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Optimized vertical axis wind turbine for harnessing highway wind energy

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Abstract

Amidst the global energy crisis and the push for net-zero emissions, renewable energy sources like wind power are gaining prominence. This project aims to design an optimized vertical axis wind turbine (VAWT) to harness untapped wind energy generated by moving vehicles on highways. Wind energy is among the fastest-growing renewable sources, and highways present a viable opportunity due to consistent vehicle movement, traffic density, and high-speed airflow. A VAWT is selected over horizontal axis turbines due to its omnidirectional wind capture capability, eliminating the need for alignment with wind direction. This allows strategic placement on road medians to capture airflow from both lanes. Computational fluid dynamics (CFD) simulations are employed to analyze wind distribution patterns and average velocities induced by passing vehicles, ensuring optimal turbine positioning and design. Blade profile optimization is conducted using simulation tools to enhance aerodynamic efficiency, maximizing energy extraction. Additional considerations include mechanical and electrical efficiency, structural durability, and mitigation of environmental impacts such as noise and wildlife disruption. Through systematic design refinement, this project seeks to develop an efficient, sustainable solution for converting highway wind energy into electricity, contributing to renewable energy advancements.

Keywords: Vertical axis wind turbine (VAWT), horizontal axis wind turbine (HAWT), wind energy, highways

Introduction

The 21st century renewable energy goals comprises of global transition sustainable energy hub, with renewable sources such as wind, hydro, and solar power playing a vital role, hoping to decarbonizes the energy sector and mitigate climate change [1]. Many developed countries are trying to harness the available renewable energy in order to produce a green energy to mitigate climate change like Saudi Arabia that aimed at reducing the country’s reliance on oil by diversifying its economy across various sectors to produce half of the country’s electricity from renewable energy sources by 2030 [2]. Realizing this goal necessitates innovative solutions in energy generation, particularly from underutilized resources such as wind energy generated along highways by moving vehicles.

Wind energy is one of the fastest-growing renewable energy sectors globally [3]. The energy crisis caused by declining fossil fuel reserves and climate change has accelerated interest in sustainable solutions such as wind energy [4]. Wind turbines, particularly Vertical Axis Wind Turbines (VAWTs), provide a solution for urban and semi-urban areas due to their lower environmental impact and adaptability to unsteady wind patterns [5].

VAWTs are more suitable for urban and highway environments compared to Horizontal Axis Wind Turbines (HAWTs) [6]. They have a low cut-in wind speed, can operate with wind from any direction, and are relatively easier to integrate with existing infrastructure [7]. The Darrieus-type (VAWT), which operates based on lift force, is favored for its high-power coefficient and ability to extract more energy from the wind per unit swept area [8]. Its design can accommodate fluctuating winds, making it ideal for the conditions created by moving vehicles on highways.

Harnessing the wind energy created by the movement of vehicles on highways presents a viable opportunity to contribute to the renewable energy mix. VAWTs offer a promising approach to capture this wind energy and convert it into electricity for various applications, such as powering streetlights or supplying energy to the national grid.

Objective of the Research

The primary objective of this project is to design a VAWT capable of harnessing wind energy produce by moving vehicles along the highways. The specific objectives include:

- Determining the optimal airfoil shape for the VAWT under the specified operating conditions.
- Designing and constructing a prototype to be tested in a wind tunnel, comparing experimental data with theoretical predictions.

Methodology

The project employed a combination of theoretical modeling, wind tunnel testing, and data collection from highways. The methodological process comprises of the following:

Simulation

JavaFoil software was used to simulate the turbine’s aerodynamic behavior, generating data on lift and drag coefficients for design optimization. MATLAB was employed to model the turbine’s performance under varying wind conditions.

Prototype Testing

A prototype was constructed and tested in a wind tunnel to compare empirical data with theoretical predictions. Key parameters, including power output and efficiency, will be measured.

Data Collection

The goal of this project was to design a VAWT which can be used to harness impact wind energy on highways. The magnitude of this impact wind depends on the speed of vehicle, size and intensity of traffic. Therefore, it is imperative that data on these factors are obtained.

