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Using miniature wind turbines in the design of experiments on wind energy

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ABSTRACT: Miniature wind turbines were designed, built, analysed and tested as part of mini projects that are embedded in a fluid mechanics laboratory course at the Junior level. These turbines were used by engineering students in experiments that investigated the influence of many variables that affect the power produced by a wind turbine. The experiments so created were hands-on applications in which students experienced the integrated use of a variety of theoretical concepts learned in previous courses, such as Thermodynamics, Dynamics, Fluid Mechanics, Kinematics, Material Science, Strength of Materials, Electrical Circuits and Electrical Machines. Dozens of undergraduate students have participated in these projects and, in the process, demonstrated that miniature wind turbines can be constructed, tested and analysed at modest expense.

INTRODUCTION

Extracting electrical energy from wind has attracted the interest of many individuals, small communities and energy companies around the world for many decades. However, the production of energy from wind has not been uniformly distributed around the world, because different countries assigned different priorities to this activity. Some countries with vast wind resources have been slow in using them for energy production, while others with modest resources have become leaders in the development of this technology.

The majority of the wind power plants in the world are found in Europe and in the United States, where government programmes help support the development of electrical power from wind energy [1-6]. For example, in 2008, the United States ranked first in the world in terms of wind power capacity; Germany was second, Spain third, China fourth and Denmark ninth. Yet, that same year, Denmark generated about 20% of its electricity from the wind, whereas in the USA, the corresponding percentage was 1.3% [7][8].

The amount of electricity generated from wind has been growing rapidly in recent years within the USA. It almost doubled between 2006 and 2008, when it reached 52 billion kilowatthours (1.3 %). Although the fraction itself was small, the energy produced was enough to provide electricity to serve 4.6 million American households. The current target is to provide 5% of the nation's electricity from wind energy by 2020 [8-10].

The conversion of energy from wind and other sources into electricity can be introduced in the engineering classroom and laboratory as a practical means of illustrating the integrated application of a variety of theoretical concepts that students have learned in earlier courses, such as Thermodynamics, Dynamics, Fluid Mechanics, Kinematics, Material Science, Strength of Materials, Electrical Circuits and Electrical Machines (Figure 1).

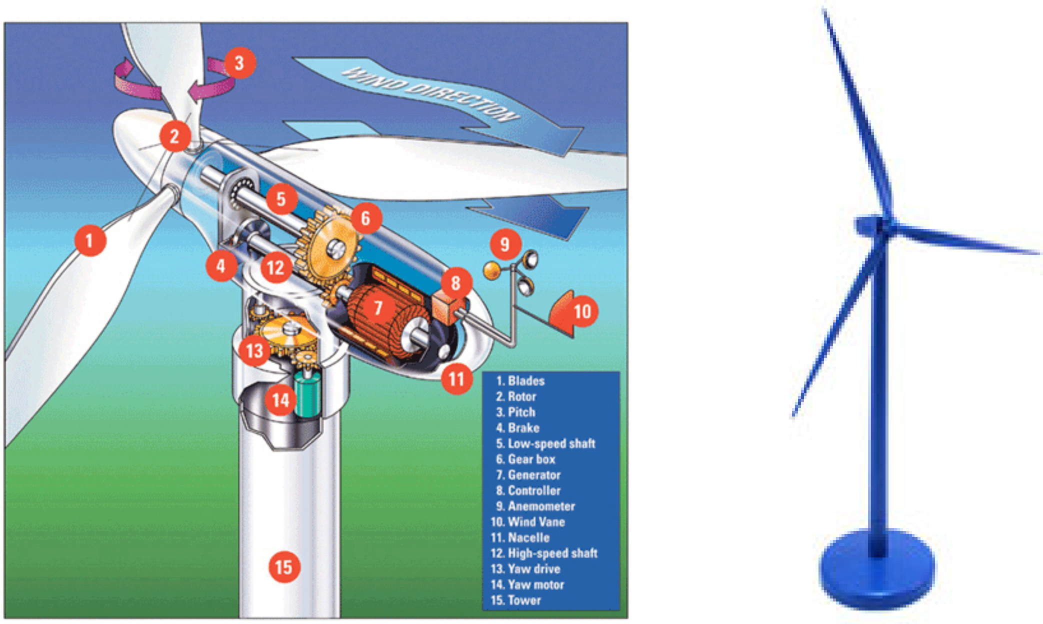
Miniature wind turbines can be constructed and tested by undergraduate students at modest expense; and voltages produced from those turbines can be read by ordinary voltmeters and multimeters commonly found in engineering laboratories or by meters that can be purchased at local stores [11][12]. Wind speeds can be generated using compressed air in laboratories, if available. If compressed air is not available, then household fans and hand-held hair dryers can be used; they work well, too. It is possible to use miniature wind turbines to set up experiments to investigate the influence of the many variables that affect the power produced by a wind turbine. In this article, a brief introduction to the use of miniature wind turbines to study the conversion of wind energy into electrical energy is presented.

