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Influence of the magnitude of the angle of attack on the voltage produced by a miniature wind turbine

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ABSTRACT: Miniature wind turbines were used to investigate the influence of the magnitude of the inclination (*angle of attack*) of turbine blades on the power produced by a wind turbine. The same turbine and the same set of blades were utilised in all experiments. Thirteen different inclinations were tested through a variety of wind speeds generated by a household fan that had three different fan speeds: low, medium and high. It was found that the voltage output varied greatly with the angle of inclination. Four ranges of inclination were identified: at very small angles and at very large angles, the turbine generated no output. In intermediate ranges, increasing the angle led to continuous increases in output until a peak value was reached; thereafter, further increases in inclinations led to continuous decreases in output. The inclinations at which maximum outputs were measured varied with the distance between the fan and the turbine and with the speed setting of the fan. However, all the inclinations where peak voltages occurred were clustered between 20^0 and 30^0 relative to the vertical axis.

INTRODUCTION

Effective production of electricity from wind implies a high-efficiency energy conversion. This requires the use of turbine blades that can generate lift. The blades are twisted and tapered airfoils that are similar to aeroplane wings [1]. Therefore, blades for wind turbines are necessarily three dimensional surfaces that often have variable curvatures and angles of attack that vary along their lengths. Students often enquire why these shapes are necessary and how they work. The aerodynamic theory of the interaction between a turbine blade and the wind is both very complicated, inexact and entails many simplifying assumptions [2-5]. An effective way to help undergraduate students begin to gain some insight into the aerodynamics of turbine blades is hands-on experience. To this end, a series of tests was conducted using rectangular blades to explore the role of the angle of attack in the production of a voltage by a miniature turbine [5].

The article is organised in the following manner: First, the experimental setup is described. Then, the procedure used to collect data is presented. Next, the collected data are presented in tabular and graphical forms that allow for the investigation of the effects of the speed-setting of the fan and the angle of attack on the voltage produced by the turbine. Finally, salient results on the role of the angle of attack on voltage production are summarised.

EXPERIMENTAL SETUP

Although they had access to a 60-mph (approx. 100 km/h) wind tunnel, a 100-mph (approx. 160 km/h) wind tunnel, compressed air, and a well-equipped machine shop in the laboratories, engineering students in their junior year were asked to construct simple wind turbines using ordinary items that were available to them, as part of a hands-on class project to explore how wind turbines work through their own experience [6].

The assignment consisted of designing an experiment that would allow data to be collected to see the extent to which the magnitude of the angle of attack of turbine blades affected the voltage generated by the turbine. They designed and built a wide variety of experimental stations. The one from which collected data are reported here consisted of the following items: A DC motor recycled from an old racing car that served as a generator, Figure 1a; a Craftsman 82026 Voltmeter with prongs that was used to measure the output voltage from the generator, Figure 1b; a turbine that was equipped with three rectangular blades made from cardboard cut-outs of dimensions 1.5 in x 4.5 in (3.81 cm x 11.43 cm) [7]; and a piece of cork that served as the hub around which the blades were attached 120^o apart by means of large paper clips (Figure 1c). The assembled components are shown in Figure 1d. They used a HOMETRENDS 9-inch (22.86 cm) diameter high-velocity fan that is equipped with 3 speeds, Figure 1e. The speed settings of that fan came already labelled by the manufacturer as low, medium and high, respectively.

a) b) c) d) e)

Figure 1: Basic components of the experimental setup used for the testing of wind turbines: a) the motor; b) the voltmeter; c) the blades; d) the assembly; and e) the fan.

EXPERIMENTAL PROCEDURE

The distance between the face of the fan and the face of the blade was made a variable. Varying that distance made it possible to change the speed of the air that reached the turbine blades at a fixed fan speed. In order to fix the orientation of the fan to the turbine, a horizontal coordinate axis was set up; it was defined by the line connecting the centres of the face of the turbine and that of the face of the fan. The origin of the axis was located on the face of the turbine and the axis was oriented in such a way that the positive direction pointed away from the turbine and toward the fan. The faces of the fan and turbine were in the vertical plane; this made the direction of motion of air from the fan horizontal and parallel to the established axis. This horizontal axis was used to move the fan to and from, thereby, varying the speed of the air that reached the turbine blades. Twelve different positions of the fan were possible; each corresponded to one of the twelve established stations that are shown in Figure 2. However, only eleven of them were used. The station represented by the letter L in Figure 2, the closest one to the turbine, was not used, because the housing of the fan turned out to be too close to the turbine blades at that location. The turbine was fixed and the fan was moved away from the turbine in a progressive manner from station K to stations J, I, H, G, F, E, D, C, B and A, in succession. Distances between stations and the turbine are shown in Table 1.

