Stationary and Windmilling Propeller Drag

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Abstract:
This investigation sought to determine which has more drag, a windmilling propeller or one that is held stationary. A

measurement of the drag on stationary and windmilling propellers was conducted considering the length, pitch, rotational frequency of the propeller and the wind velocity. It was found that there is a point at which the drag of a windmilling propeller and a stationary propeller are equal. This crossover point was found to be dependent on the pitch and length of the propeller and independent of wind velocity.

1. Introduction:

Should a pilot in a fixed-pitch propeller plane stop the propeller or allow it to windmill if the engine stalls in flight? If there is less drag on a stationary propeller than on one that is allowed to windmill, should the pilot stop the propeller to decrease the drag thus allowing the plane to glide farther, or should the pilot let it windmilling to make it easier to restart the engine? Is the loss of airspeed to stop the propeller worth the decrease in propeller drag? This investigation was designed to help answer these questions by investigating the drag force of windmilling and stationary propellers.

Adam Scharf initially investigated the question of whether a stationary propeller has more drag than a windmilling propeller. His paper only considered the results of a literature search. Scharf conducted no experimental work himself. He could not find any papers that dealt specifically with this question. His only references were from electronic mail correspondences and a book by S.F. Hoerner. All but one claimed that a windmilling propeller had more drag than one held stationary. The only source that claimed that a stationary propeller has more drag came from Scharf's father, Marc Scharf, an amateur pilot. He came to this conclusion by actually doing an experiment in his own plane (Garrison 98). The question was left open.

No additional sources found for this investigation beyond Scharf's original research. The available publications and information in the area of propeller drag are almost non-existent, not because of any difficulties of the research sophistication, but because of the simplicity of it. To investigate propeller drag one does not need electronics and a large grant, one only needs a wind tunnel and a spring for a quick measurement. Therefore, most of the research in this field was done before articles were indexed as they are now. It was not until I found some journals from the 1930's that I could actually piece together trails of research. These trails eventually lead off to journals I did not have access to. One source suggested that I look at NASA files before 1960 (Brahly). Many of my possible sources said that they had done some research in the field but did not elaborate. One problem is that a lot of the research done today is done by private companies which do not release their data to the public, or at least make it difficult to obtain.

I decided that more background research would not have yielded any information that would have changed the investigation due to the constraints on what could be tested with the apparatus that was available to me. So I decided to undertake the investigation using my own ideas.

Although the main goal of this investigation was to simply determine whether a windmilling propeller has more drag than one held stationary, the dependence of the drag of a propeller on length, pitch, rotational velocity, and wind velocity was also studied.

Ideally, the surface area should be investigated rather than the length, but since the length reflects the surface area of a propeller, and it was much easier and cheaper to test only the length due to the unavailability of propellers, only the length is tested here.

2. Apparatus:

Wind Tunnel	Leybold – Heraeus Model: 373 12
Stroboscope	Monarch Instruments NovoStrobe Model: DB Plus 115/230
Force Sensor	Pasco Scientific Student Force Sensor Model: Cl-6519
Software	Logger Pro 1.0.7 Tufts University and Vernier Software
Propellers	Grish Products Tornado Propellers Master Airscrew Propellers

Table (1) The equipment used in the investigation.

The size of the wind tunnel was 15 cm x 15 cm x 50 cm. This limits the size and availability of propellers that can be used. Also, the maximum wind velocity of the tunnel is 5 m/s. The propellers used were designed for model airplanes and modified as needed to fit the tunnel. These model airplanes fly at velocities between 25 and 50 m/s. Therefore, the wind velocities tested here were less than 20% of the design speeds for the propellers. A uniform flow was assumed throughout the length of the tunnel. The tunnel is 50 cm long and the propellers were mounted between 35 and 40 cm from the rear of the tunnel.

2.1 Setup:

The mount for the propellers required movement only in one direction in which a force was measured. The propeller rotation was to be as free as possible. The final design can be seen in Figure (1).

The force sensor was clamped above the tunnel. A threaded rod was bolted to a loop on the measuring arm of the force sensor and dropped into the wind tunnel through a ¼" slot that runs down the center of the top of the tunnel. A common safety pin was used to mount the propellers. It was attached to the bottom of the rod by looping the spring of the pin around the rod. The pin was then bolted in place to prevent twisting as seen in Figure (2). The rod was positioned so that the pin was in the center of the tunnel.