Since it is beyond the scope of this project to conduct a data survey on highways in order to obtain information on the average wind speed and distribution pattern, efforts have been made to obtain such information from available data if any.

The National Metrological Department was consulted for such information but only data on environmental wind speeds were available. The lack of such data prompted for an investigation into the nature of impact wind distribution on highways.

The scope of this project left us with no choice but resort to search for such experimental data. The HMS Institute of Technology, Tumkur, India, led a research on determining the average wind velocity on highways resulting from the impact of running vehicles. The result of the experiment was used as basis for the design in this project.

Design Calculations

The design calculations were done using Microsoft Excel Spread Sheet to obtain the Tip Speed Ratio (TSR) and which was also used calculate the range of angle of attacks and Reynolds. The design calculation was segmented into three parts;

Power calculation

The cells of the spread sheet were embedded with power density formula, TSR, Reynolds and Angle of attack range.

Inputs parameters					
Rotor Diameter	1.5	m	59.06	in	*Chosen for various
Blade Length	1.25	m	49.21	in	Reasons
Wind Velocity	10	m/s	22.4	mph	*Typical rating wind speed
Cp	0.59		59.0	%	*Estimated Coefficient of performance
					(Max 59.3%), 0.59 is a guess.
Air Density **r**	1.22	kg/m^3			
Outputs Parameters					
Turbine area:		1.88	m^2		
Power available in wind:		1143.8	Watts		
Power produced by turbine:		674.8	Watts	*Power from turbine, not power delivered to load.	

Tip Speed Ratio Calculation

The TSR was calculated based on acceptable acceleration relative to the gravity of the turbine during rotation. This helps in determining the maximum rotational speed for safer operations.

Input parameters						
Rotor Diameter	1.5	m	59.06	in		
Limits (RPM at given air velocity)						
Wind Velocity	16	m/s	35.8	mph	*Max wind before cutoff	
Rotation Limit	500	RPM	52.35	rad/s	*Max desirable RPM	
Output Parameters:						
TSR	2.45		*Max desirable TSR			
Acceleration	2056.70	m/s^2				
G's	210	G's kg-m/s^2				
	G's	Accel	Speed	Speed	TSR	
	kg-m/s^2	m/s^2	rad/s	RPM		
100%	210	2057	52.35	500	2.45	
90%	189	1851	47.12	450	2.21	
80%	168	1645	41.88	400	1.96	
70%	147	1440	36.65	350	1.72	
60%	126	1234	31.41	300	1.47	
50%	105	1028	26.18	250	1.23	

Aerodynamic Force Coefficients (Lift and Drag)

α [°]	**Cl [-]**	**Cd [-]**			**Cl / Cd [-]**
12.5	1.4	0.03756			37.27
9.5	1.14	0.02513			45.36
6.5	0.824	0.01767	Optimal Characteristics		46.63
3.5	0.447	0.01566			28.54
0.5	0.064	0.016			4.00
-2.5	-0.317	0.01659			-19.11
-5.5	-0.693	0.01848			-37.50
-8.5	-1.036	0.02278			-45.48
-11.5	-1.324	0.03201			-41.36

Range of Angle of Attack & Reynolds

Inputs parameter:						
Diameter	1.5	m	59.06	in		
Chord	0.2	m	7.87	in		
No. of Blades	3					
TSR	2.5		*Selected based on acceptable acceleration 100%			
Interference factor	0.67		*Upwind interference factor (Betz flow a = 0.67)			
Wind Velocity Max	16.00	m/s	*Cut out speed for maximum Re			
Wind Velocity Min	3.00	m/s	*Cut in speed for minimum Re			
Kinematic Viscosity.	1.617E-05	m^2/s	*Kinematic viscosity of air at 32.33°C			
Outputs Parameter:						
Solidity	0.80		80	%		
Induction down	60.00		*Downwind induction factor approx. 10% less			
Initial estimates for initial airfoil selection& Analysis						
Max upwind angle of attack:			12.5	deg	Max Re:	485776
Max downwind angle of attack:			-12.5	deg	Min Re:	91083
					Avg Re:	288430

The result obtained from the above calculations was then used for performance analysis of the airfoil.