The remainder of the article is organised in the following manner. First, to familiarise the reader with pertinent terminology, parts of an installed wind turbine are presented in pictorial form and briefly identified; they are contrasted with parts of the typical miniature turbine built by students and used in laboratory projects. Next, a brief review of the one-dimensional analysis of a wind turbine is presented. It shows the method of analysis, the basic results and the variables that are important. After that, those variables easily tested using a miniature wind turbine are discussed. Lastly, the types of experiments run by students are sketched out. Owing to space limitation, the specific technical details and results of these experiments are left out, for they will be presented in specific papers to be published later. Important issues that arise often and, hence, must be planned for are pointed out along the way.

PARTS OF AN INSTALLED HORIZONTAL-AXIS WIND TURBINE

Table 1: Description of the parts of an installed turbine (from the US Department of Energy [8-12]).

1. Blades: Most turbines have either two or three blades. Wind blowing over the blades causes the blades to *lift* and rotate.
2. Rotor: The blades and the hub together are called the rotor.
3. Pitch: Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low to produce electricity.
4. Brake: A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.
5. Low-speed shaft: The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.
6. Gear box: Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1,000 to 1,800 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine, and engineers are exploring *direct-drive* generators that operate at lower rotational speeds and do not need gear boxes.
7. Generator: Usually an off-the-shelf induction generator that produces 60-cycle AC electricity.
8. Controller: The controller starts up the machine at wind speeds of about 8 to 16 miles per hour (mph) and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph because they might be damaged by the high winds.
9. Anemometer: Measures the wind speed and transmits wind speed data to the controller.
10. Wind vane: Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.
11. Nacelle: The nacelle sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller and brake. Some nacelles are large enough for a helicopter to land on.
12. High-speed shaft: Drives the generator.
13. Yaw drive: Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines do not require a yaw drive, the wind blows the rotor downwind.
14. Yaw motor: Powers the yaw drive.
15. Tower: Towers are made from tubular steel (shown here), concrete or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.



a) b)

Figure 1: Horizontal-axis wind turbines: a) An installed wind turbine and its parts (from Alliant Energy); b) A miniature wind turbine (from Kidwind).

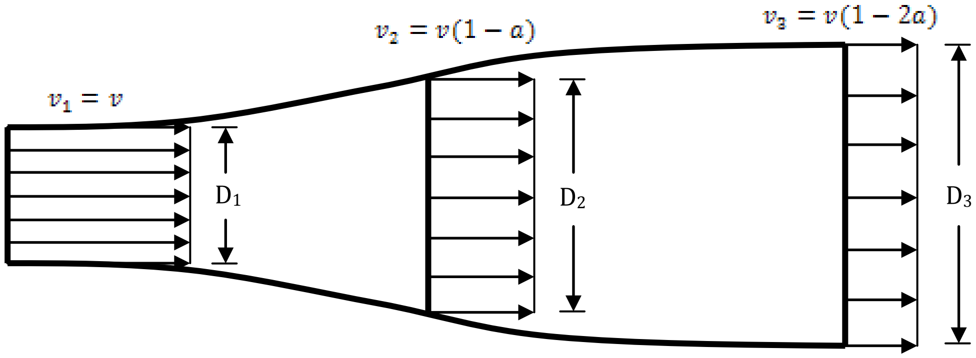


Figure 2: A stream tube around an actuated disk used to represent a horizontal-axis turbine in one-dimensional analysis.

ESSENTIAL PARTS OF A MINIATURE WIND TURBINE

Instead of the 15 parts that are in an installed wind turbine, as shown in Figure 1a, students designed miniature wind turbines that only had five essential parts: a base, a tower or some other support structure, a hub, turbine blades and a generator. The support structure holds the hub; the hub supports the turbine blades and is connected to the shaft of the generator; and, in turn, the generator is connected to a voltmeter, a millimetre or a data-acquisition system of some sort. The whole apparatus rests on a sturdy foundation that is referred to as the base, as can be seen in Figure 1b.

