison to Main Engine Power					AVERAGE	
	50 [rpm]	100 [rpm]	150 [rpm]	200 [rpm]	250 [rpm]	Wind speed	Rotor speed
10	0.48%	0.95%	3.49%	3.82%	5.42%	2.83%	1.22%
20	0.92%	1.83%	5.84%	9.91%	14.81%	6.66%	2.43%
30	1.51%	3.01%	9.42%	16.36%	25.56%	11.17%	6.77%
35	1.96%	3.93%	8.33%	13.60%	21.94%	9.95%	10.92%
							16.93%

TABLE 2
OUTPUT COMPARISON TO MAIN ENGINE POWER FOR MODEL 3.

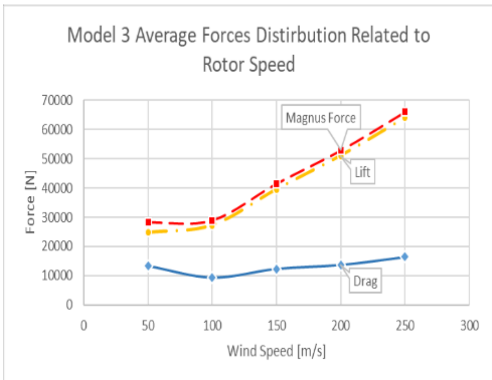
Model 3							
Wind speed [m/s]	Output Comparison to Main Engine Power					AVERAGE	
	50 [rpm]	100 [rpm]	150 [rpm]	200 [rpm]	250 [rpm]	Wind speed	Rotor speed
10	0.45%	1.77%	4.05%	6.47%	10.17%	4.58%	2.22%
20	0.93%	3.67%	7.94%	14.29%	22.17%	9.80%	4.55%
30	2.44%	5.78%	12.22%	20.61%	33.51%	14.91%	9.79%
35	5.06%	6.96%	14.97%	25.24%	38.16%	18.08%	16.65%
							26.00%



(A)

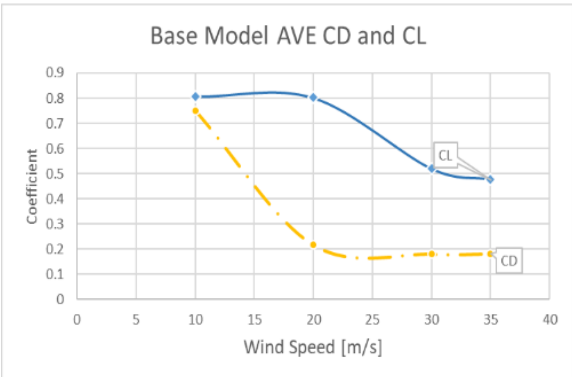


(B)

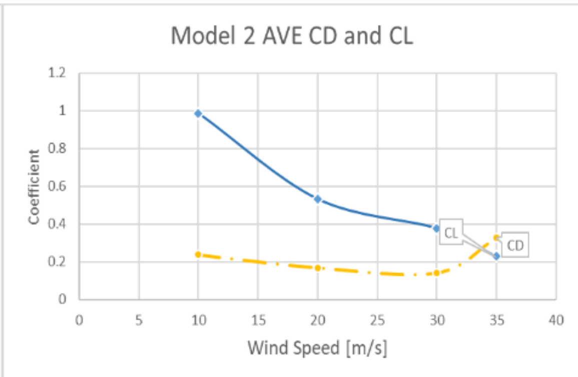


(C)

Figure 5 Average Forces Distribution.



(A)



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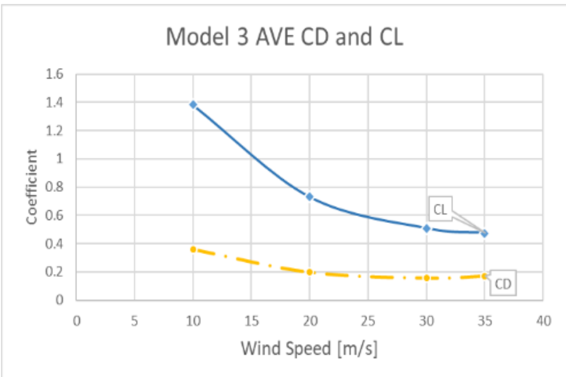

(C)

Figure 6 Average Lift and Drag Coefficients.