Performance Analysis

Each blade generates lift and drag (Cl and Cd) relative to the incoming flow. For the purpose of performance analysis, it is convenient to transform Cl and Cd into cylindrical form with Cn and Ct as the sectional force coefficients normal and tangential to the direction of rotation or CN and CT for the entire blade. Ca and CA represent the sectional and overall axial force coefficients. The power coefficient Cp generated by the VAWT is calculated By;

Blade Element Momentum (BEM) Model

Under normal operating conditions will encounter several different flow phenomena. Conceptually, the blade element momentum method combines conservation of momentum on an actuator disk (following Glauert's theory) with an integration of the aerodynamic forces over all blade elements. The inflow conditions for each blade element are determined using the kinematical equations that define the turbine motion combined with the induction velocity the aerodynamic forces are found from look-up tables for a given section, angle of attack, and Reynolds number. BEM models achieve closure by equating thrust of the rotor calculated from momentum and blade element equations [9].

One of the first attempts at modeling the aerodynamic performance of a VAWT was a single stream tube model implemented by Templin for the National Research Council of Canada. The model consists of a single actuator disk where the induced velocity is assumed to be constant over the entire disk. In comparison with experimental data the Templin model can accurately predict the maximum power coefficient (Cp) but is not adequate in describing how it varies with tip speed ratio [9].

Later on, at Sandia National Laboratories, the BEM model was developed into Double Multiple Stream Tube (DMST) model as an improvement on Templin's work. The main difference between these two models is that in DMST model, the swept area is segmented into several independent stream tubes each with its own induction velocity and all of which are integrated to allow for a more precise prediction of induction, a key factor in relation the swept Area.

The DMST model was adopted for this performance analysis using the Matlab codes.

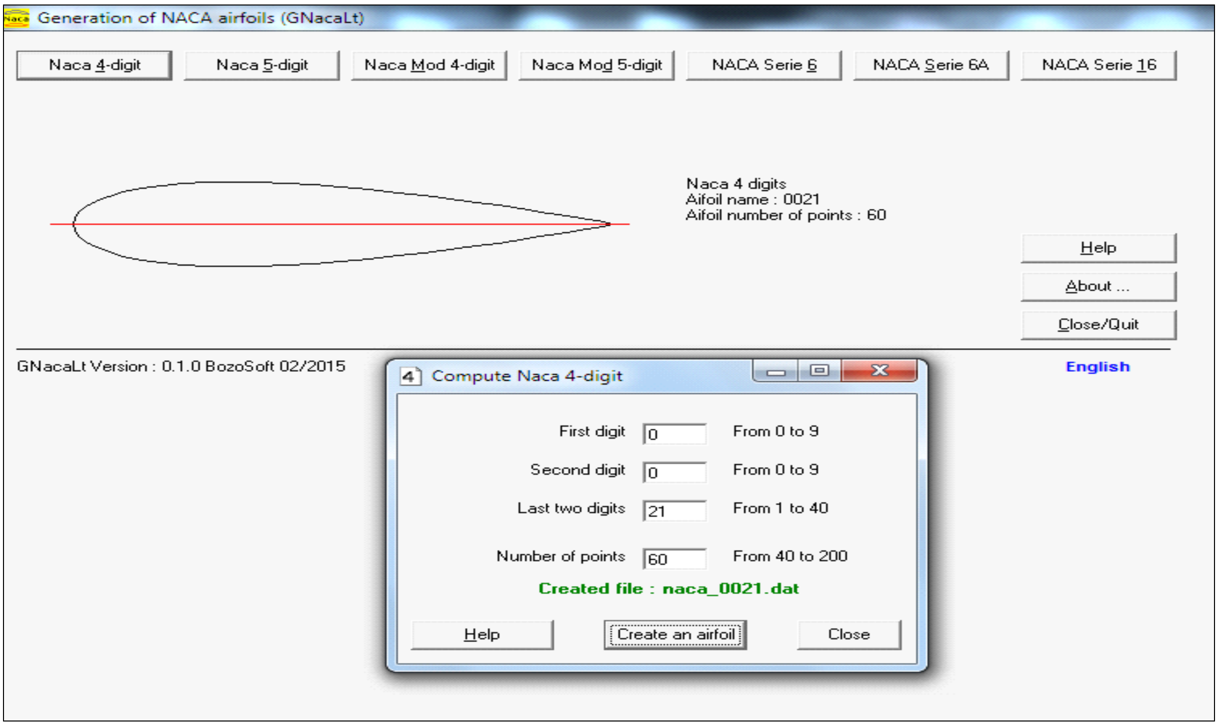
But before then, the aerodynamic force coefficients need to be obtained from an experimental data of some sort of computational analysis tool. For this purpose, a panel method was used.