ONE-DIMENSIONAL ANALYSIS

One-dimensional analysis of a wind turbine assumes that its behaviour is similar to that of an actuated disk of radius R, that receives a thrust F_T from the moving stream of air that is presumed to be moving with a uniform velocity distribution at each section along its path. The hypothetical stream tube that is affected by the presence of the disk is postulated to have the appearance illustrated in Figure 2. Far upstream from the disk, the velocity of the air is assumed to have a uniform distribution with a magnitude $v_1 = v$. The magnitude of the velocity of the moving air is reduced as air travels downstream, as a consequence of the flow energy that is extracted from the stream by the disk. Following the Rankine hypothesis [13-16], half of the reduction of the speed occurs upstream from the disk and the other half downstream from it [15][16]. Accordingly, the velocity of the air immediately upstream of the disk is smaller than v. Let it be $v_2 = v(1-a)$ and velocity far downstream from the disk is smaller still. Let it be $v_3 = v(1-2a)$. The symbol *a* denotes the interference factor, so called because it attempts to take into account the fact that the moving air interacts with the rotating turbine blades. The presence of the disk causes an abrupt change in the static pressure of the moving air, which yields a thrust that is experienced by the disk. An expression for that thrust is obtained by applying the conservation of mass and the linear momentum equations along the stream tube. It is found to be given by [15]:

$$F_T = 2\pi\rho v^2 R^2 a(1-a) \tag{1}$$

Similarly, the ideal power extracted from the air by the disk is found to be given by [15]:

$$P_{ideal} = 2\pi\rho v^3 R^2 a(1-a)^2 \tag{2}$$

It can be seen that the ideal power is a function of the cube of the free stream speed and the square of the radius of the blade; the latter represents the area swept by the rotating blades. Experience shows that, for a given turbine, the interference factor is not a constant, but depends upon the free stream speed of the wind, the angle of the blades and on the frictional losses that are present in the system.

The power extracted from the wind is usually compared to the flow energy that is available far upstream in the undisturbed air stream. The energy per unit volume carried by that flow is:

$$\frac{Energy}{Volume} = \frac{1}{2}\rho v^2 \tag{3}$$

Consider a hypothetical disk that has the same radius R as the actuated disk. In the absence of any interference, the volume of that air that would be crossing the surface of that hypothetical disk per unit time is:

$$\frac{Volume}{time} = v\pi R^2 \tag{4}$$

Therefore, the flow energy per unit time that would be crossing the surface of the disk without obstruction is called the Kinetic Energy Flux (KEF) of the fluid stream, and it is given by:

$$KEF = \frac{1}{2}\rho v^3 \pi R^2 \quad (5)$$

A measure of the efficiency (also called the power coefficient) of this turbine model in extracting energy from the wind is obtained by taking the ratio between the ideal power and the kinetic energy flux. It is:

$$\eta = \frac{P_{ideal}}{KEF} = 4a(1-a)^2 \quad (6)$$

A plot of the efficiency as a function of the interference factor is shown in Figure 3. It can be seen, from Figure 3, that efficiency is at a minimum when a = 0, at a maximum when a = 1/3, and at a minimum again, when a = 1. Inserting a = 1/3 back into the expression for the efficiency, Equation (6), gives the familiar maximum efficiency of 59.3%, which was first derived by Betz [13]. It is sometimes called the Betz efficiency.

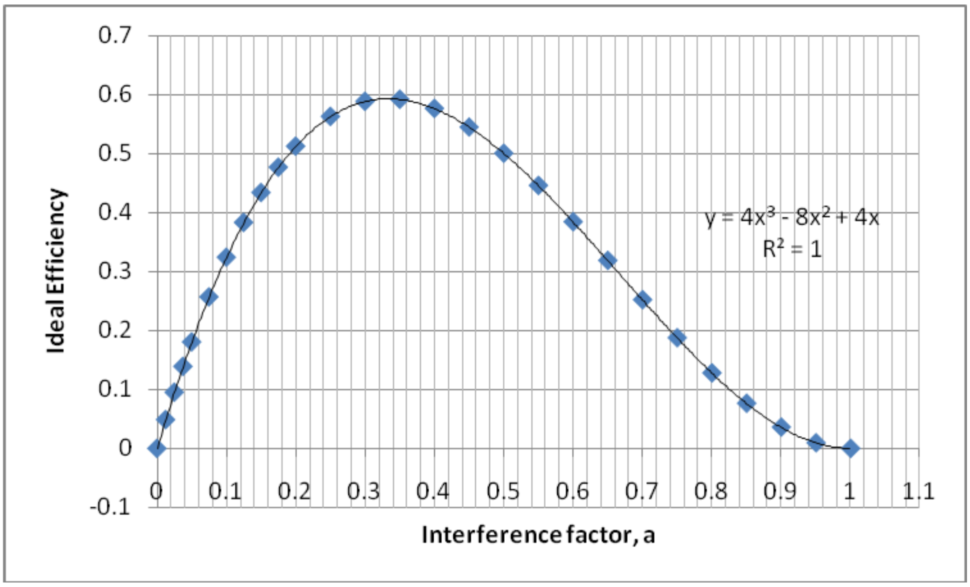


Figure 3: Variation of the ideal efficiency of the turbine with the interference factor, Equation (6).

