Analysis of Down-Wind Propeller Vehicle

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Abstract – In the last decade many researches have been carried out on wind driven vehicle; a large number of academic publications have been presented. There have been many "Down Wind Faster Than The Wind (DWFTTW)" arguments based on energy flow. Wind driven vehicle systems travel faster than the wind along its direction. This paper deals with energy conversion mechanism of a vehicle driven by wind. The Downwind vehicle is designed with a propeller that pushes it along like an aircraft's propeller does. The propeller is connected to the wheels of the vehicle through a chain/belt drive, so that when the vehicle moves forward, the propeller spins in such a way to provide a thrust that will speed up the vehicle if there is energy available from a tailwind, which explains the energy conversion mechanism. Specifically, focus is on the horizontal axis propeller of a downwind vehicle to make it have a relative motion with the wind at a speed greater than the speed of the wind. The simulations of the analysis are carried out in JavaProp software.

Index Terms – Aerofoil, DWFTTW, Momentum, Propeller, Thrust Force

I. INTRODUCTION

The energy crisis, environmental concerns and scarcity of conventional fuel have increased interest in green engineering. Using wind-power to produce energy in order to propel a vehicle is one such application of green engineering.

If a uniform wind is available over a level surface, is it possible to construct a man-carrying vehicle which by use of wind energy alone can accelerate in the wind direction from zero speed up to a speed larger than the wind speed? The work described in the paper has been carried out for the purpose of answering this problem.

The first downwind vehicle was created by Andrew Bauer [1] in 1969 which went downwind at a speed of 1.2 times the wind speed. In 1978, B. L. Blackford [2] applied the basic laws of mass, energy and momentum conservation to this novel wind-craft. Later in 2002, a wind test apparatus was introduced by Frank Bailey [3] which offered a means of testing a model of the downwind vehicle. The apparatus basically consisted of a wind tunnel erected over a towing tank so that velocity could be measured along the course of the model.

In 2003, a suggestion was made by Theo Schmidt [4] to use either an ogival or an un–cambered profile propeller in combination with a swiveling drive so that the thrust produced by it pushes the vehicle forward. In addition to it, Victor Korepanov [5] in 2004 explained the analysis behind achieving a speed of four times the wind speed. Also there has been an unofficial claim of going 4.2 times faster downwind, but there has been no authentic tests run of it.

John C. Wilson [6] in 2005 demonstrated that the appropriate principle to get forward thrust in a downwind vehicle is that the propulsion mechanism must be moving at a speed less than the wind speed. The same year, in July, Peter A. Sharp [7] proposed a simplified demonstration model of a Bauer air propeller vehicle that was relatively easy to construct.

In 2006, Jack Goodman [8] explained that the correct gearing of the propeller to the wheels of the car will speed up the car if energy is available from a tailwind. Again John C. Wilson [9] in 2007 conducted a study of the gear-ratio between the speed of the propeller and the speed of the wheels for a Bauer vehicle.

In 2009, Mark Drela [10], [11] formulated the Velocity as well as the Power analysis for the downwind vehicle. Later, the same year, a simple optimization method for both the wind turbine and propeller rotor, based on the Blade Element Momentum Theory was presented by Mac Gaunaa, Stig Øye and Robert Mikkelsen [12].

A comparison of the various aerofoil profiles was made by Shethal Thomas Kodiyattu [13] in 2010 while designing the propeller of a downwind vehicle. The latest explanation was given by S. Morris [14] in the same year, in June, which compared the propeller of a downwind vehicle to that of an aircraft.

The most successful and the latest wind-driven vehicle was the Blackbird [15] built by thin Air Designs Team in July 2010 which travelled downwind upto 2.8 times the wind speed, according to the NALSA speed regulations [16].

Nomenclature

V	Vehicle Speed
W	Wind Speed
F_t	Drag Force on Vehicle
F_p	Thrust Force on air Propeller
F_{net}	Net Thrust of the Vehicle
C_t	Coefficient of Thrust
C_p	Coefficient of Power
C_r	Coefficient of Rolling Resistance
P_t	shaft Power of Vehicle wheels
P_p	shaft Power of air Propeller
P_{net}	Net Power developed
A_d	Air Drag Area
A_p	Area of air Propeller disk
N	rpm of Propeller
D	Diameter of Propeller
D_{sp}	Diameter of Spinner or hub
ρ	Density of Air
η_g	Gearing/transmission Efficiency
η_p	Total Efficiency of air Propeller
η_{swirl}	Swirl Efficiency of air Propeller
ΔV	Change in Velocity of Vehicle
ΔW	Change in Velocity of air Propeller

II. RESEARCH AND ANALYSIS

A. Force and Power Analysis

Considering the forces acting on the vehicle as shown in the Figure 1,

$$F_{net} = F_p - F_t$$

Since we know that $P_p = P_t\, \eta_g$ or

$$F_p \frac{V-W}{\eta_p} = F_t\, V\, \eta_g$$

Therefore $F_{net} = F_t \,.\, \left(\frac{V}{V-W} \,.\, \eta_g \,.\, \eta_p - 1\right)$

which is positive only as long as

$\frac{V}{V-W} \,.\, \eta_g \,.\, \eta_p > 1$ (requirement of DWFTTW)