At the start, the fan was placed at station K, 1 foot (approx. 31 cm) away from the wind turbine. First, the wind speed of the fan was set on high and the angle of attack of the turbine blade was set to a preselected value; next, the voltage produced by the turbine was measured for that position of the fan and angle of attack. Then, the fan was moved further away from the turbine using a ½ foot increment and the measurement of the voltage was taken at the new location of the fan. This process was continued until the fan was so far away that the turbine blades were no longer moved by the supplied air.

A--------B--------C--------D--------E--------F--------G---------H--------I--------J--------K--------L--------Turbine
6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0

Figure 2: Fan stations: locations of the fan and the corresponding distances to the location of the wind turbine (in ft).

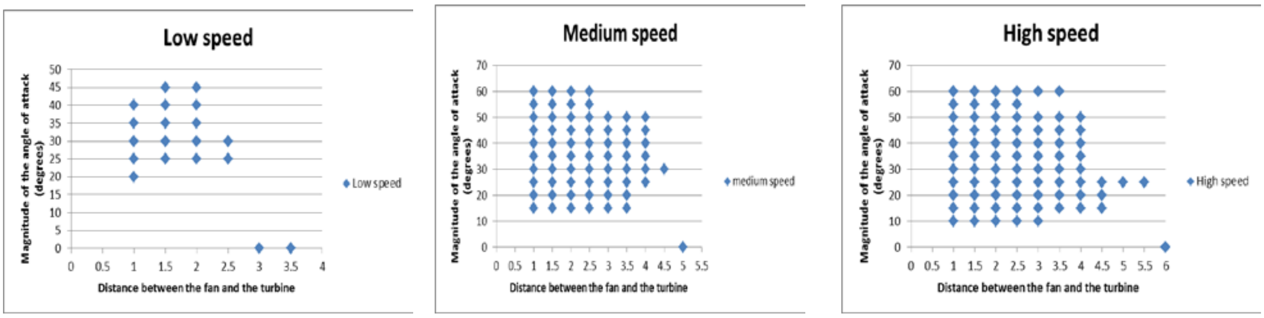
Table 1: Distances between individual fan stations and the location of the wind turbine.

Distance	1 ft	1.5 ft	2.0 ft	2.5 ft	3.0 ft	3.5 ft	4.0 ft	4.5 ft	5.0 ft	5.5 ft	6.0 ft
Distance	0.31m	0.46m	0.61m	0.76m	0.91m	1.07m	1.22m	1.37m	1.52m	1.68m	1.83m
Speed Setting											
Low	K	J	I	H	G	F	E	D	C	B	A
Medium	K	J	I	H	G	F	E	D	C	B	A
High	K	J	I	H	G	F	E	D	C	B	A

At each fan station, the air speed generated by the fan was varied by using the high-speed setting of the fan first, then, the medium-speed setting, and finally, the low-speed setting in succession. These settings will be referred to as low, medium and high, respectively. Nineteen different inclinations of the turbine blades to the stream could be tested. They are: 0^{o}, 5^{o}, 10^{o}, 15^{o}, 20^{o}, 25^{o}, 30^{o}, 35^{o}, 40^{o}, 45^{o}, 50^{o}, 55^{o}, 60^{o}, 65^{o}, 70^{o}, 75^{o}, 80^{o}, 85^{o} and 90^{o}. These angles were measured relative to the vertical plane. Thus, when the angle was 0^{o}, the surface of the turbine blade was vertical and the incoming stream of air was perpendicular to it. When, on the other hand, the angle was 90^{o}, the surface of the turbine blade was horizontal and the incoming stream of air from the fan was parallel to it. Conventionally, in the theory of airfoils, the angle of attack is defined as that between the direction of the incoming stream of air and the chord of the airfoil. Even though the angles used by the students were measured with respect to the vertical, they will be referred to as angles of attack in this article. Thus, it must be borne in mind that the angles used in this article and those used in conventional airfoil theory are complementary. The angle of inclination of the blades was first set to 0˚, then, it was increased using 5^{o} increments until one reached 90^{o}, or until the turbine blades would no longer spin, whichever came first. The nineteen angles of attack could be tested at each of the eleven stations used; and that set of trials was repeated three times, once for each speed setting of the fan. It can be seen that 627 trials were necessary. Fortunately, it was demonstrated quite early that the highest angle of attack for which air from the fan at any speed setting could cause the turbine to run was 60^0. This eliminated many trials. Furthermore, when at slow speed, the maximum distance from which the air from the fan could cause the turbine to run was 3 ft. Similar distances for the medium and high settings were, 4ft and 5.5 ft, respectively. This eliminated additional trials. In the end, the actual number of trials from which data were collected was about three hundred.

