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Wind Power Extraction from Wind Energy Wasted by Moving Vehicles

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Abstract—*With the rising demand of per capita energy consumption and the depletion of non-renewable energy sources, a demand for newer technologies for renewable energy generation is higher than ever. A new technology of harvesting wind energy from the wind energy wasted (pushed aside) by moving vehicles is analyzed here. Geometry of turbine is assumed, and the number of blades of the turbines is changed. The change in velocity, blade position, angular velocity, power generated and efficiency is analyzed for each of the wing number cases. The analysis is done in the commercial software ANSYS fluent student version 2022, with the help of k-ϵ model. The results are validated from data taken from the literature and theory. Two types of vehicle have been considered, essentially a truck and a car for better understanding of the turbine performance. Analysis has been limited to one vehicle passing the installed turbine at a time, which is an ideal case and not many vehicles together, which is a more realistic case. Future direction of this technology is also discussed at length in the end.*

1. INTRODUCTION

The concept of deriving useful electrical energy from wind energy wasted by a moving vehicle or a series of moving vehicles, with the help of Vertical or Horizontal Axis Wind Turbines, is fairly new. Although this technology has been implemented sparingly, it has proven to be very economical and efficient whenever used, especially on highways, where cars, buses, and trucks move at high speeds at regular intervals.

The concept of wind energy is not new to us. It was developed long back, approximately in 1888, and since then, it has come a long way, with more costly, sophisticated, and efficient devices being developed. One of the first devices ever built was the offshore wind turbine. It was easy to implement due to the abundance of wind in the coastal atmosphere [1]. After that, scientists and engineers shifted their focus to domestic appliances, investigating different building geometries numerically and experimentally to understand how they interacted with wind and where the turbines could be placed for efficient power generation [2].

Scientists then started thinking about capturing the wasted wind from fast-moving vehicles to power street devices like lamp posts. [3] and [4] conducted numerical investigations on wind energy captured by small turbines installed on the front of a train, where the high-velocity air is channeled through small air vents fitted on the front. Numerical and experimental studies were conducted on heavy-duty trucks and a matrix of many trucks to understand the flow profile made behind the vehicles, i.e., wake generation, the effect made by interactions due to multiple vehicles, and the power of wasted wind energy [5]. [6] conducted experimental and numerical simulations on wind energy generation by moving vehicles. A portable horizontal axis diffuser-augmented wind turbine was put near the roof of the car, where the airspeed is highest due to aerodynamic considerations. The main concept was to recharge the battery used in the car. [7] investigated three procedures for getting electricity from a moving train. Wind energy was captured by vertical axis wind turbines strategically placed in front of a moving train. When a train or car moves at high velocity, it pushes its air in front, creating a vacuum. This makes the air from the sides rush into the low-pressure region, giving a high velocity. The paper also discusses techniques of solar energy and bioenergy. [8] constructed a vertical axis wind turbine for generating electricity from the roadside due to wind and solar energy. This technology of wind energy harvesting has been commercialized by very few companies, such as Devecitech and Shell Global, due to a lack of comprehensive information and analysis. [9] provided us with a design scope of a Diffuser Augmented Wind Turbine (DAWT), functioning for the same purpose.

[10] use a mathematical model to calculate the power contained and velocity wasted by a moving vehicle. The paper uses a horizontal axis wind turbine placed in a random location around the moving vehicle. [11] used the results of the previous paper and simultaneously modified the power generated by incorporating vibration energy from the road. The concept of vibration energy from both roads and the body of the wind turbines by piezoelectric devices is left for future studies. Very few works have been done on this technology. Our paper will deal with a complete performance analysis of electrical energy generation by wind turbines.

This paper starts with a brief history of wind turbine development in India. This is followed by a comprehensive detail about the numerical method used. The numerical analysis will be conducted in the commercial software of ANSYS Fluent. The following section will consisting of results and discussions, with proper numerical accuracy measurement (grid independence test) and validation with the literature.

2. MODEL AND NUMERICAL SET-UP

2.1. Governing equations

The Navier-Stokes equations and the continuity equations form the basis of all fluid flow problems, and hence are solved. One of the most popular ways of simplifying the unsolvable non-linear equations of NS, is by time averaging the primitive variables and replacing them in the main equation. From this, we get the RANS equation.