Applying energy conversion principle, the net power developed by the vehicle could be written as the sum of power produced by propeller thrust and power lost by drag force on the vehicle and kinetic energy deposited in vehicle and air,

$$P_{net} = P_t - P_p$$

$$= F_p W - F_{net} V - \frac{F_t \Delta V}{2} - \frac{F_p \Delta V}{2}$$

In steady-state operation, P_{net} must be sufficiently positive to balance the remaining power losses in the system. A positive P_{net} indicates that the power delivered by wind energy could be used to accelerate the vehicle beyond the wind speed. The other losses not accounted for were power-transmission losses, profile-drag losses on the propeller and turbine blades, and swirl losses in the propeller and turbine slipstreams.

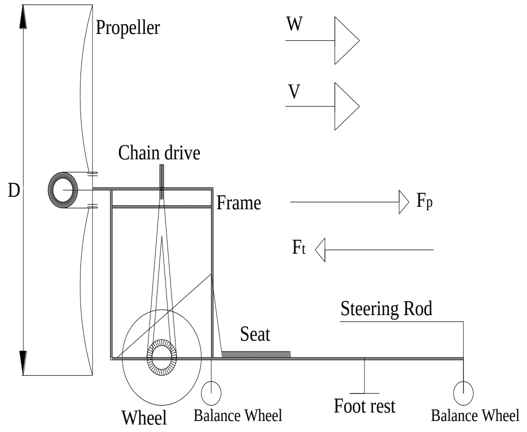

Figure 1: Side view of the air propeller vehicle

For optimization purposes, the following dimensionless parameters were introduced which characterize the operation of any Downwind vehicle.

Excess Thrust Ratio: $F = \frac{F_{net}}{F_p}$

Apparent Velocity Ratio: $Z = \frac{V-W}{W}$

Air Propeller Thrust Coefficient: $C_t = \frac{2F_p}{\rho V^2 A_p}$

Using the above relations, the equation could be rewritten as

$$\frac{W}{F_p} C_r + Z^2 \frac{1}{C_t} \frac{A_d}{A_p} = \left\{ 1 + \left[\frac{2\eta_g \eta_v}{z + \sqrt{z^2 + \frac{C_t}{\eta_{swirl}}}} - 1 \right]^{-1} \right\}^{-1}$$

Z could be replaced here by $\frac{V-W}{V}$ to obtain the $\frac{V}{W}$ ratio.

B. Analysis using JavaProp

For a quick and accurate analysis of the various forces acting on the propeller, JavaProp software was used.

The input parameters of the propeller required to be given in this software were Propeller name, Propeller Diameter, Spinner (or Hub) Diameter, Speed of rotation, axial inflow Speed, Number of blades and Thrust/power/torque required. For these input parameters as shown in Table I, the output obtained in JavaProp are as shown in Table II.

The basic equations used for the analysis were

$$C_t = \frac{F_p}{\rho n^2 D^4}$$

$$C_P = \frac{P}{\rho n^3 D^5}$$

Advance Ratio, $J = \frac{V}{nD}$

Efficiency, $\eta = \frac{V}{nD} \frac{C_t}{C_p}$

Table I: Input values in design tab of JavaProp

Propeller Name	NACA 6412
Propeller Diameter, D	4 m
Spinner Diameter, D_{sp}	0.15 m
Revolutions per minute (rpm)	120 rpm
Velocity, V	4 m/s
Number of Blades, B	2
Thrust	100 N

The output given by JavaProp included Advance Ratio, Efficiency, Thrust, Power, Coefficient of Thrust, Coefficient of Power and Pitch.

Table II: Output result in design tab of JavaProp

$\frac{V}{n\,D}$	0.5	$\frac{V}{\Omega R}$	0.159
Efficiency, η	70.47%	*loading*	medium
Thrust, T	100 N	C_t	0.08
Power, P	567.65 W	*Cp*	0.0568
β at 75% R	18°	*Pitch H*	3.05 m

Solving for $\frac{V}{W}$ using η_{swirl} = 0.95, $\frac{W}{Fp}C_r$ = 0.02, $\frac{A_d}{A_p}$ = 0.04 and with the result obtained from Table II, it was obtained that $\boldsymbol{\frac{V}{W}}$ **= 2.525** which indicates that the velocity of vehicle is 2.525 times faster than the velocity of wind. Correspondingly, $\frac{V}{W}$ Vs C_t graphs have been drawn for various values of η_{net} as shown in Figure 2 which confirms that $\frac{V}{W} > \boldsymbol{1}$.