2.6.Speed variations

The base model will be subjected to several different wind speeds through multiple simulations, the wind speeds affecting the rotors will be: (10, 20, 30, and 35) [m/s] respectively. Furthermore, the rotor efficiency is measured under different rotations per minute, to find out the highest lift and drag forces the rotor will be affected by while under these different wind speeds.

III. Results and Discussion

Figure 5(A) and Figure 6(A). Average forces and coefficient charts for Base Model show the relationship between the Lift and Drag coefficients alongside the lift and drag forces affecting the rotor, where we can see that the Lift and Drag coefficients start closely at the same point due to the Drag and lift forces being close in value, afterward, the drag coefficient drops because the drag force is increasing slowly, but regains a little higher value at 35 m/sec wind speed due to the drag force value. The Lift coefficient keeps a similar amount at 20 m/sec wind speed and then drops to a new level corresponding to the Lift force.

Figure 5(B) and Figure 6(B). Forces and coefficient charts Model 2 rotor shows the relationship between the Lift and Drag coefficient alongside the lift and drag forces affecting the rotor, where we can see that the Lift coefficient is higher with a lower lift force and becomes increasingly lower with a higher lift force. Moreover, the Drag coefficient keeps a relatively steady value because of the linear relation between the increase in the drag force and relative wind speeds. Furthermore, at 35 m/sec wind speed, we can notice the drag coefficient is now higher than the lift coefficient, and this is due to the sharp drop in lift force due to the change in pressure around the rotor.

Figure 5(C) and Figure 6(C). Forces and coefficient charts Model 3 rotor shows the relationship between the Lift and Drag coefficient alongside the lift and drag forces affecting the rotor, where we can see that the Lift coefficient is higher with a lower lift force and becomes increasingly lower with a higher lift force. Moreover, the Drag coefficient keeps a relatively steady value because of the linear relation between the increase in the drag force and relative wind speeds.

The simulation process for each mode consists of 4 different wind speed variations with a combination of 5 different rotation speeds for the simulated rotor model, which results in 20 simulations for every model, and with 3 variations containing the base model, model 2, and model 3, the total number of simulations is 60 simulations. The simulation running time on Numeca software has varied depending on each model's complexity, and the running time for one simulation for the basic model was around 24 hours of continuous running, and with each model running 20 simulations, the base model's run times accumulated to 480 hours.

Moreover, the model 2 running hours were close to the basic model run time, however, the increased complexity scheduled 28 hours per simulation running, which has brought the total accumulated run times to a total of 560 hours. The complexity in model 3 was almost as double the one from the base model with a run time of 36 hours per simulation, and with each model running 20 simulations, the base model's run times accumulated to 720 hours.

The combined estimated work hours for all the models and simulation, while neglecting the model 1 results amounts to 1760 work hours, however, one method to address this increased work time was to run 2 simulations at a time cutting the required time in half.

The basic model has registered results comparable to real-life rotor regarding the efficiency and percentage of savings, which has set the baseline for all of the following simulations and comparison events, moreover, we can see the linear pattern in the power return from the rotor simulations as it is increasing with faster wind speeds and faster rotations per minute for the rotor.

While model 1 and its variations failed to register any improvement whatsoever with the power outcome, it has set the expectation on how to handle the generated lift force presented by the Magnus effect, where the break in the wind flow caused the effect to be nullified, therefore all of model 1 variations were considered imperfect and new models were to be created and inspected for better simulations.

Model 2 has kept up with the basic model and showed comparable results, especially at low wind speeds, however, the model did not register any noticeable improvements, and only registered better performance at 10 m/sec wind speed with a rotation speed of 150 RPM, and the improvement is 1.11% greater than the basic model provided as Model 0 registered (2.38%) efficiency and Model 2 registered (3.49%) efficiency under the same conditions.

Nevertheless, Model 3 was able to show considerable improvement, even though, the improvement was not in every wind speed and rotation, however, it has improved more than enough to shed light on the theory that was presented in this final model design, as it does not only use the Magnus effect lift force but also combines it with the wind turbine lift force, which is the same concept that model 1 and its variations try to use.