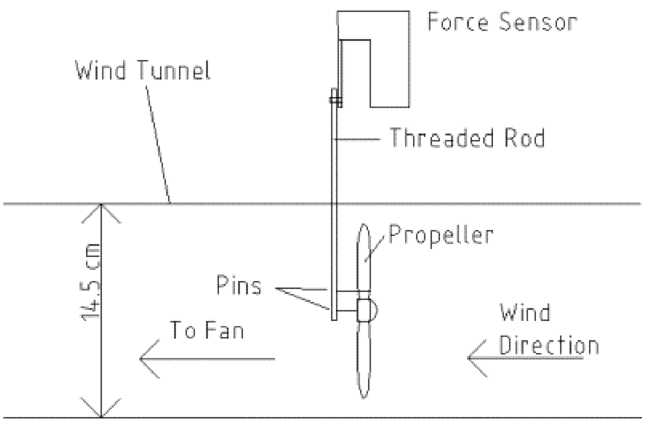

Figure 1: The side view of the setup. The finer details of the mounting of the propeller on the pins are shown in Figure 2.

To mount the propeller onto the safety pin, customized spinners were machined out of aluminum. First, a cylinder of aluminum was machined to be the same diameter as the hub of the propeller. The rear of the cylinder was machined down to the diameter of the bearing of the propeller. The depth of this thinner part was the same as the depth of the hub. Both the spinner and bearing were threaded to keep the propeller attached to the spinner. The front end was rounded to improve the airflow around the front of the hub. A small hole approximately the same depth as the hub was drilled down the center of the spinner from the rear. The propeller was then mounted onto the pin by sliding the pin into the small hole. Oil was dropped into the mounting hole to reduce friction. To hold the propeller stationary, another pin was bolted above the mounting pin. It also pointed away from the direction of the flow. This pin protruded past the blades and kept the propeller from spinning. The pin was simply turned out of the way to allow the propeller to windmill. This is shown in Figure 2 with a close-up of the bolts and pins.

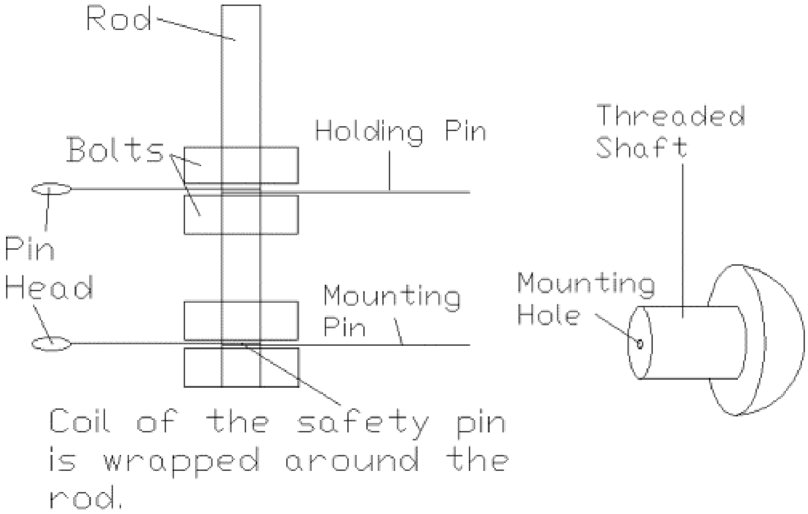

Figure (2): A close up of the bolts, pins, and the spinner. The spinner mounts on the mounting pin. The shaft cannot be seen on the spinner because it is covered by the hub. The setup shown here was used to measure the force on a stationary propeller. To measure the force on a windmilling propeller, one of the bolts was loosened and the holding pin was simply rotated out of the way.

