ENGINEERING PROTOTYPING PROJECT

Wind-Powered Vehicle

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Table of Contents

Abstract

A team of four engineering students constructed a wind-powered vehicle (WPV) that harnesses wind energy to travel against the wind. The vehicle incorporated a standard turbine inspired by the design of an American farm-style windmill, crafted according to provided engineering blueprints. The team had the flexibility to adjust blade angles and blade count for testing different configurations to optimize the vehicle's performance.

The team also engineered the rolling chassis of the vehicle. Its primary objective was to transport a payload across a 2-meter track, with the main assessment metric centred around the mass/time ratio. Wind tunnel experiments conducted in November 2023 showcased the vehicle's best performance, achieving a mass/time ratio of 600 grams/second while carrying a 10.12 kg payload and completing the track in 18 seconds.

This achievement was benchmarked against similar WPVs tested concurrently. Factors influencing this relatively favourable performance included considerations such as gear ratio, turbine diameter, vehicle weight, among other relevant parameters.

Figure 1 - Wind Powered Vehicle

Introduction

Currently in the developmental phase, a small-scale wind-powered vehicle (WPV) strives for enhanced performance by optimizing the payload-to-speed ratio. Key factors such as gear ratio, bearings, wheel size, turbine blade count and type, blade angles, among other operational parameters, significantly influence the vehicle's effectiveness. Despite this understanding, the lack of precise quantitative data impedes the comprehensive advancement of WPVs.

This report introduces the design and testing of a functional prototype WPV, intending to fill the void in quantitative data necessary for informing future designs and developments. The objective is to establish a standardized framework for testing these vehicles under specified conditions, ensuring consistency across various developmental teams. As per the set criteria outlined by Brown (2023b), these vehicles must maneuverer a 2-meter course within a wind tunnel while carrying a payload. Additionally, a prescribed storage box accommodates the fully assembled WPV rolling chassis, maintaining uniformity in testing parameters.

Theoretical Framework and Practical Applications for WPVs

Theoretical Foundations

The evaluation and optimization of wind-powered vehicles (WPVs) draw upon fundamental theories and equations governing wind energy conversion devices. These principles guide engineers in designing efficient systems capable of harnessing wind energy effectively.

Equations and Fundamental Principles

Power Extraction and Torque

Equations (1) and (2) define the maximum power and torque extracted from the wind (Brown 2023a). Understanding these equations allows for the optimization of design parameters, such as area and turbine radius, to enhance energy conversion efficiency.

$$P = C_P \frac{1}{2} \rho A v^3 \tag{1}$$

$$T = C_T \frac{1}{2} \rho A v^2 R \tag{2}$$

Turbine Rotational Dynamics

Equation (3) establishes the relationship between turbine rotational speed, tip speed, and tip speed ratio (Brown 2023a). This knowledge assists in determining optimal operational speeds for achieving desired efficiency levels.

$$\lambda = \frac{V}{v} = \frac{R\omega}{v} \tag{3}$$

Blade Element Momentum Theory (BEM)

BEM deconstructs turbine blades to analyse aerodynamic forces. This theory aids in predicting and refining blade profiles, leading to improved turbine performance.

Solidity Calculation

Solidity, expressed in Equation (4) (Brown 2023a)., highlights the ratio of total blade area to rotor swept area. Understanding solidity provides insights into blade design efficiency and influences the overall performance of the WPV's turbine system.

$$Solidity = \frac{Total\ blade\ area}{Rotor\ swept\ area} \tag{4}$$

Practical Implementation

Betz's Law and Efficiency Limit

Betz's Law defines the upper limit of theoretical efficiency achievable in wind energy extraction. This principle underscores the critical significance of optimizing efficiency when harnessing energy from wind streams. It acts as a guiding framework, emphasizing the imperative nature of maximizing the conversion of wind energy into usable power, thereby driving advancements in wind energy technology and applications.

Significance of Solidity

Incorporating Solidity concepts alongside other theoretical underpinnings plays a crucial role in optimizing blade design, exerting a significant influence on the efficiency and performance of wind energy conversion devices, particularly in advancing wind-powered vehicles.