VARIABLES THAT AFFECT THE PRODUCTION OF POWER

The variables that affect the power that can be extracted from a free stream of air fall into three general categories: variables related to the supply of air, represented by the velocity, v, in Equation (2); variables related to the turbine blades used, represented by the radius, R, of the blade; and variables related to the interaction between the blades and the moving air, represented by the interference factor, a. Discussion of interaction variables is beyond the scope of this article.

Variables related to the supply of air include the magnitude and the spatial distribution of the air speed, the size of the stream tube of air that is affected by the rotation of the turbine blades, and the distance between the source of air and the turbine:

1. Air speed: Air speed can be generated using a household fan or a hair dryer. A fan or hair dryer with variable speeds allows for the collection of a l arge set of data. One can also use compressed air, if available in the laboratory.
2. Spatial distribution of the air speed: The one-dimensional model assumes that the velocity of the air is uniform across the turbine blades. Whether one uses fans, hair dryers or compressed air that issues from a nozzle, the extent to which the velocity distribution of air over the face of the turbine is uniform, must be assessed.
3. The size of the stream tube: The size of the stream tube is affected by the size and speed of the fan (hair dryer) and the distance between the fan (hair dryer) and the turbine [16-20]. Clearly, in the case of compressed air, air pressure and the size and location of the nozzle relative to the turbine are very important [17][18].
4. The distance between the fan and the turbine blades: The distance between the fan (hair dryer or nozzle) and the turbine blades affects both, the air speed at the surface of each blade and the size of the stream tube between the source of air and the turbine. The surface area of the fan must be larger than the area swept by the moving blades in order to have any reasonable chance of creating a uniform velocity distribution over the swept area [16-20].

Five variables that are related to the turbine blades include the number, the geometric shape, the size, the angle and the dimensionality of the turbine blades used [21]:

1. The number: The number of blades can vary from one to five in tests. Most commonly, however, two, three, and four blades are used in laboratories.
2. The shape: The geometric shape of the blades affects the power that is extracted from the wind.
3. The size: The size of the blades also affects the power that is extracted from the wind.
4. The angle of the blades: The angle of the blades relative to the direction of the wind has a large influence on the power that is extracted from the wind.
5. Dimensionality: It is important to assess whether one has a two-dimensional blade, the face of which lies in one plane, or a three-dimensional blade, the face of which does not lie in one single plane. Naturally, it is much easier for students to produce and characterise blades that are two-dimensional.

FOUR TYPES OF EXPERIMENTS

The nine variables listed above can be used to design different types of experiments and students have performed many of them using miniature wind turbines that they designed and built in the undergraduate laboratories, with good results. The most popular experiments that were carried out are briefly described below. Four blade variables and one wind variable were used in those experiments. The blade variables are: the number, the shape, the size and the angle of the blades to the oncoming wind; and the average speed of the wind is the wind variable. These five variables provide ample opportunity to study the mechanical behaviour of wind turbines.

Angle experiments: These experiments aim to determine the optimal angle of inclination of a blade. In these types of experiments, there are two key variables: the wind speed and the angle of inclination of the blade to the oncoming wind. Accordingly, one selects the number, the shape and the size of the blades, and varies both the wind speed and the angle of inclination of the blade to the oncoming wind. In the actual conduct of the experiment, it is considerably less taxing to fix the angle of the blade, and test that configuration through all speeds that are available to the experimenter. The reason is that adjusting the blade angle can be cumbersome, depending upon how the blades were designed to be attached to the hub of the turbine. For example, let us suppose that the selected number of blades is two, the shape of turbine blades is rectangular and the dimensions of the rectangle have been settled upon; then, one can start by, say, fixing the orientation of the blade to the oncoming air stream in such a way that the plane of the blade is perpendicular to the wind velocity; then, one measures and collects the generated voltages over the whole range of available wind speeds with that configuration unchanged. Next, one sets the orientation of turbine blades to a new value, say, 45^{o} to the wind stream, and repeats the test over the same range of wind speeds. This is continued until one has used all angles. In the university laboratories, the chosen angles typically vary from zero to 90 degrees, using five-degree increments. Plotting and analysing the resulting data should yield the orientation of the blades that gives the largest output voltage.