2.2 Propellers:

As stated before, the propellers used are modified Master Airscrew and Grish Tornado propellers. Few propellers are made with diameters less than 15 cm. Therefore propellers longer than 15 cm were cut down to the desired length. They were cut to just over the desired length with a band saw and then were finished off by sanding. The tips were rounded in order to preserve the original shape of the propeller as much as possible. This process created a source of error because it was impossible to make both blades of the propeller identical. Even with this process it was still difficult to obtain a wide range of pitches. To get a wide range of pitches, one needs to go to longer and longer propellers. But the longer the propeller is the larger the hub is. Larger hubs add more weight and take up more room in the tunnel thus decreasing the effect of the propellers. Also, it was feared that if the propellers were too short, some of the properties and characteristics would be lost. The set of propellers used for this experiment are summarized in Table (2).

Brand	Length (cm +/- 0.1cm)	Pitch (inches/revolution)
Tornado	8.25	3
Tornado	10.2	3
Tornado	12.0	3
Tornado	13.7	3
Tornado	7.9	8
Tornado	9.7	8
Tornado	11.8	8
Tornado	13.8	8
Master Airscrew	13.7	3
Master Airscrew	13.7	4
Master Airscrew	13.7	5
Master Airscrew	13.7	6

Table (2) The propellers used in this investigation.

The pitch of a propeller is a measurement of the angle of the blades relative to the axis of rotation. In this paper it will be in units of inches/revolution and average angle. The higher the pitch number, the greater the angle of the blade. A propeller with pitch and average angle of 0^o has blades perpendicular to the direction of airflow and a propeller with average angle of 90^o has blades parallel to the direction of the flow. The average angle is the angle of the blades at 70% of the radius (Hoerner 13-21). In this investigation, propellers with pitches of 3, 4, 5, 6, and 8 inches/revolution are used. The propeller is like a screw. As it turns, it "screws" its way through the air. These numbers represent the number of inches that a propeller would move forward if it went through one revolution (assuming no slipping). A propeller with a pitch of eight has steeper blades than that of a propeller with pitch three. The average angle units only apply to one case in this investigation, found in figure (8). The conversion between the two sets of units for the relevant pitches and angles is shown in Table (3). Since the units of inches/revolution will be used much more that the average angle, when the word "pitch" is used in this paper, it is referring to the units of inches/revolution. The pitch numbers come from the specifications of the propeller by the manufacturer, they were assumed to be true in all cases and were not checked in any way during this investigation[1].

Pitch	Average Angle
3	14.194
4	18.636
5	22.85
6	26.83

Table(3): The conversion between pitches and average angle are shown here.

To convert between the pitch in inches/revolution and average angle, the formula

$$\tan q = pitch / 2pr \qquad (1)$$

was used. 2pr is the distance that a point on the propeller at distance *r* from the center will travel in one revolution, i.e. the circumference of a circle with radius *r*. The pitch (in inches/revolution) is a constant. If it was not constant, different regions of the propeller would have different pitches and cause a different amount of thrust. Therefore, this formula has only two variables, q and *r*.

2.3 Data Collection:

The wind velocity in the tunnel was not measured directly in the tunnel itself, but at the outlet of the fan. It was found empirically that the velocity inside the tunnel was 27% of the velocity of the outlet. This was done simply by measuring the velocity inside the tunnel and then at the velocity at the outlet. The average of the ratios was 0.27. The scale on the manometer is on a quadratic scale with tick at every m/s. The ticks become farther apart at higher wind velocities than they are at lower velocities. There was 2.3 cm between 5 m/s and 8 m/s and between 18 m/s and 19 m/s. Data were recorded to the tenth of a meter per second with the last digit being an estimate.

The data from the force sensor were sent through an analog to digital converter and then to the computer where they were analyzed using Logger Pro software. An absolute scale was not used. The main reason for this was that the sensor shifted over time. Before taking a set of data, the software was calibrated so that when there was no propeller mounted a force of 0 would be read. Occasionally, the scale shifted in the course of the experiment. The shift could be up to 10mN at times. For this reason, the "zero" point was measured often. This number was recorded and taken into account in the next set of measurements. For example, if the first set of data read 20 mN with the zero at 0 mN, then a force of 20nM would be recorded. If the zero shifted to –1 mN and a force of 19 mN was measured, then a force of 20 mN would be recorded again. The point at which the shift occurred could not be determined. It is most likely that this shift occurred when a propeller was being removed. Removing the propeller involved stopping it if it was rotating which often jolted the apparatus. It does not matter if the data were collected and then the zero was measured, or whether a zero was taken and then used for a subsequent set of data. Either way, the recorded value would be the same (assuming a constant shift each time).