Vehicle Performance

Payload-to-Time Ratio and Energy Consumption Optimization

Optimizing the m/t ratio (mass of payload over time taken) stands as a critical factor in enhancing WPV performance. Strategies aiming to improve this ratio, such as reducing vehicle weight or refining aerodynamics for achieving higher speeds, directly impact the vehicle's overall efficiency. Moreover, equation (5) elucidates the significance of the WPV's kinetic energy at the finish line, prompting considerations for minimizing energy consumption or maximizing energy recovery during vehicle operation (Brown 2023a).

$$U = \frac{1}{2}M(v_{WPV})^2 \tag{5}$$

Data Acquisition Systems and Performance Analysis

The utilization of on-board data acquisition systems, exemplified by Arduino-based tools, is invaluable for capturing essential performance metrics. These systems provide invaluable insights into distance versus time relationships and acceleration patterns. For scenarios without on-board systems, alternatives such as video recording are suggested to ensure accurate data acquisition for comprehensive performance analysis.

Utilizing Kinematic Relationships for Performance Estimation:

The application of kinematic equations (equations 6, 7, and 8) holds practical significance in estimating vehicle speed and acceleration based on distance and time measurements (Brown 2023a). The assumption of constant acceleration enables the use of simplified kinematic relationships, facilitating analysis and prediction of vehicle performance based on these fundamental principles.

$$v = u + at \tag{6}$$

$$s = ut + \frac{1}{2}at^2 \tag{7}$$

$$a = \frac{2s}{t^2} \tag{8}$$

Substituting (8) into (6) gives:

$$v = \frac{2s}{t} \tag{9}$$

Enhancement Strategies Based on Kinematic Relationships:

Strategies aimed at optimizing vehicle acceleration and speed can be derived from the kinematic relationships established. Exploring modifications in vehicle design, propulsion systems, or aerodynamics in alignment with these equations may potentially lead to improved acceleration profiles and overall WPV performance.

Materials and Methods

Wind tunnel details

The wind tunnel used for WPV testing featured a rectangular cross-section, boasting a painted timber floor, along with Perspex sides and roof panels. Its dimensions measured 900 mm in width, 800 mm in height, and extended to a length of 3 meters. To simulate wind flow, a readily available floor-standing domestic fan from hardware stores was employed. Positioned at a distance of 2.4 meters from the starting point, the fan's centre was aligned precisely with the wind tunnel's cross-sectional centre.

Wind speed measurements at the wind tunnel exit were conducted using a handheld anemometer, which provided precise details about the airflow. The anemometer recorded wind speed specifically at the centre of the wind-tunnel cross-section. A total of three measurements were taken independently by two different individuals, yielding values outlined in Table 1. The average wind speed across all measurements stood at 2.0 m/s.

wind speed (m/s)	Person 1	Person 2	Person 3
measurement 1	2.07	1.98	2.02
measurement 2	2.02	2.00	2.01
measurement 3	1.94	1.96	2.03
Mean	2.003	1.98	2.02

Table 1 - Wind Speed Measurements

Wind-Powered Vehicle Details

The wind-powered vehicle (WPV) is designed with the primary components focused on achieving efficient wind energy conversion into motion. The main features of the vehicle include a simple turbine which in turn will enhance the power of the wind to turn the turbine, spinning the turbine shaft, therefore spinning the pully. The string and pulley system we have utilised, uses the momentum generated by the turbine to spin the back axle propelling the vehicle forwards.

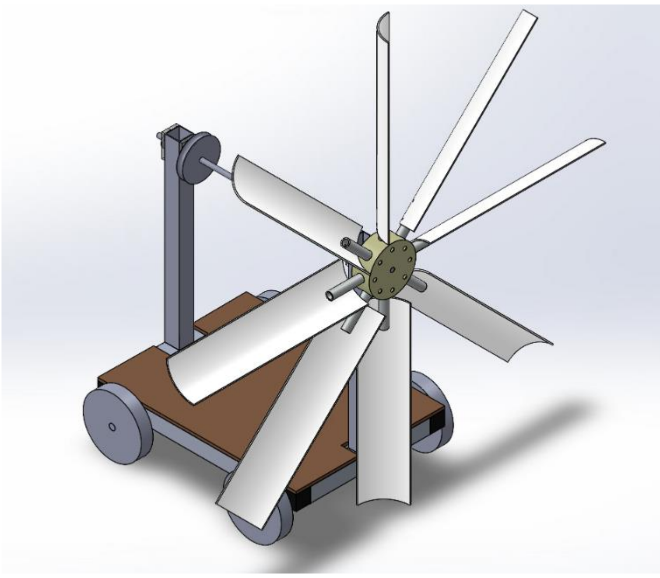

Figure 2 – Overall configuration of WPV

Vehicle Dimensions

- Overall dimensions with turbine: height 780 mm, width 700 mm, length 400 mm
- Overall dimensions without turbine: height 415 mm, width 295mm, length 340 mm
- Weight: 2.12 kg

Turbine Specifications

The turbine, a pivotal component for harnessing wind energy, has 8 equally spaced blades, these blades were angled at 45 degrees to best harness the conversion of wind to power. Through trial and error, we were able to determine that this was the optimal angle.