The efficiency improvement can clearly be shown in the average efficiency generated at 10 m/sec wind speed and in the average efficiency generated at Average rotor speeds of (50, 150, and 200) respectively. In general, Model 3 shows improvement in 10 wind speed and rotor speed conditions, while falling just a little short on the remainder 10 conditions for the simulation.

Moreover, the general wind speed conditions at the sea level tend to be on the lower side of the spectrum, making the model 3 modification as a valid and operational model that will create a sustainable power output through the average wind speed of 10 m/sec. Furthermore, the lower rotation speed average for Model 3 output is (2.22%) at 50 RPM speed, while the basic model registered (1.87%) efficiency, making model 3 also more efficient in the same condition with an improvement of (0.35%) for one rotor, however, the efficiency will also be reflected by the number of rotors used.

TABLE 4
DRAG FORCE, LIFT FORCE, DRAG COEFFICIENT, LIFT COEFFICIENT, MAGNUS FORCE.

	Base Model				Model 2				Model 3			
Wind Speed	10	20	30	35	10	20	30	35	10	20	30	35
Drag	2160.7	8482.8	19331.0	24436.3	1544.6	5386.0	11237.3	17719.3	1673.9	4813.9	14424.8	32758.3
	6492.2	8222.4	18597.9	25403.0	2275.6	5878.9	11213.2	32703.3	2630.3	6738.1	11646.8	16665.3
	6793.6	8465.2	16531.1	20901.7	3177.6	7570.0	14221.3	37749.7	4461.8	9179.2	15676.9	20277.6
	10012.1	9951.3	16943.9	21945.5	2916.6	9027.0	17010.1	53362.1	4618.0	10569.0	16360.7	23420.6
	16698.0	13550.3	19934.0	32381.1	3451.7	10241.0	18387.0	84709.6	6922.9	13221.6	20979.7	24698.8
Drag Average	8431.3	9734.4	18267.6	25013.5	2673.2	7620.6	14413.8	45248.8	4061.4	8904.4	15817.8	23564.1
Lift	7245.7	14336.0	27014.9	28427.5	5858.0	10330.0	15464.4	17525.3	5481.3	10718.9	27397.4	55298.0
	6595.0	27006.1	41247.8	53664.1	10111.9	19972.1	27666.8	8598.4	10952.3	22338.1	34817.6	40905.4
	7439.5	31279.0	37024.0	42120.8	14445.3	23545.4	37263.8	21595.6	16542.4	32330.3	49295.6	60011.8
	10024.6	51949.8	61439.5	69850.3	11763.7	30154.0	49069.6	48069.6	20004.6	44109.8	63342.4	76627.3
	14106.3	55946.3	96280.3	134590.0	13330.0	36179.3	62262.5	62627.5	24872.1	54728.3	82483.0	93710.8
Lift Average	9082.2	36103.4	52601.3	65730.5	11101.8	24036.2	38345.4	31683.3	15570.6	32845.1	51467.2	65310.7
Magnus Force	7561.0	16657.7	33218.9	37486.7	6058.2	11649.8	19116.1	24922.1	5731.2	11750.3	30962.8	64272.6
	9254.3	28230.1	45246.6	59373.0	10364.8	20819.4	29852.8	33814.7	11263.7	23332.2	36713.9	44169.9
	10074.7	32404.3	40546.9	47021.7	14790.7	24732.4	39885.3	43490.4	17133.6	33608.1	51728.4	63345.1
	14168.1	52894.3	63733.1	73216.6	12119.9	31476.2	51934.2	71820.6	20530.7	45358.4	65421.2	80126.6
	21858.9	57563.8	98322.2	138430.5	13769.6	37600.8	64920.7	105346.7	25817.6	56302.7	85109.3	96911.0
Magnus Force Average	62916.9	187750.2	281067.8	355528.5	57103.2	126278.5	205709.1	279394.5	80476.8	170351.6	269935.5	348825.3
Lift Coefficient	0.6	0.3	0.3	0.2	0.5	0.2	0.2	0.1	0.5	0.2	0.3	0.4
	0.6	0.6	0.4	0.4	0.9	0.4	0.3	0.1	1.0	0.5	0.3	0.3
	0.7	0.7	0.4	0.3	1.3	0.5	0.4	0.2	1.5	0.7	0.5	0.4
	0.9	1.2	0.6	0.5	1.0	0.7	0.5	0.3	1.8	1.0	0.6	0.6
	1.3	1.2	1.0	1.0	1.2	0.8	0.6	0.5	2.2	1.2	0.8	0.7
Lift Coefficient Average	0.8	0.8	0.5	0.5	1.0	0.5	0.4	0.2	1.4	0.7	0.5	0.5
Drag Coefficient	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
	0.6	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.1
	0.6	0.2	0.2	0.2	0.3	0.2	0.1	0.3	0.4	0.2	0.2	0.1
	0.9	0.2	0.2	0.2	0.3	0.2	0.2	0.4	0.4	0.2	0.2	0.2
	1.5	0.3	0.2	0.2	0.3	0.2	0.2	0.6	0.6	0.3	0.2	0.2
Drag Coefficient Average	0.7	0.2	0.2	0.2	0.2	0.2	0.1	0.3	0.4	0.2	0.2	0.2