Another reason that an absolute scale is not used is due to the extremely small forces that are being measured. The forces of the propellers ranged from 5 to 50 mN. Therefore the sensor does not need to shift much to create a noticeable difference in the data. An uncalibrated apparatus was used most of the time because even though the measured magnitudes changed, the relative differences in the data remained the same. For example, if the drag force due to a 10 cm propeller was found to be 80% of the drag of a 12 cm propeller one day, the same ratio would be found the next day, regardless of the actual numbers that were being recorded. At one time data were being recorded from a calibrated setup, however it took too much time to recalibrate the setup everyday. This lack of absoluteness is acceptable because the goal of this investigation is to find relationships between propellers under different conditions, not to find absolute numbers.

To collect data on each propeller, Logger Pro was set to collect data for a duration of one second at a rate of 4000 samples per second. The average of the 4000 samples was found and recorded. This process was repeated at least five times in a row. Then the variable that was measured was changed in the experiment. The process was repeated until all of the possible states were measured. Then the process was repeated at least once more. The average of all of the data were averaged to produce one data point shown on the graphs.

When testing the dependence of the drag force on the length of the propeller, five sets of data were collected on the longest propeller, then data were collected on the second longest, the third longest, and finally the shortest. This scheme was then repeated two more times. In the case of taking data on different days, normalized data were used due to the shift. This same process was used to investigate the effect of the pitch. When testing wind velocity, the wind velocity was changed until enough data were taken on one propeller and then the propeller was changed. All 15 of the averages for each propeller were then averaged together.

A sample of the Logger Pro display is shown in Figure(3). The noise is caused partly by the electronics, but mostly by the vibration caused by the propeller. The mounting hole in the spinner was made as small as possible with conventional drill bits, but it still had a diameter nearly twice that of the safety pin giving the propeller plenty of room to move around. Making the pin larger in diameter also meant increasing the length. But an increase in length caused even more vibration due to the added torque, so the smaller pin was chosen.

There was a problem in either Logger Pro or the A-D converter that made choosing the sample rate and duration difficult. Sometimes, the data were continuous as in Figure(3), and sometimes discrete as in Figure(4). The cause for this is unknown. At certain sample rates and durations the data were always discrete and for other sample rates and durations, they were always continuous. The problem is that the discrete data and the continuous data yielded different results. The continuous data were used because they appear to be more accurate. However, it is possible that the discrete data would have given equally reliable results.

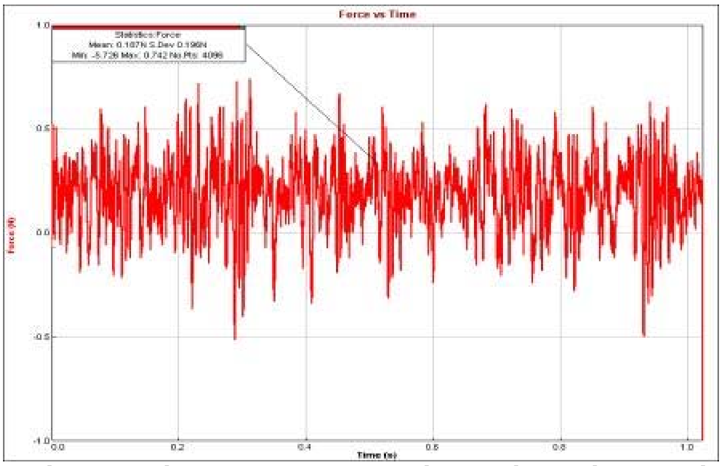

Figure 3: This is the way the continuous data appeared in Logger Pro. Force is on the vertical axis and time is on the horizontal axis. The box in the upper left is a statistics box generated by Logger Pro. It lists the mean, standard deviation, minimum and maximum points, and the number of points in the set of data.