EXPERIMENTAL RESULTS

The angles of attack at which the turbine generated non-zero voltages are shown graphically in Figure 3 for various distances between the fan and the turbine. Figures 3a, 3b, and 3c represent the raw data collected when the speed of the fan was set on low, medium and high, respectively. It can be seen that at a low speed, six angles of attack yielded non-zero voltages 17 times; at medium speed, 10 angles of attack yielded non-zero voltages 63 times; and at high speed, 11 angles of attack yielded non-zero voltages 76 times. It is clear, therefore, that changing the speed setting not only changed the number of angles of attack at which the turbine blades became productive, it also changed how often they did so. How these times are distributed with the distance between the fan and the turbine is shown in Table 2. More specific details are discussed below, Figure 4.

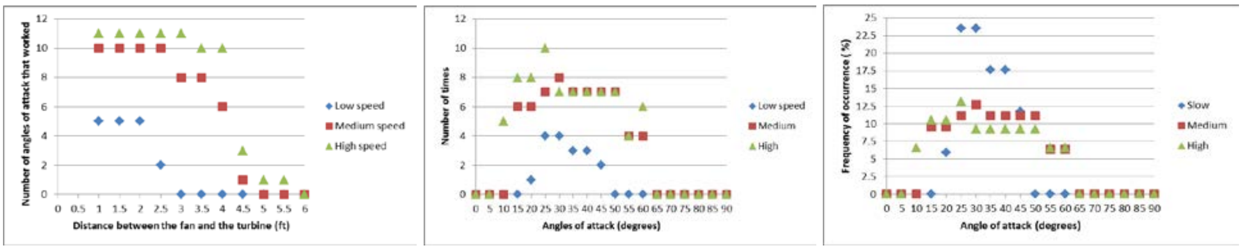


a) b) c)

Figure 3: Angles of attack at which the turbine generated non-zero voltages vs location of the fan: a) fan set at low speed; b) fan set at medium speed; and c) fan set at high speed.

Table 2: Total number of times that angles of attack caused the turbine to produce a voltage.

Distance from the turbine (ft, m)	At low speed setting	At medium speed setting	At high speed setting
1.0 to 2.5 ft , (0.31 to 0.76 m)	17	40	44
3.0 to 4.5 ft , (0.91 to 1.37 m)	0	23	30
5.0 to 5.5 ft , (1.52 to 1.68 m)	0	0	2
6.0 ft, 1. 83 m and higher	0	0	0
1.0 to 6.0 ft, (0.31 to 1.83 m)	17	63	76



a) b) c)

Figure 4: Data on angles of attack that caused the turbine to generate non-zero voltages: a) number of angles of attack; b) number of times; and c) frequency of occurrence.

Effects of Increasing the Fan Speed from Low to Medium.

Figure 4a shows that at each fan station that was tested, the medium fan speed caused an increase in the number of angles of attack at which the turbine became productive. Comparing Figures 3a and 3b, one sees that when the fan speed was set on medium, it was observed that each magnitude of blade inclination that yielded a turbine output when the fan speed was low also yielded a turbine output. In other words, no angle of attack yielded non-zero voltage when the setting was at low that did not also do so when the setting was at medium. Therefore, going from the low-fan speed to the medium-fan speed preserved the angles of attack that had been productive at the low fan speed. However, it did not preserve the number of times that those same angles of attack become productive. Indeed, it increased them as shown in Figure 4a and 4b. In addition, air from a fan set on medium speed caused blade angles that had not produced any voltage at low speed to become productive. Whereas low-speed tests only engaged angles of attack with magnitudes between 20° and 45°, medium-speed tests engaged angles of attack with magnitudes between 15° and 60°. It can be seen that at medium fan speed, the air stream engaged four additional magnitudes of angles of attack that had not been engaged before: 15°, 50°, 55° and 60°. This effect amounted to widening the range of angles of attack that become responsive.