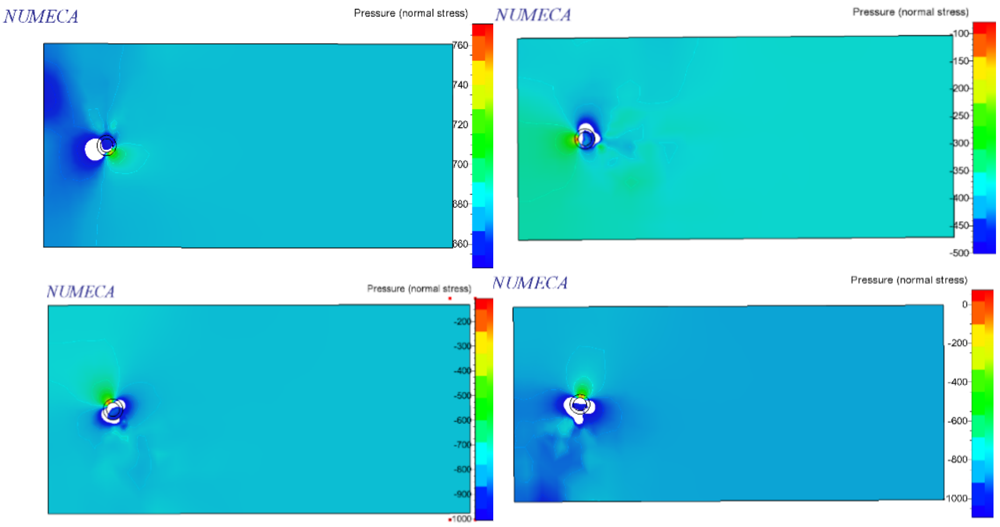

Figure 7 Pressure at Wind speed 10,20,30,35 [m/sec] with 50 RPM rotor speed for Base Model.

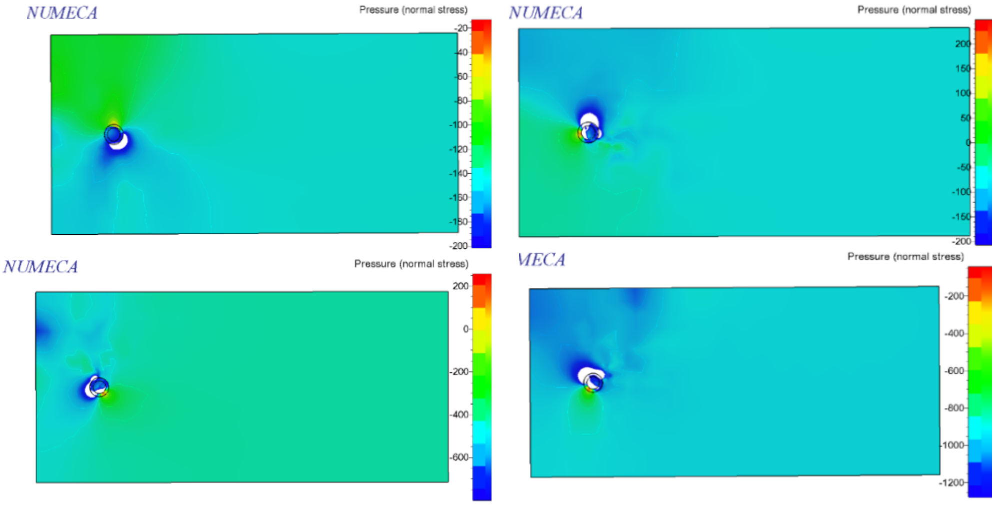

Figure 8 Pressure at Wind speed 10,20,30,35 [m/sec] with 100 RPM rotor speed for Base Model.