In this RANS equation, a new set of terms are introduced, which makes the number of unknowns more than the number of equations. Hence, approximations have been made to solve these terms in the literature. A lot models have been developed like Spalart-Allmaras one equation model, k-ϵ two equation model, k-ω two equation model, k-ω SST three equation model, Reynolds Stress Transport five equation model, etc. [15] tells us the closeness of results of the k-ϵ and the k-ω models (k-ω model beigh a little bit superior), and Soe and Khaing, 2017 tells us the superiority of the k-ϵ model with specifically the Realizable version of the model. Hence the Realizable k-ϵ model have been used in this analysis. A comprehensive detail about the Realizable k-ϵ model is also provided by Soe and Khaing, 2017.

2.2. Geometry and Mesh

In this paper, a two-dimensional cross-sectional area of four Vertical Axis Wind Turbines (VAWT) in a rectangular domain has been considered. Each of these turbines has a different number of wing blades, namely 3, 4, 6, and 8. The wing blades used in all cases are of type NACA 0012 and have a chord length of 0.5 m, while the radius of the turbine is set at 0.5 m as well. The analysis domain is a rectangular region surrounding the wind blades, with a size of 4 m height and 9 m length. Figure 1(a) shows the flow domain that will be analyzed. Subsequently, Figures 1(c), (e), and (g) show the geometry for the 4, 6, and 8 winged body cases, respectively.

Figure 1(b) depicts the mesh considered for a 3 winged body, which will be made of quad elements of size 0.01 m × 0.01 m each. The total number of mesh elements is 189920, and the mesh region has been divided into two segments: a circular region right in the vicinity of the turbine blades (marked by green and with a diameter of 2m) and a rectangular region (excluding the circular region). To capture the rotating turbine blades due to the air pressure exerted, a sliding 6 DOF dynamic mesh has been used. The inner circular region has been treated as a fluid rigid body with passive 6 DOF since this region is only supposed to move with the turbine rotation. The outer region has been treated as a deforming body with active 6 DOF mesh. In the 6 DOF setting, only one rotating DOF has been chosen. The turbine mass and moment of inertia about the Z-axis (rotating axis) have been set to 5 kg and 2.14 kg/m^2, respectively. No spring load effect has been provided to the 6 DOF motion. Figures 1(d), (f), and (h) show us the mesh for the 4, 6, and 8 winged turbine cases, respectively.

2.3. Boundary Conditions

The analysis has been done in transient mode with the acceleration due to gravity value taken as -9.81 m/s^2 (negative y axis). The turbulent model has been taken as the k-ϵ turbulent model. The medium has been chosen as air, and dynamic mesh has been chosen for all the air zones. The far left vertical surface has been chosen as a velocity inlet. For moving truck case, 15 m/s inlet velocity has been provided, while for the moving car case, 9 m/s inlet velocity has been chosen for all the four wind turbine cases. All the vehicle properties and extra wind turbine properties have been mentioned in Table 1. The derivation of the inlet velocity form the car and truck velocity has been taken from Kumar et al. (2016). The far right vertical surface has been chosen as a pressure outlet with the value of standard atmospheric pressure.