- Overall Diameter: 700 mm
- Blade Material: 90° section of 90mm internal diameter, 2 mm thick PVC stormwater pipe
- Blade Length: 300mm
- Blade Angle of Attack: Adjustable, constant along the length, however, 45 degrees was the final angle determined.
- Number of Blades: 8

Chassis/Frame Construction

The vehicle chassis/frame was mainly constructed of 25 mm x 25 mm x 1.2 mm square hollow aluminium tubes, that was cut to the desired lengths. Connecting these tubes was plastic elbow or tri joints, these fit tight inside the tube and help the frame together with a considerable amount of strength. To carry the payload a plate made from plywood was bolted into the frame that said on top of the frame with a portion cut out allowing the string to wrap around the bottom pully without obstruction.

Shafts/Axles Details

The vehicle incorporates various shafts/axles critical for operation, all the shafts/ axles were made from 8 mm threaded aluminium rod. For the bottom axles to allow the vehicle to spin efficiently we used saddle clamps and ball bearing to make our own saddle type ball bearings. This used the same function but did not involve the cost of having to buy this product. For the turbine shaft ball bearings where also utilised to allow the shaft to spin freely. To hold the bearings in place we laser printed a series of bearing mounts that were riveted into the side of the framework.

- Bearings: 22mm x 12mm x 8mm ball bearings
- Axle: M8 threaded rod
- Bearing mount: 40mm x 25mm with a 22mm hole directly in the centre and two smaller 3.5mm holes 15mm above the Centrepoint.
- Saddle clamps: 20mm clamps

Gearing Type

- Type: string and pulleys
- Turbine shaft pulley diameter: 8 mm (string wound directly on shaft)
- Drive shaft pulley diameter: 8 mm (string wound directly on shaft)
- Drive ratio (output torque/input torque): 8/8 = 1:1
- Torque transmission:

- Turbine hub to shaft: 3.2 mm roll/spring pin
- Drive shaft to pulley and drive wheels: double-nut locking
- Non drive axle to wheels: 3.2 mm roll/spring pin

WPV calculations and parameters

Estimation of maximum power that may be extracted from the wind, from equation (1)

$$P = C_P \frac{1}{2} \rho A v^3$$

Area of turbine,

$$A = \frac{\pi d^2}{4} = \frac{\pi (0.7)^2}{4} = 0.3848 \text{ mm}^2$$

Wind speed,

$$v = 2 \text{ m/s}$$

Density of air,

$$\rho = 1.2 \text{ kg/m}^2$$

Power coefficient,

$$C_p = 0.2 \text{ , estimate from Brown (2023a)}$$

Power,

$$P = (0.2)\frac{1}{2}(1.2)(0.3848)(2)^3 = 0.369 \text{ W}$$

Estimation of maximum torque that may be extracted from the wind, from equation (2)

$$T = C_T \frac{1}{2} \rho A v^2 R$$

Torque coefficient,

$$C_T = 0.2 \text{ , estimate from Brown (2023a)}$$

Torque,

$$T = (0.2)\frac{1}{2}(1.2)(0.3848)(2)^2(0.35) = 64.65 \times 10^{-3} Nm$$

Estimation of rotational speed of turbine

$$\lambda = \frac{V}{v} = \frac{R\omega}{v}$$

Results and Discussion

Figure 1- Figure 1 - Wind Powered Vehicle

The WPV was placed in a wind tunnel with the results were collected over three runs with different payloads measuring the time it took to complete the track.

Run	Payload (g)	Time (s)	g/s
1	2000	120	16.66667
2	8000	24	333.3333
3	10210	22	464.0909