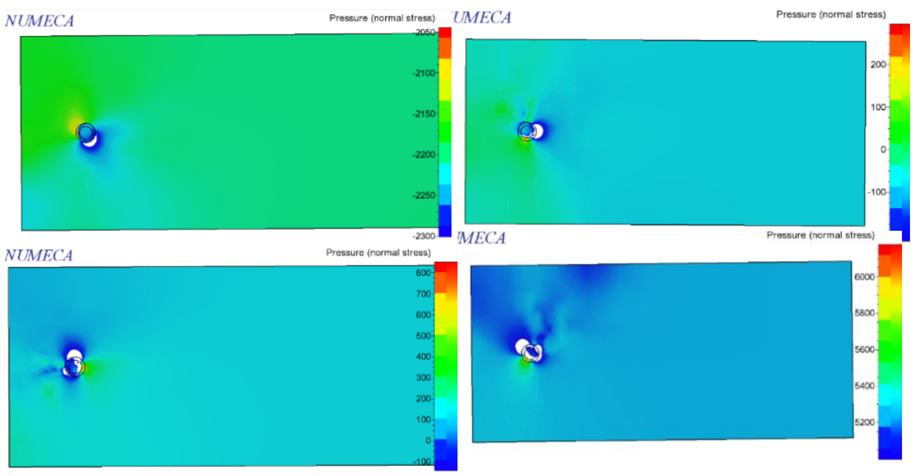

Figure 9 Pressure at Wind speed 10,20,30,35 [m/sec] with 150 RPM rotor speed for Base Mod

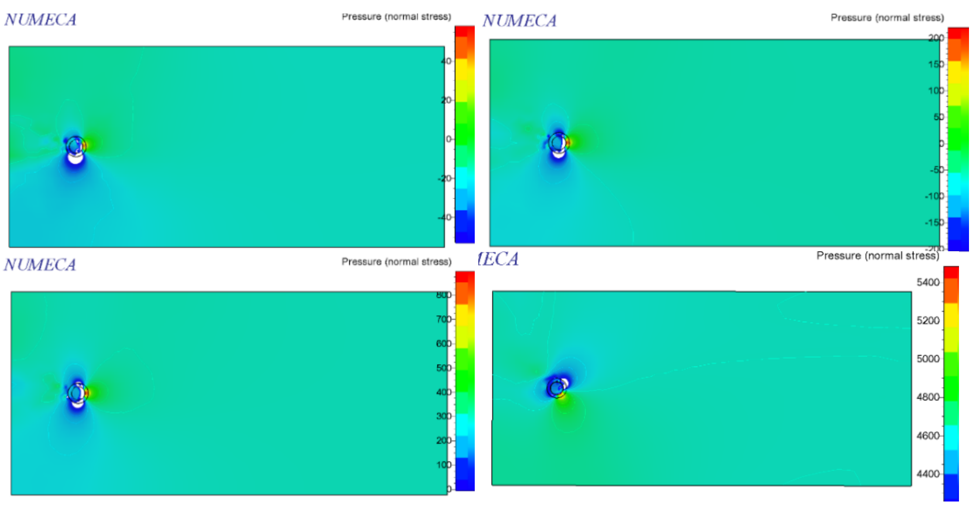

Figure 10 Pressure at Wind speed 10,20,30,35 [m/sec] with 50 RPM rotor speed for Model 2.