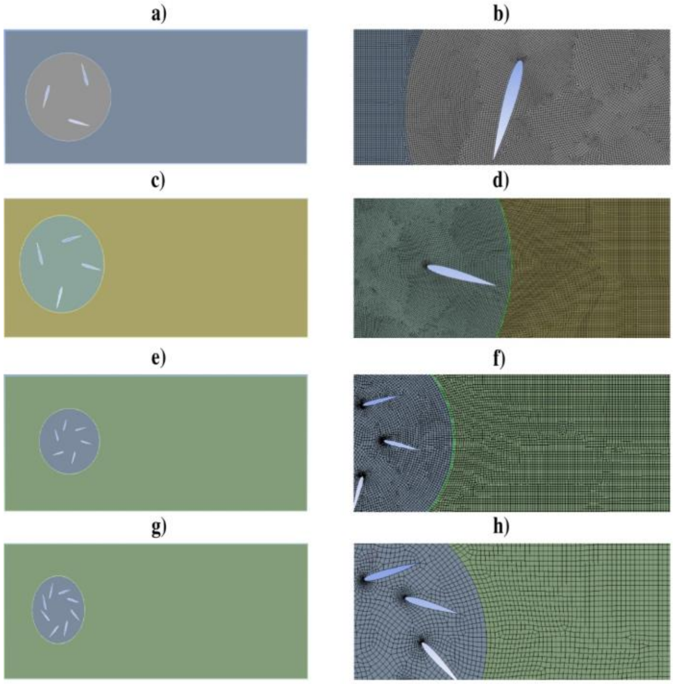

Figure 1: Total geometry consideration of a) 3-winged c) 4-winged e) 5-winged g) 6-winged and enlarged mesh considered for b) 3-winged d) 4-winged f) 5-winged h) 6-winged

Table 1: Vehicle and turbine parameters

Vehicle	K	Mass	ρ_{wind}	dρ
Car	0.01	1500 kg	1.3kg/m^3	0.01kg/m^3
Truck	0.01	4000 kg	1.3kg/m^3	0.01kg/m^3

Vehicle	$R_{turbine}$	$H_{turbine}$	Velocity
Car	0.5 m	2 m	25 m/s
Truck	0.5 m	2 m	35 m/s

The upper and lower horizontal surface has been provided with the symmetric boundary condition. The turbine has been treated as perfectly smooth walls.

The pressure velocity coupling has been done by SIMPLE algorithm, and the pressure, mommentum, turbulent kinetic energy and turbulent dissipation rate spatial discretization have been set to Second Order Upwind Scheme. For gradient spatial discretization, Least Square Cell method has been used. Second Order Implicit Transient formulation has been chosen for our analysis. Convergence criterion of 0.00001 has been chosen for higher accuracy. Each calculations have been run for 2000 time steps of 0.01s time step size and each step having 10 iterations each. Iterations have been saved after every 100 time steps or 1s, for animating the entire process.

3. RESULTS AND DISCUSSIONS

3.1. Angular Velocity

The angular velocity distributions created by 3 and 4 winged turbine have been shown. Figure 2 shows the angular velocity ω attained by the three winged wing turbine powered by a truck. From the figure, it is quite evident the angular velocity till 12 seconds is quite high, but as we move towards 20 s, the angular velocity decreases. Hence this proves that the angular velocity is higher at the beginning, and more fluctuating but as we go further into the time steps, the angular velocity stabilizes and decreases considerably (Conclusion 1). Owing to the inertia of the rotating turbine, this decrease in angular momentum will not serve as a major issue, till the next vehicle passes by after a few seconds.

From Figure 2, it is possible to calculate the maximum angular velocity (approx. 15.15 rad/s) and the average angular velocity (approx. 4.5 rad/s). The maximum angular velocity has been used for our further analysis.

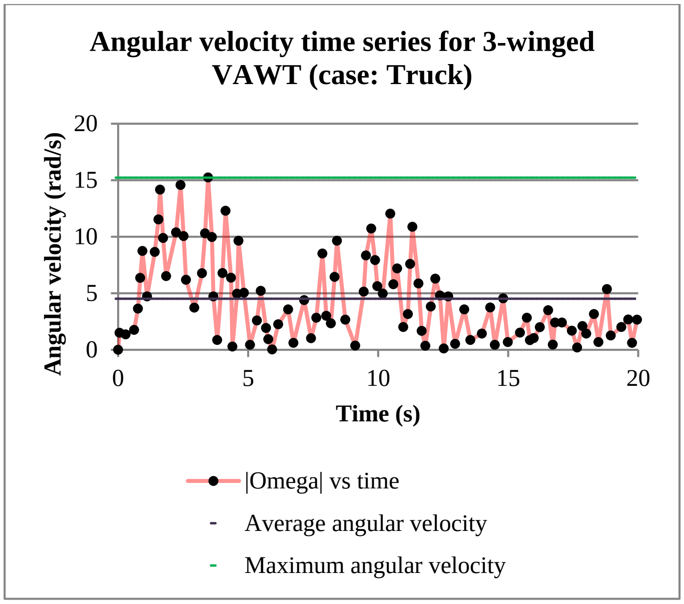

Figure 2: ω vs. t for 3 winged turbine powered by a truck.