Panel Method

Panel methods may be thought of as an extension to vortex methods in that they treat the wake in same way, but do not require a look-up table for sectional Cl and Cd data, but rather model the geometry directly using the Laplace equation for inviscid/incompressible flow or the Prandtl-Glauert equation for inviscid flows with compressibility effects ($M < 0.6$) [9].

Generating Naca Light

A Naca airfoil coordinates generating software based on the original program to generate NACA airfoil coordinates version 4.5 in Basic/DOS written by David Lednicer, was used to generate the current airfoil, a symmetric NACA 0021airfoil. The coordinates of which were exported to the JavaFoil, an airfoil analysis tool is shown in Figure 1.



Naca 4 digits
Aifoil name : 0021
Aifoil number of points : 60

GNacaLt Version : 0.1.0 BozoSoft 02/2015

First digit 0 From 0 to 9
Second digit 0 From 0 to 9
Last two digits 21 From 1 to 40
Number of points 60 From 40 to 200
Created file : naca_0021.dat

Fig 1: NACA Airfoil Coordinates Tool

JavaFoil Analysis Tool

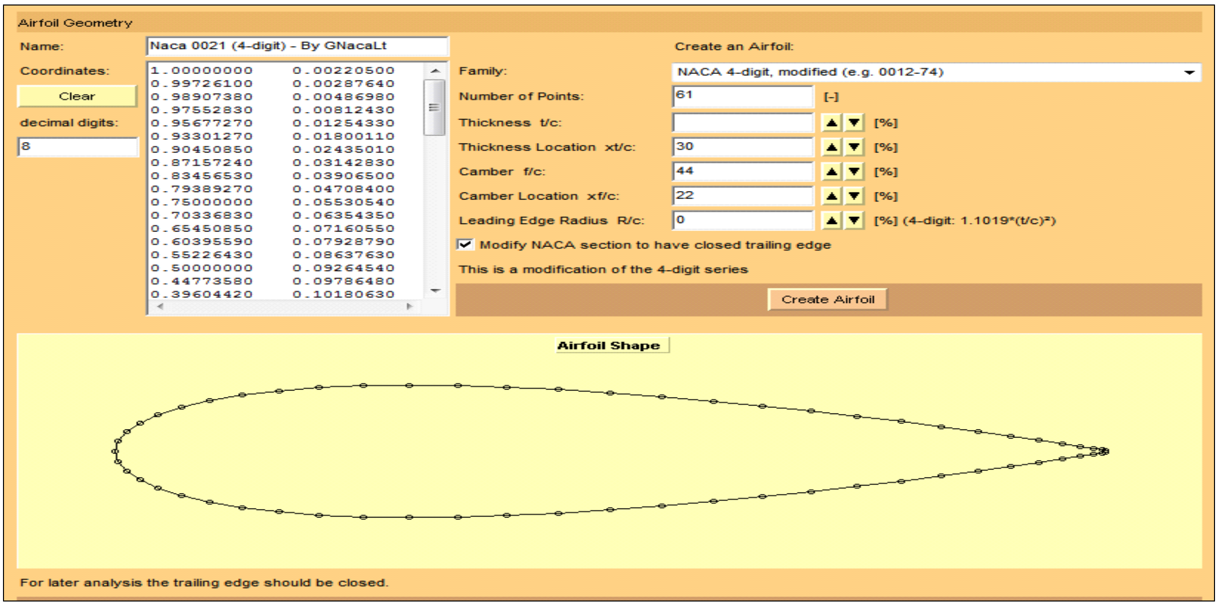
JAVAFOIL is a relatively simple program, which uses several traditional methods for the analysis of airfoils in subsonic flow.