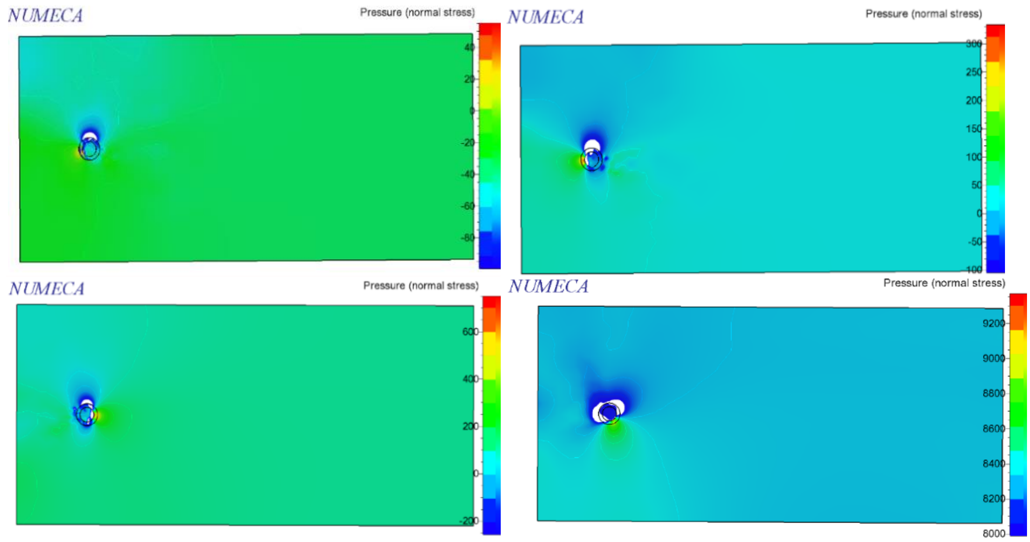

Figure 11 Pressure at Wind speed 10,20,30,35 [m/sec] with 100 RPM rotor speed for Model 2.

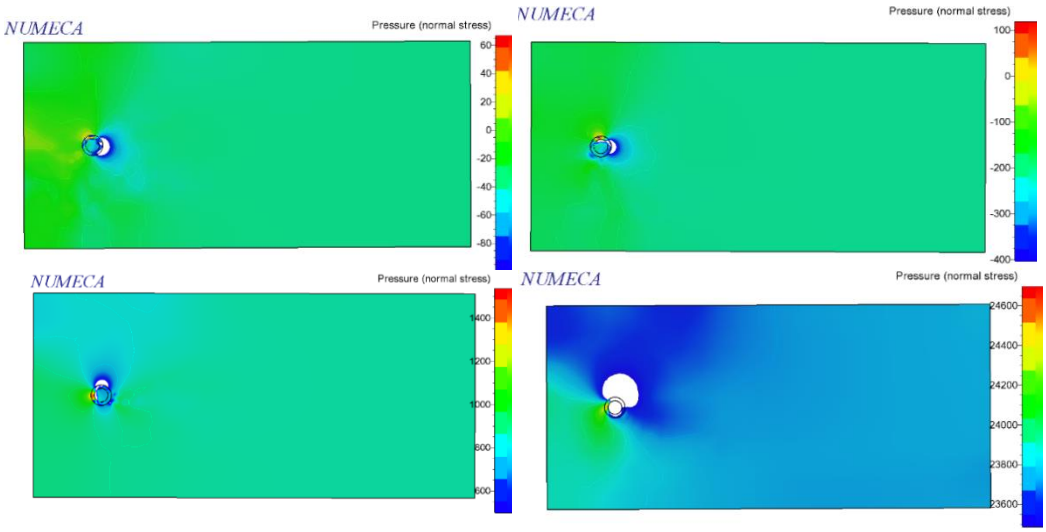

Figure 12 Pressure at Wind speed 10,20,30,35 [m/sec] with 150 RPM rotor speed for Model 2.