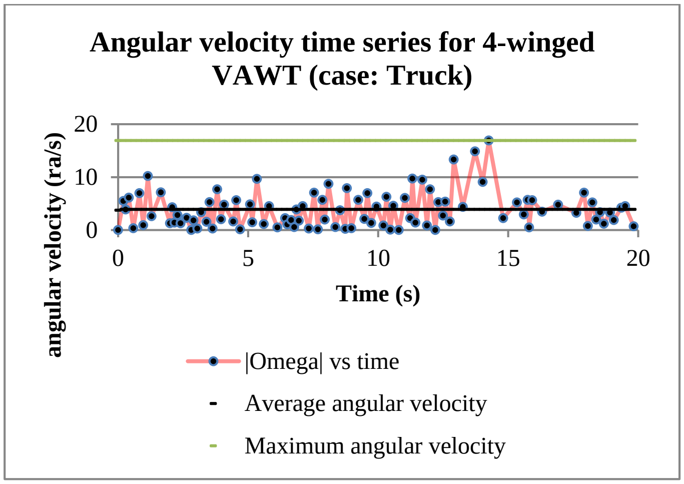

Figure 3: ω vs. t for 4 winged turbine powered by a truck.

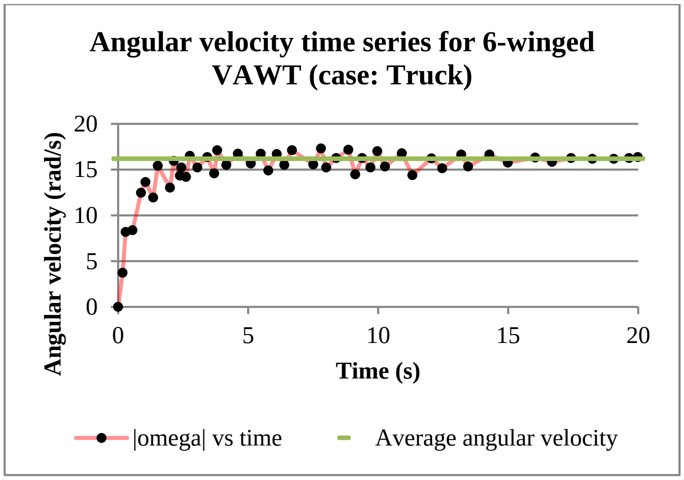

Figure 4: ω vs. t for 6 winged turbine powered by a truck.

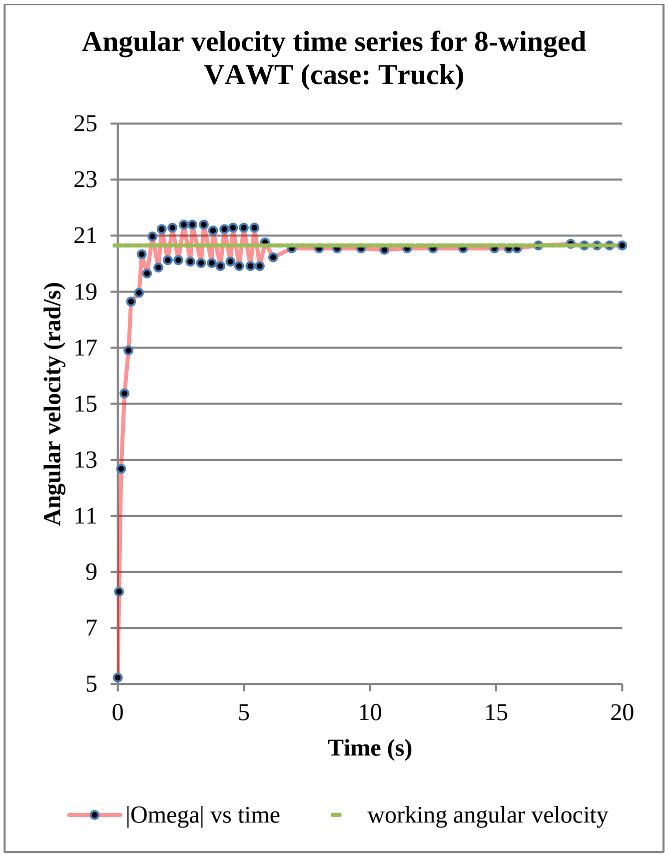

Figure 5: ω vs. t for 8 winged turbine powered by a truck.