Effects of increasing the fan speed from medium to high. Figure 4a also shows that at each fan station that was tested, the high fan speed caused an increase in the number of angles of attack at which the turbine became productive above what had been observed when the fan speed was set on medium. Comparing Figures 3b and 3c, one sees that when the fan speed was set on high, each magnitude of blade inclination that had yielded a turbine output when the fan speed was medium also yielded a turbine output. In other words, there was no angle of attack that yielded non-zero voltage when the setting was at medium that did not do so when the setting was on high. Therefore, going from a medium-fan speed to a high-fan speed preserved the angles of attack that had been productive at medium-fan speed. However, it did not preserve the number of times that those same angles of attack become productive. Indeed, it increased them. In addition, air from a fan set on high speed caused one blade inclination that had not been engaged at medium speed to become productive. Whereas medium-speed tests only engaged angles of attack with magnitudes between 15° and 60°, high-speed tests engaged angles of attack with magnitudes between 10° and 60°. Therefore, as one increased the fan speed from low, to medium, to high, the data show that air streams from the fan engaged a wider and wider range of angles of attack. The new range always consisted of all the angles of attack that had been engaged at lower fan speed plus new angles.

Further analysis of the data showed that two different, but related, mechanisms caused the turbine to become productive. The first one was the reach of the airstream that issued from the fan varied with the speed setting of the fan: when the speed setting of the fan was increased, air from the fan could reach the same set of angles of attack from farther away than air from a fan running at a lower speed. Thus, air from a fan that was set on medium reached turbine blades from longer distances than air from a fan set on low speed. Similarly, air from a fan set on high reached turbine blades from longer distances than air from a fan that was set on medium speed, Table 2. The second mechanism was that the size of the range of angles of attack that caused the turbine to produce a voltage also depended on the speed setting of the fan. When the fan was kept at a fixed distance from the turbine and set to run at low, medium and high speeds, respectively, it was observed that at least one new angle of attack that had not been productive at the lower fan speed became so at the higher one, Table 3.

A longer reach made it possible for the same angles of attack to be engaged more frequently as the distance between the fan and the turbine was increased, yielding larger incidences of productivity, *in toto*. Whereas the longest distance from the turbine at which the low setting of the fan could generate nonzero output was 2.5 ft, the corresponding distance was 4.5 ft for the medium setting; which is an increase of 80%. This increase in reach allowed the medium setting to engage angles of attack ranging in size from 20° to 45° 25 more times. Results due the longer reach are summarised in Table 2, where it can be seen that when the fan was located between 1.0 ft and 2.5 ft from the turbine, it caused the latter to produce voltage 17 times at low speed, 40 times at medium speed, and 44 times at high speed. Similar increases for the other distances are shown in that table. When the distance between the fan and the turbine was varied from 1.0 ft to 6.0 ft, while the fan operated at low speed and the experiment was repeated at medium speed and again at high speed, it was observed that angles of attack caused the turbine to produce voltage 46 more times by using the medium setting than by using the low-speed setting. Longer reach alone accounted for 25 (54%) of those 46 incidences, Table 4.

The Size of the Range of Angles of Attack that Caused the Turbine to Produce a Voltage

The medium setting engaged four additional angles of attack that had not been productive at the low-speed setting, when the fan occupied the same locations as during the low-setting trials; those angles were 15°, 50°, 55° and 60°. These four angles were engaged 21 times, Table 4. It can be seen in Table 3 that these angles of attack had not responded at low fan speed but they did so when the fan speed was increased to either medium or to high. Similarly, the angle of attack of 10° had not responded at a medium fan speed but it did so when the fan speed was increased to high. This was the lowest angle of attack that was engaged in all tests conducted. Widening of the range of angles of attack that became productive accounted for 21 (46%) of the 46 new incidences created by the medium setting: 6 were for angles of attack of magnitudes less that 20° and 15 were for angles of magnitude greater than 45° Table 4. The highest angles of attack that were engaged by the medium and high settings of the fan speed were the same. In other words, no angles of attack that were engaged were higher than those that had been so during the operation of the fan at medium speed, Table 4. At high fan speed, engagement of a wider range of angles only accounted for 5 incidences of increased productivity. Up to a distance of 3 ft from the turbine, the major difference between the medium and high settings was the engagement of the angle of attack of 10°. From 3 ft to 6 ft, the major difference between the two was due to the reach of the fan air at the high setting; and most of this manifested itself between 4.5 ft and 5.0 ft, Figure 2. When the fan speed was changed from low to medium, longer reach was responsible for 54% of the increases in productivity, while widening the range of angles of attack accounted for 46%. In going from medium to high, the corresponding numbers were 62% and 38%, respectively. These results are summarised in Table 4, where the concept of the linear density of the incidences of voltage production that were observed is tabulated. It is defined as the number of incidences for which the turbine yielded a non-zero voltage output divided by the maximum reach of the fan when its speed has been set at a specified value.