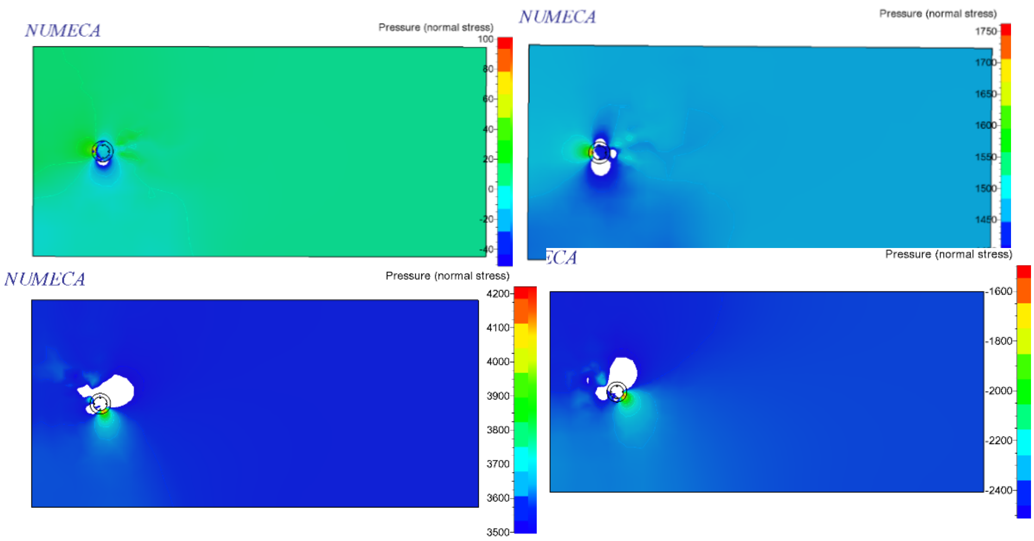

Figure 13 Pressure at Wind speed 10,20,30,35 [m/sec] with 50 RPM rotor speed for Model 3.

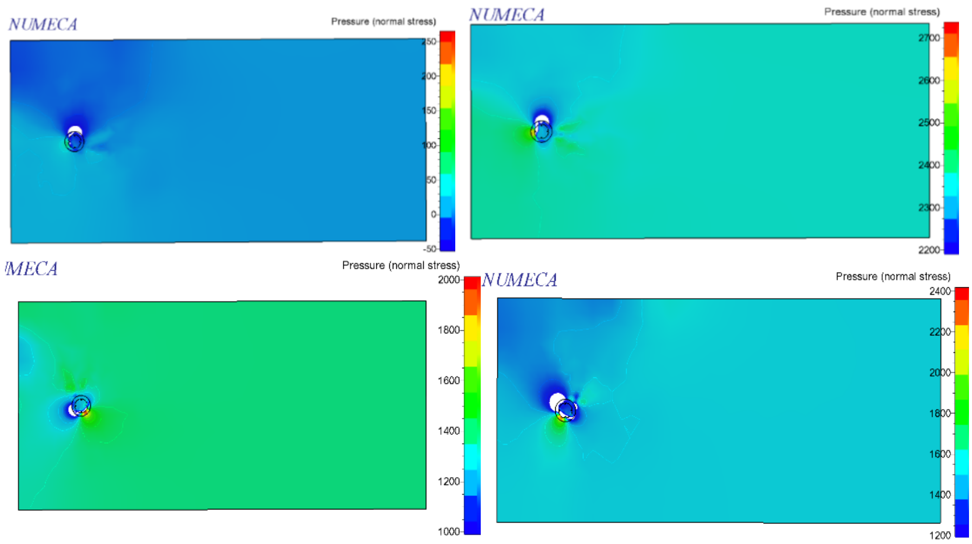

Figure 14 Pressure at Wind speed 10,20,30,35 [m/sec] with 100 RPM rotor speed for Model 3.

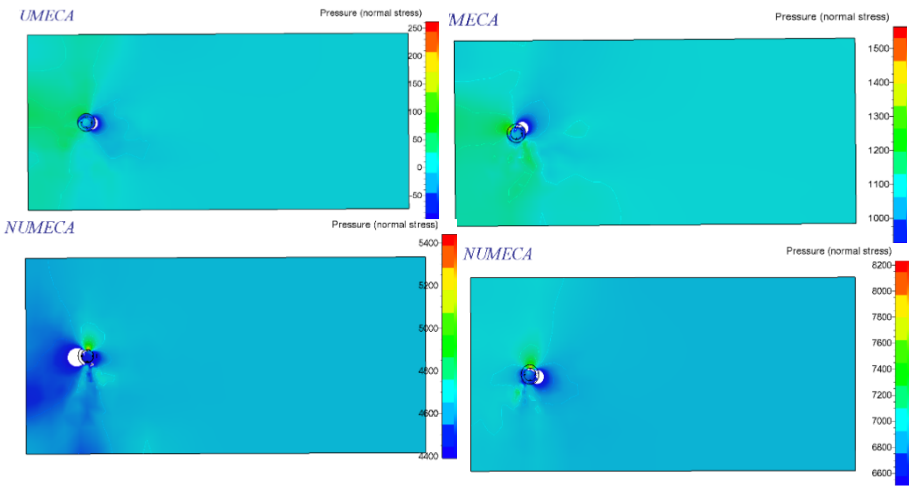

Figure 15 Pressure at Wind Speed 10,20,30,35 [m/sec] with 150 RPM rotor speed for Model 3.