Conclusion 1 is also valid for a moving car powering a 3 winged turbine (not shown here). The maximum angular velocity is approximately 3.15 rad/s. This value is very small by itself. As the end is approached, the range of fluctuation becomes limited to only 0.5 rad/s, which is very small. Hence very small dispalcement is seen in the turbine blades. The average angular velocity has been calculated as approx. 0.65 m/s. Hence, the maximum absolute angular velocity has been taken for our further investigations.

Figure 3 shows the absloute angular velocity time series for a 4 winged VAWT when powered by a moving a truck respectively. The average absolute angular velocity has been calculated as 3.5 rad/s and the maximum angular velocity has been calculated to 16.9 rad/s. The average absolute angular velocity has been calculated to 1.8 rad/s and the maximum angular velocity has been calculated to 6.5 rad/s for the case, when the turbine is powered by a car (not shown).

Now, the angular velocity fluctuations for a turbine of 6 and 8 wings have been shown. Figure 3 shows the absolute angular velocity of a 6 winged turbine when triggered by wasted wind of a moving truck.

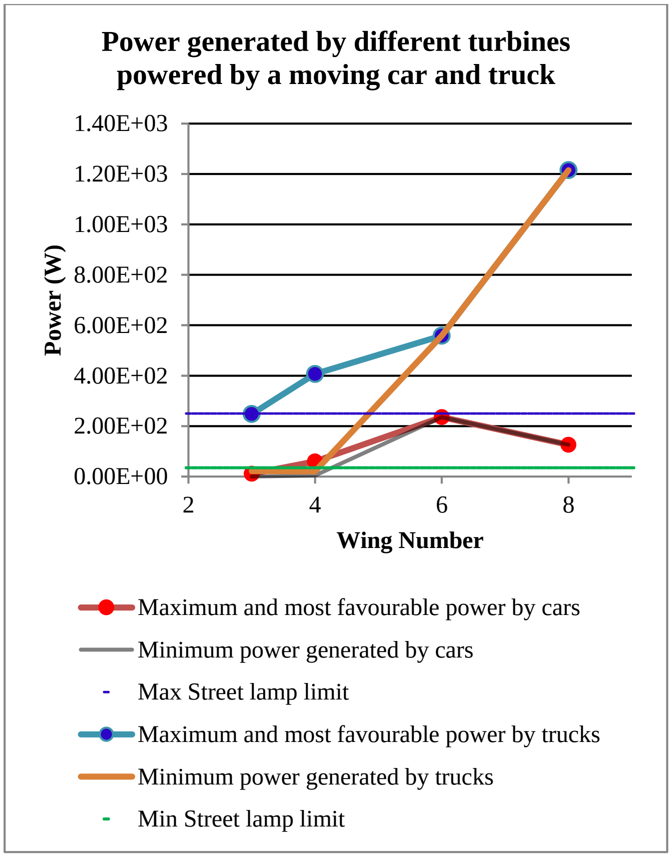

Figure 6: Power generated and its range for turbines powered by a moving car and truck

3.2. Power Generated and Efficiency

After the angular velocity generated has been calculated, the values have been used to obtain the power generated in case by the formula of $P = \frac{1}{2} I\omega^2$. The mass of each wing is taken as 1.67 kg and the moment of inertia (I) is taken as 2.14 kg.m^2, 2.85 kg.m^2, 4.27 kg.m^2 and 5.70 kg.m^2 for the 3, 4, 6 and 8 winged turbines respectively.

For the calculation of power produced by the 3 winged and the 4 winged turbines, the maximum angular velocity generated has been considered. Figure 6 shows the power generated by each of the 4 turbines when powered by a moving truck and a car respectively.