The main purpose of JAVAFOIL is to determine the lift, drag and moment characteristics of airfoils. The program will first calculate the distribution of the velocity on the surface of the airfoil. For this purpose, it uses a potential flow analysis module which is based on a higher order panel method (linear varying velocity distribution). This local velocity and the local pressure are related by the Bernoulli equation. In order to find the lift and the pitching moment coefficient the distribution of the pressure can be integrated along the surface.

Next JAVAFOIL will calculate the behavior of the flow layer close to the airfoil surface (the boundary layer). The boundary layer analysis module (a so-called integral method) steps along the upper and the lower surfaces of the airfoil, starting at the stagnation point. It solves a set of differential equations to find the various boundary layer parameters. The boundary layer data is then be used to calculate the drag of the airfoil from its properties at the trailing edge.

Both analysis steps are repeated for each angle of attack, which yields a complete polar of the airfoil for one fixed Reynolds number.

JAVAFOIL implements a classical panel method to determine the linear potential flow field around single and multi-element airfoils. In JAVAFOIL the airfoil surfaces carry a linearly varying velocity distribution. This is the same type of distribution as used in XFOIL but simpler than the higher order (parabolic) distribution used in Eppler’s PROFIL code.



Name: Naca 0021 (4-digit) - By GNacaLt

Coordinates:

1.00000000	0.00220500
0.99726100	0.00287640
0.98907380	0.00486980
0.97552830	0.00812430
0.95677270	0.01254330
0.93301270	0.01800110
0.90450850	0.02435010
0.87157240	0.03142830
0.83456530	0.03906500
0.79389270	0.04708400
0.75000000	0.05530540
0.70336830	0.06354350
0.65450850	0.07160550
0.60395590	0.07928790
0.55226430	0.08637630
0.50000000	0.09264540
0.44773580	0.09786480
0.39604420	0.10180630

decimal digits: 8

Family: NACA 4-digit, modified (e.g. 0012-74)
Number of Points: 61 [-]
Thickness t/c: [%]
Thickness Location xt/c: 30 [%]
Camber f/c: 44 [%]
Camber Location xf/c: 22 [%]
Leading Edge Radius R/c: 0 [%] (4-digit: 1.1019*(t/c)²)
☑ Modify NACA section to have closed trailing edge
This is a modification of the 4-digit series

For later analysis the trailing edge should be closed.

Fig 2: JavaFoil Geometry Card

From the From the GNacaLt airfoil generating tool, the coordinates were imported into the geometry generation card of the JavaFoil applet (See Figure 2). The polar card (See Figure 3) enables entry of the range of Reynolds and the angle of Attack in order to generate the lift and drag coefficients Cl and Cd.


Airfoil Polars

first Reynolds Number: 544069 [-]

last Reynolds Number: 116586 [-]

Reynolds number step: 30000 [-]

Surface Finish: smooth finish

T.U.: 100 [%]

T.L.: 100 [%]

first Angle of Attack: 12.5 [°]

last Angle of Attack: -12.5 [°]

Angle of Attack step: 3 [°]