Table 3: Total count of the types of angles of attack at which voltage was produced by the turbine.

Size of the angles of attack	At low speed setting	At medium speed setting	At high speed setting
0^0 to 5^0	0	0	0
10^0	0	0	5 (6.57%)
15^0	0	6 (9.52%)	8 (10.53%)
20^0 to 45^0	17 (100%)	42 (66.67%)	46 (60.53%)
50^0 to 60^0	0	15 (23.81%))	17 (22.37%)
60^0 to 90^0		0	0
Grand total	17	63	76

Table 4: Measured characteristics of the fan used: reach, range, incidences of productivity and linear density.

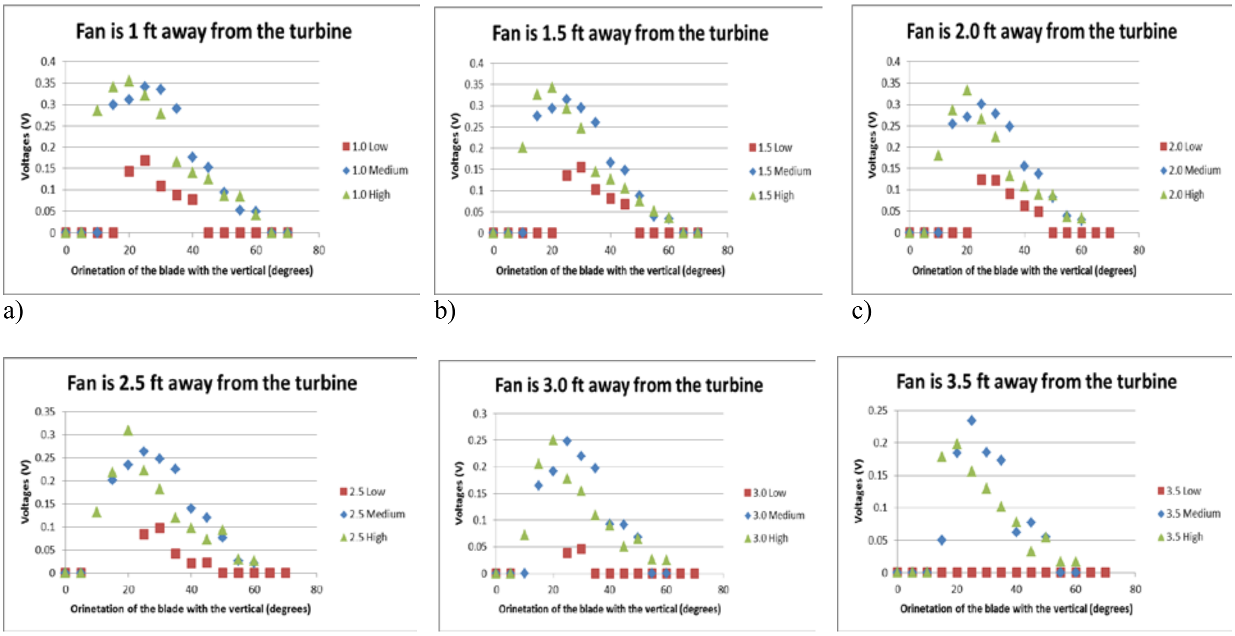
Fan speed	Reach (ft)	Range of angles (^{o})	Total number of Incidences	Incidences by reaching	Incidences by widening	Linear density: incidences /ft
Low	2.5	20^o to 45^o	17	17	0	6.8
Medium	4.5	15^o to 60^o	63	42	21	14
High	5.5	10^o to 60^o	76	71	5	13.8

MAGNITUDES OF THE VOLTAGE OUTPUTS

Experiments showed that at very low angles of attack, the turbine produced no power; however, as the angle of attack increased the turbine started producing a voltage and the voltage produced increased with increasing angles of attack up to a peak value. Thereafter, increasing the angle of attack yielded decreasing values of the voltage produced. This pattern was observed at the low-speed, medium-speed and high-speed settings of the fan. These results are illustrated graphically by the data that are graphed in Figure 5, where the voltage produced by the turbine is plotted against the angle of attack, using the distance between the fan and the turbine and the speed of the fan as parameters. If a critical angle of attack of a turbine blade of a given geometric shape is defined as the angle at which that blade caused the turbine to produce the maximum voltage output when exposed to a wind of given pattern but with varying speed, then it can be seen in Table 5 that the size of critical angles varied with the speed setting of the fan.