In figure 6, the red and blue line represents the maximum or the most favorable power generated while the grey and orange line represents the minimum amount of power generated for all the four turbines powered by a truck and car respectively. The in between region is where the power generation will lie for all the cases.

The normal street lights are of a power consumption range 35 W to 250 W as shown in Figures 6. When the turbines are powered by trucks, it can be seen the power generated for all the cases lay above 250 W except for the 3 winged cases (almost 250W). Hence, all the turbines will give a satisfactory power generation when powered by a truck and can be used for all commercial street lamps. The three winged turbine powered by a car falls below limit and hence is unusable. All the others fall within the 250 W limit, and hence can be used where the street-lamp power rating is lower than power generated. Hence, unlike when powered by a truck we cannot use a car wind source for all commercially available street lamps.

The efficiency of the wind turbine has been calculated not considering the efficiency of the electrical generator. The length of turbine blades has been considered as 1 m. Hence area swept for all the turbines will be 1 m^2 (rectangular area swept, not circular unlike HAWT). Hence the incoming wind energy is $P_{in} = \frac{1}{2}\rho A v^3$; where v is the wind velocity. v is 15 m/s and ρ is 1.25 kg/m^3. Figure 7 shows the efficiency comparison for all the eight cases (4 turbine powered by truck and car each). For an 8 winged turbine powered by a truck case, the efficiency reaches as high as 70 %. For the 6 winged turbine powered by a truck, it is close to 30 % and it is less than 20 % for all the other 6 cases.

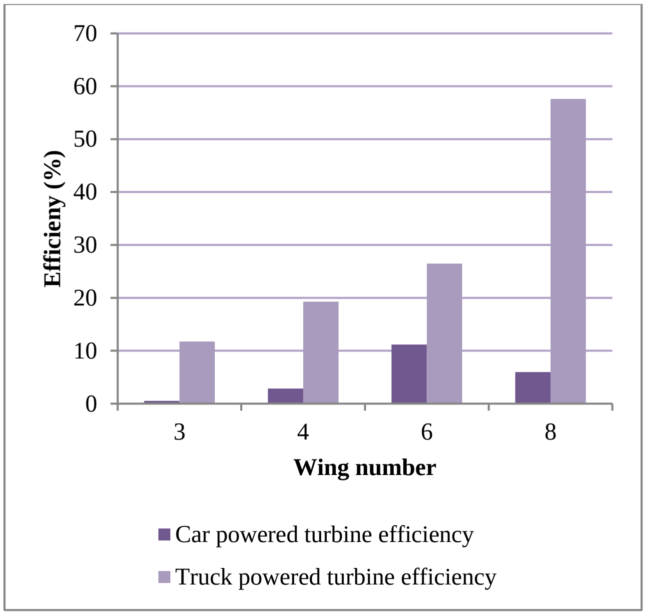

Figure 7: Efficiency comparison

4. CONCLUSION

As it can be seen in figure 7, even though the efficiencies are not at a satisfactory level, it still serves the purpose. Since, we can see from figures 6; most of the cases are able to light a street lamp. Now the question is which one is the most optimal for usage. The three and four winged turbines gave us poor performance for both truck and car triggered cases, as we can see from the power generation cases. Also, the angular velocity tries to change its direction of rotation (negative angular velocity) which hinders the free rotation of the wind turbine. Hence, the three winged and the four winged turbine are currently out of consideration. The six and eighth winged turbines perform comparatively lot better than the former two. The eighth winged turbine gives us a more suitable result. Its efficiency is high and the power generation is also the most as compared to the six winged turbine. There is one more important factor to consider. With respect to the power generation by the eighth winged turbine when powered by a moving truck, the power generation by a moving car is much lower. It is not consistent and convenient for usage for both trucks and cars.

While, for six winged turbine, its performance when powered by truck and when powered by a car is equally high. For the car powered cases it is the highest amongst all. Also, an eight winged turbine is bulky and also expensive to be installed on every street lamp as compared to a six winged turbine. Hence, a six winged turbine is optimum for road side applications.

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