Shape experiments: These experiments aim to determine the optimal shape of a blade. Clearly, the previous set of experiments can be repeated using blades of the same shape, but different sizes or aspect ratio, or with blades of the same size or aspect ratio, but of different shapes.

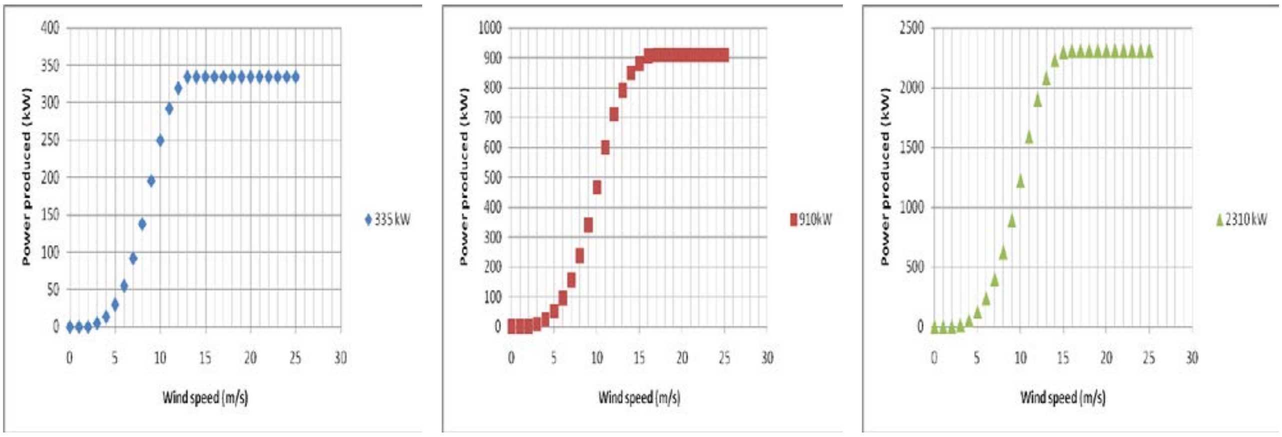
Number experiments: These experiments aim to determine the optimal number of blades that can be fitted profitably to a given turbine. The previous set of experiments can be repeated with the same hub after it has been fitted with three, then, four, or five blades of the same size as before. Clearly, here, as before, the experiment can be repeated with blades of the same shape but different sizes, or with blades of the same size but different shapes. It can be seen that there is a wide variety of experiments to choose from. Accordingly, it is important to use analysis beforehand to clearly decide what it is that one is looking for and why.

Power experiments: These experiments aim to determine the power curve of a given turbine, which is defined as a plot of the power generated by the turbine as a function of the corresponding wind speeds. The power curves for a 1 kW Enercon turbine, a 910 kW Enercon turbine, and a 2,300 kW Enercon turbine are shown in Figure 4, respectively. It can be seen that, in general, the power curves of wind turbines have similar shapes but different scales [22].

In power experiments, there is one key variable: the wind speed. This is because these experiments follow those that were described above from which one will have already determined the optimal angle of inclination of the blade to the oncoming wind and the optimal number of blades that must be fitted to one's turbine. In these experiments, then, one fixes the number, the shape and size of the blades, and the angle of inclination of each blade to the oncoming wind. Indeed, careful review of earlier work may reveal that the data needed during this experiment already have been collected in the course of performing the experiments described earlier. In some cases, however, such may not be the case. This typically happens because earlier tests missed the optimum angle of inclination, as it happened to fall between two angles that were tested. In that case, naturally, the data would need to be collected afresh for the optimal angle of inclination.

CONCLUSIONS

Miniature wind turbines were designed, built, analysed and tested as part of mini projects that are embedded in a fluid mechanics laboratory course at the junior level. Dozens of undergraduate students have participated in these projects and, in the process, have demonstrated that: 1) miniature wind turbines can be constructed and tested by undergraduate students at little expense; 2) the voltages that are produced can be read by ordinary voltmeters in engineering laboratories; and the resulting turbines can be used in laboratory experiments that investigate the influence of many variables that affect the power produced by a wind turbine, including the wind speed, the number, shape, size and orientation of the turbine blades. The experiments so created are examples of hands-on applications in which students experience the integrated use of a variety of theoretical concepts that they learned in previous courses.



a) b) c)

Figure 4: The power curves for: a) a 1 kW (Enercon) wind turbine; b) a 910 k W (Enercon) wind turbine; and c) a 2,300 kW (Enercon) wind turbine.

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