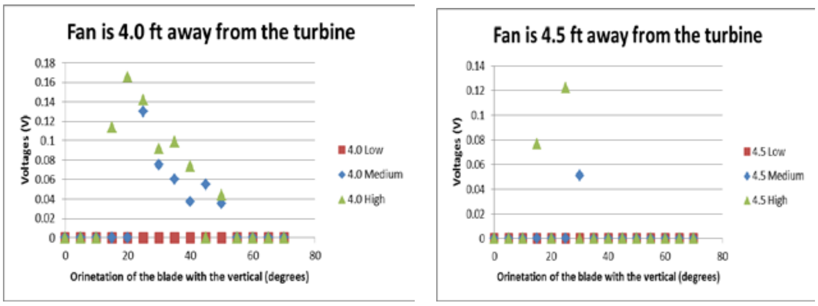
Table 5: Critical angles: angles of attack at which maximum voltages were measured.

	At 1.0 ft	At 1.5 ft	At 2.0 ft	At 2.5 ft	At 3.0 ft	At 3.5 ft	At 4.0 ft	At 4.5 ft
Speeds								
Low	25^0	30^0	30^0	30^0	30^0	N/A	N/A	N/A
Medium	25^0	25^0	25^0	25^0	25^0	25^0	25^0	30^0
High	20^0	20^0	20^0	20^0	20^0	20^0	20^0	25^0



a) b) c)

d) e) f)



g) h)

Figure 5: Voltage produced by the turbine vs the angle of attack using distance and fan speed as parameters: a) fan at 1 ft from the turbine; b) fan at 1.5 ft. from the turbine; c) fan at 2.0 ft from the turbine; d) fan at 2.5 ft from the turbine; e) fan at 3.0 ft from the turbine; f) fan at 3.5 ft from the turbine; g) fan at 4.0 ft from the turbine and h) fan at 4.5 ft from the turbine.

As can be seen in Figure 5, measured voltages were found to vary with the distance between the fan and the turbine and with the fan speed. Voltages that were measured when the fan speed was set on low were always smaller than those that were measured when the fan speed was set on medium. This was the case at each distance between the fan and the turbine where tests were run. However, voltages measured at medium fan speed were not always smaller than voltages measured at high fan speed. When the angles of attack were small, voltages measured at medium fan speed were indeed smaller than those measured at high fan speed. This was the case at each distance between the fan and the turbine where tests were run. This was observed to be the case before peak voltages for the high-speed setting were reached. After those peak voltages were reached, however, the voltages measured at the medium fan speed became larger than those measured at high fan speed, until the fan exceeded a certain distance from the turbine. This was the case at each distance between the fan and the turbine that was less than 4.0 ft. When that distance became greater than 4.0 ft, voltages measured at medium fan speed became smaller than those measured at high fan speed again did. The peak voltages varied with the distance between the fan and the turbine and with the fan speed, although variations with distance were less pronounced than those with fan speeds. These patterns are displayed by the data in Table 5.

CONCLUSIONS

Miniature wind turbines were used to investigate the influence of the magnitude of the inclination (*angle of attack*) of turbine blades on the voltage produced by a wind turbine. The same turbine and the same set of blades were utilised in all experiments. Thirteen different inclinations were tested through a variety of wind speeds generated by a household fan that had three different speeds. It was found that the voltage output varied greatly with both the angle of inclination of the blades and with the speed setting of the fan. Four ranges of inclinations were identified: at very small inclinations, the turbine generated no measurable output; at very large inclinations, it generated no measurable output either. At inclinations between these two ranges, there existed a critical inclination at which the production of voltage was maximum; it separated a subcritical region from a supercritical one. Increasing the magnitude of the inclination in the subcritical region was accompanied with an increase in voltage generation, while increasing this magnitude in the supercritical region was accompanied by a decrease in voltage generation. The size of the critical inclination varied, both with the distance between the fan and the turbine, and with the speed setting of the fan. Whereas nonzero voltage outputs were measured for inclinations between 10^o and 60^o, critical inclinations were between 20^o and 30^o with the vertical axis.

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