Table 2 – WPV test runs

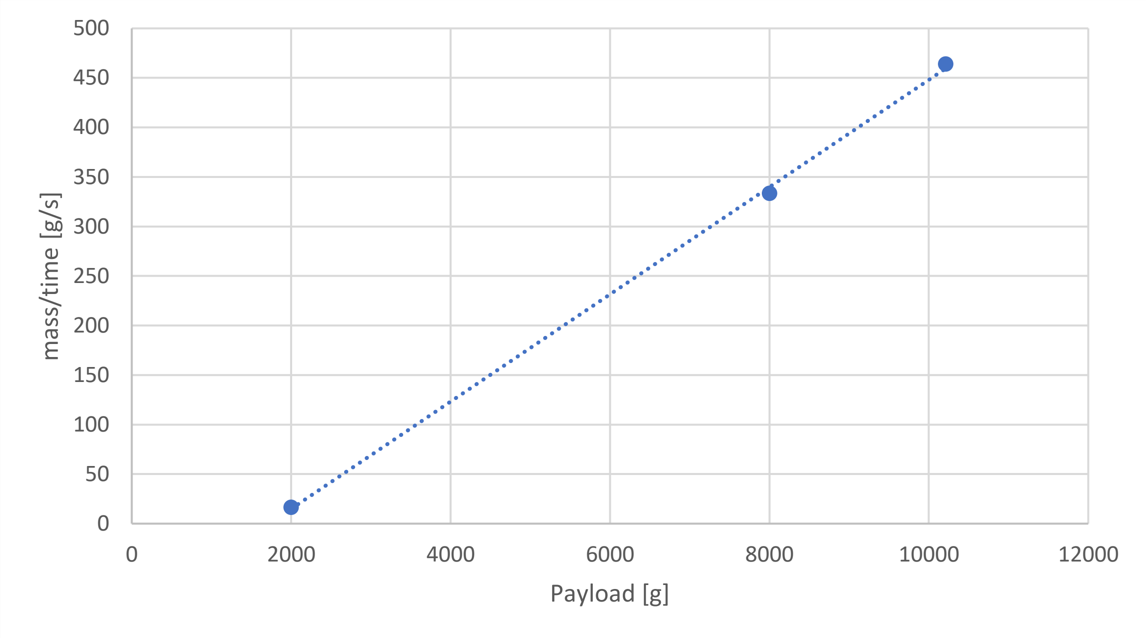

Figure 3 - WPV tests run results.

In our testing we receive excesses of the desired outcome of 400 g/s. The best marked time the vehicle achieved was 22 seconds with a payload of 10.21 kg resulting in 460 g/s power to rate ratio. Initially we had a 1:10 drive ratio, with the idea that that would be the best way to make the wheels spin faster. However, we did not consider that there is a lot of force required to spin a turbine with that type of ratio, when we went to test the vehicle, where were surprised to see no movement. After some reconsideration, we confirmed that our problemed lied with the gear ratio, so we then changed it to a one-to-one ratio, and we saw very promising results in our practice tests. our second run we added more weight because of the lower drive ratio we new that it would be able to hand more weight, however with 333.333g/s we were not satisfied. Changing the angle of the blades to 45 degrees gave the vehicle a better ability to covert wind to energy and is how we were able to obtain the result of our last run.

WPV Energy/Power

Estimation of energy and power extracted from the wind by the best performing vehicle. From equation (5), work (or change in energy) is given:

$$U = \frac{1}{2}M(v_{WPV})^2$$

M = 2.21 (vehicle) + 10.12 (payload) = 12.33 kg

Assuming that the acceleration is constant and using equation (9)

$$v = \frac{2s}{t}$$

With s = 2 m and t = 22 s, $v_{WPV} = \frac{2\times2}{22} = 0.182$ m/s

Therefore, $U = \frac{1}{2}(12.33)(0.182)^2 = 0.204$ J

Power = work/time = U/t = 0.204/22 = 9.2822 x 10^{-3} W

The power that could be extracted from the wind by the turbine was estimated to be 0.369 W.

Mechanical efficiency η of the WPV is given by

$$\eta = \frac{P_{out}}{P_{in}} = \frac{0.0092822}{0.369} = 0.025 \text{ (or 2.5\%)}$$

This result is lower than expected. Possible reasons for the low value are:

- Aerodynamic Limitations like inefficient blade design or insufficient wind-catching capabilities might hinder optimal energy extraction from the wind.
- Frictional Losses such as mechanical losses within the vehicle's components, such as bearings, drivetrain, or aerodynamic drag, could dissipate energy, reducing overall efficiency.
- Turbine Performance can come into question, when the wind turbine's design or operational conditions might not be optimized, it will limit the amount of energy harnessed from the wind.
- Systematic Errors like inaccuracies in measurements, calculations, or assumptions during the estimation process could impact the derived mechanical efficiency.

Conclusions and Recommendations

We were able to build a working wind powered vehicle that achieved the 400g/s that we aimed for. For future advances, to better our results we will need to test more drive ratios and how they interact with the payloads, different payloads will work better or worse with different ratios. Higher ratios will favour lower payloads and will go faster but will be slower to start, on the other hand lower ratios have a lower maximum velocity but can take more payload. However, we were able to achieve the desired 400 g/s so future improvements are favourable but not a necessity.

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