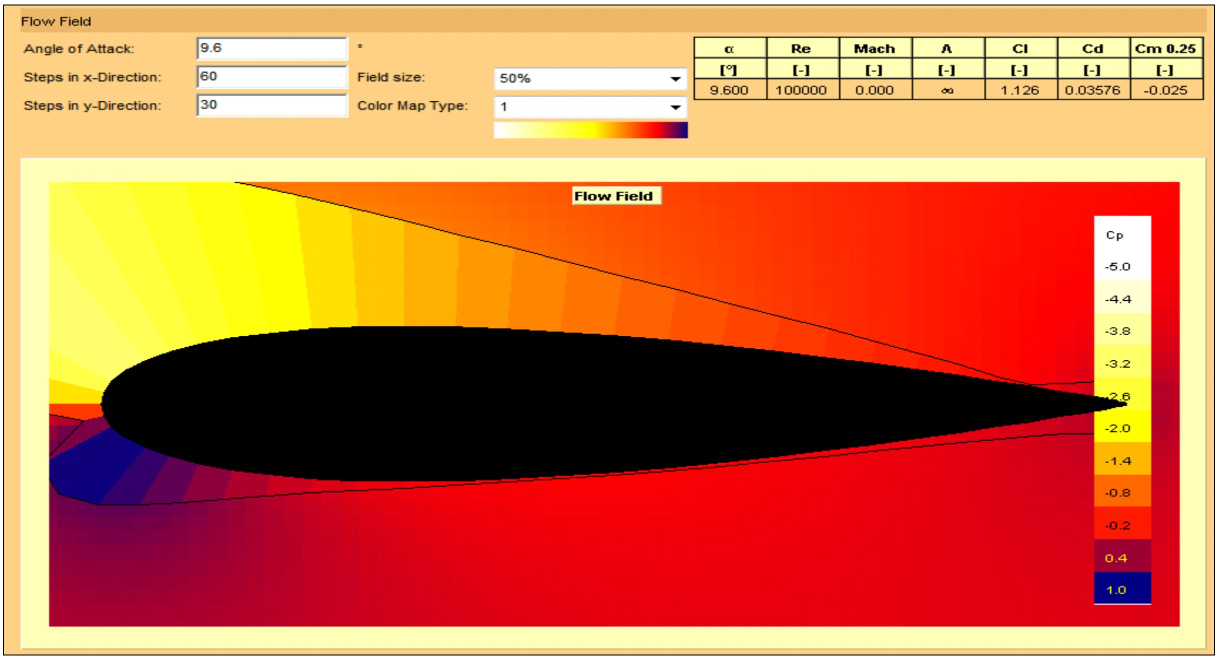
Stall model: Calcfoil

Transition model: Eppler standard

Fig 3: JavaFoil Polar Card

Analysis of this range of Cl & Cd along the ranges of Reynolds and Angles of Attack, facilitates the performance analysis in the Model by use of the optimum Cl/Cd at specified Angles of Attack.

The flow field card (See Figure 4) enables flow analysis at a specific angle of attack and a color map shows a visual indication of pressure gradient along the surface of the airfoil.


Flow Field

Angle of Attack: 9.6 °

Steps in x-Direction: 60

Steps in y-Direction: 30

Field size: 50%

Color Map Type: 1

α	Re	Mach	A	Cl	Cd	Cm 0.25
[°]	[-]	[-]	[-]	[-]	[-]	[-]
9.600	100000	0.000	∞	1.126	0.03576	-0.025

Fig 4: JavaFoil Flow Field Card

Prototype Design

Based on the design parameters and calculations, a prototype was designed using Solid Works software (See Figure 5) and the blades were printed using Poly Lactic Acid Plastic in a 3D printer (See Figure 6). The pole structure and the bearing housing with the couplings were fabricated and assembled in the workshop

Fig 5: Model Design in Solid Works

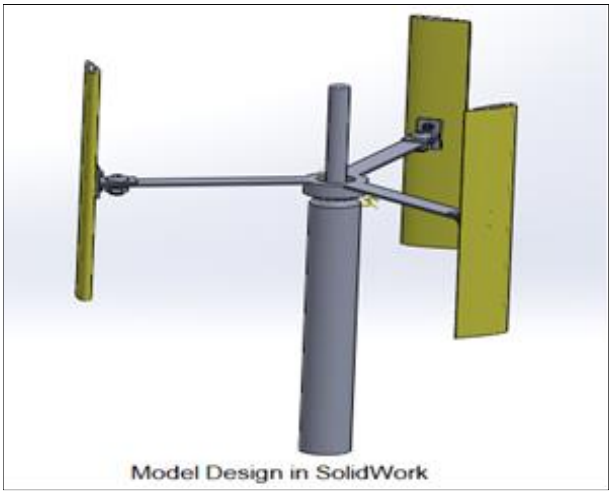


Fig 6: Fabricated Model Assembly

Conclusion

This project aims to harness the untapped potential of wind energy generated by moving vehicles along highways, contributing to the 21st century renewable energy goals. By leveraging VAWT technology, this project aligns with broader renewable energy targets and offers a practical, innovative solution for sustainable energy generation.

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