Model 3 Rotor speed averages at 150 RPM, and 200 RPM is (9.79%) and (16.65%) respectively, while the basic model efficiency average at the same rotations speeds is (7.68%) and (16.07%) respectively, with the improvement of (2.11%) and (0.58%). However, in general Model 3 falls a little short of the basic Rotor at average wind speeds of (20, 30, and 35) with the basic model registering efficiency of (10.55, 15.62, and 20.20) percent respectively, while model 3 registers under the same conditions an average efficiency of (9.80, 14.91, and 18.08) % respectively while coming short with (0.75, 0.71, and 2.12) percent.

IV. CONCLUSION

While Model 3 doesn't register better results at every condition, it still performs better than the basic model for the lower wind and rotation speeds, which makes it more valuable in current working conditions over the high seas. At low wind speeds with a set of four rotors, the efficiency increase will have a total of (4.32%) and this will show clearly as four rotors of the basic model will amount to a total savings of (14%) while Model 3 rotor set of four under the same low wind speed conditions will have a total savings of (18.32%) which is not only reflected as fuel savings but also as less harmful emissions.

Furthermore, the estimated average annual wind speed in different sea areas shows that the average annual wind speed doesn't exceed the minimum wind speed of 10 m/sec that was set in the simulation. According to data from NASA Surface meteorology and Solar Energy for the period 1983–1993 (Rehmatulla et al., 2017). Therefore, making the Model 3 a better rotor than the base model in real-life wind speeds over the seas.

Further improvements can be added to Model 3, as it can be the base for an improvement study that will take into account all the possible variations for the inverted fins or ridges used to harness more of the wind power without interrupting the Magnus effect, as the current ridges are oversimplified for the study purposes and the number and positioning weren't put into account as well while focusing more on the improved results collected from the model.

Model 3 can be improved more by studying the optimum number of ridges, and the shape and size of each ridge, leaning more on to the aerodynamic aspect of the ridge and the compatibility with the flattener rotor without interrupting the Magnus effect.

Model 2 has shown acceptable results, and might be the subject of further improvement, however, the multiple end plates need to be improved on since it didn't give the expected effect of increasing the Magnus force further than the normal rotor and might have introduced more drag instead of lift to the rotor design. The only registered improvement is recorded at 10 m/sec wind speed and 150 rpm rotation speed for the rotor, and this introduces the possibility for a better output after further improvements.

Model 3 has shown a significant improvement and this can be further enhanced by studying how the ridges affect the generated power alongside the Magnus effect, the number of ridges can be manipulated to find the optimal number, also the size of each ridge, width, height, and volume, these all will help reach a better and more enhanced output. Furthermore, the ridges' aerodynamics can be more optimized as the current shape is only a vertical squared shape, and it is not the best for catching the wind flow around the rotor.

Model 2 design can also be improved upon by addressing the size and shape of the end and middle plates, furthermore, the expected result might have been hindered by the small thickness chosen for the plates, as the optimum thickness can be studied and used for better results as the plates were expected to increase the Magnus effect at multiple points of the rotor.

Model 1 design and its variations, can be ignored from any future modifications due to the interruption introduced by the fins cutting the airflow around the rotor body and only generating very low output on their own since the rotor is already rotating around its axis, however, for a more detailed output about the Model 1 behavior as a wind turbine only, we should remove the rotation from the model while running the simulation.

The data collected from the research amounted to a total of 5TB, of simulation results, thus making the main problem of the research the limited disk space, therefore, any future research should address this problem before starting with the simulation process to avoid any interruptions with the process, saving more precious time, and reaching a conclusion in a shorter amount of time.

The running times for 1 simulation were a minimum of 24 hours and a maximum of 38 hours depending on the complexity of the rotor design, and this can be managed by running multiple simulations at the same time which can result in cutting the simulation expected times in half.

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