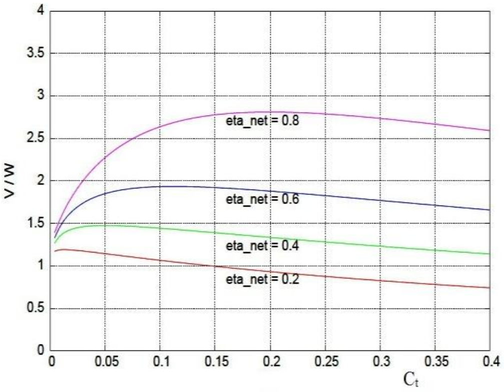

Figure 2: $\frac{V}{W}$ ratio vs. propeller thrust coefficient (C_t)

III. RESULTS OF SIMULATION

The results shown in this paper are for NACA 6412 aerofoil profile which was chosen after comparison between CLARK Y, NACA 6412, NACA 9412 and MH 114 profiles since it has a better L/D ratio, less camber and is comparatively easier to construct. The profile and geometry for NACA 6412 are shown in Table III and Figure 3.

Table III: Aerofoil profile characteristics

Propeller Profile Name	NACA 6412
Thickness	0.12c
Camber	0.06c
Trailing edge angle	14.2°
Lower flatness	0.812c
Leading edge radius	0.17c
Max CL	1.785
Max CL angle	12.0°
Max L/D	60.34
Max L/D angle	4.0°
Max L/D CL	1.268
Stall angle	4°
Zero lift angle	-6.0°

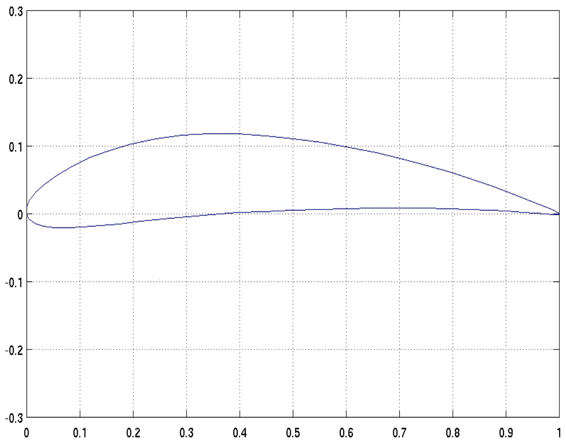

Figure 3: Geometry of NACA 6412 aerofoil profile

When analyzed using JavaProp for 4m and 8m diameters of the propeller, it was seen that the thrust and power coefficients decreased as the diameter was doubled (Figure 4) and the efficiency remained approximately the same but for a smaller advance ratio (Figure 5) of the propeller.

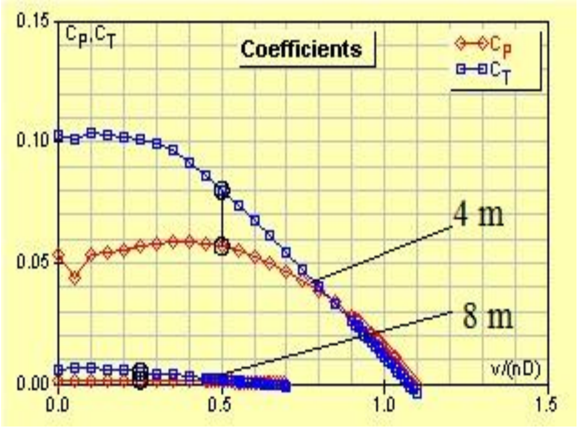

Figure 4: C_t, C_p vs. advance ratio $\frac{V}{nD}$ for NACA 6412 aerofoil for different diameters

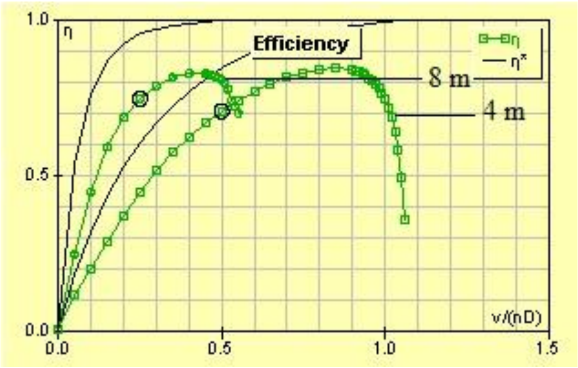

Figure 5: Efficiency (η) Vs advance ratio $\frac{V}{nD}$ for NACA 6412 aerofoil for different diameters

IV. CONCLUSION

It is theoretically possible to build a wind driven vehicle that can go in the downwind direction faster than the free stream wind speed (using a propeller in the air). There does not exist a definite upper limit for vehicles of this kind. As long as efficiencies are improved, the velocities would also increase unasymptotically. The calculations above show that it was possible to go downwind even 2.5 times the speed of wind in a wind propelled vehicle.

A variable pitch propeller is suggested so that by varying pitch angle we can maintain an optimal angle of attack (maximum lift to drag ratio) on the propeller blades as vehicle speed varies. Further analysis using computational software is suggested to understand the velocity and pressure changes that occur around the propeller in order to get a better design to travel faster downwind.

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