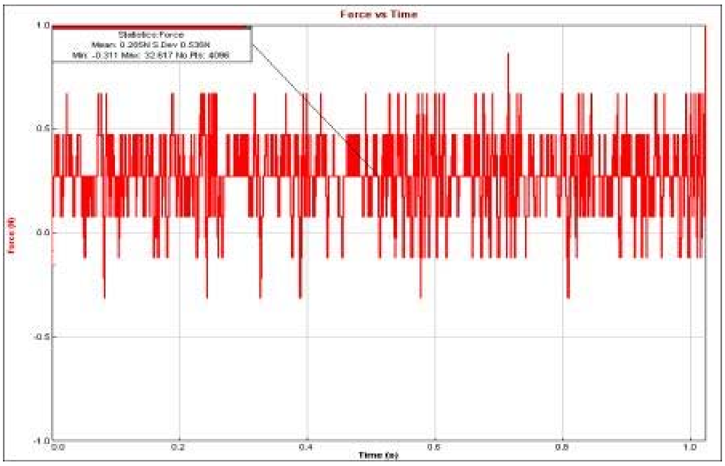

Figure 4: This is an example of discrete data.

3. Results:

This section is broken down into four parts, each one considering the effects of the four variables considered: rotational frequency, pitch, wind velocity, and length. Two themes are prevalent in this section. The first is the dependence of the variables on each other. For example, in section 3.4, the drag force versus the length of the propeller changes behavior with pitch. The second theme is the inability to extrapolate the data. The small range makes many of the relationships appear linear. This problem is demonstrated in section 3.2 where some previously taken empirical data is compared to my data.

3.1 Drag Force vs. Rotational Frequency:

The rotational frequency of the propellers was measured using a stroboscope. An ink mark was placed on one blade for reference. The stroboscope is capable of measuring up to 14,000 Hz and has an accuracy of 0.01 Hz. It was not possible to utilize this accuracy because the propellers did not maintain a constant rotational frequency to this accuracy. They varied by at most 0.5 Hz during a measurement, so each rotational frequency shown here is accurate to within 0.5 Hz.

The problems with measuring the rotational frequency very accurately turned out to be moot points because the rotational frequency is dependent on the wind velocity. In Figure(5) we see that the rotational frequency does not change with the length of the propeller over the range of wind velocities. This was done using Tornado propellers of pitch 3. Frictional forces become a factor below 2 m/s. At these velocities the propeller continued to spin if it already had been spinning, but it would not begin to spin if it was previously stationary. For this reason, all data taken at wind velocities below 2 m/s are highly questionable. At higher wind velocities it does appear that there is a slight difference, but it is minimal. In Figure(6) we see once again that the rotational frequency is some constant times the wind velocity. But we also see that the constant is dependent on pitch. Direct drag force versus wind velocity measurements are unnecessary because of the linear relationship between wind velocity and rotational velocity.

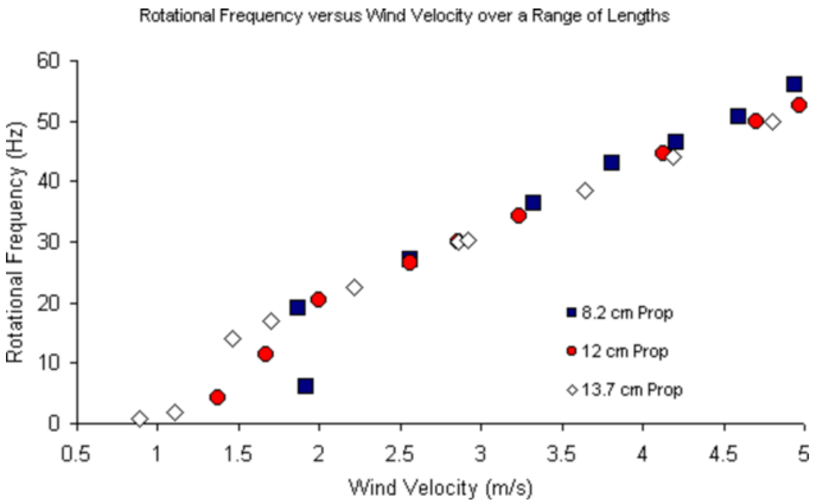

Figure (5): This data is generated using the Tornado Pitch 3 propellers. For the region looked at in the investigation, the rotational frequency is not dependent on length and appears to be a linear relationship of the wind velocity.

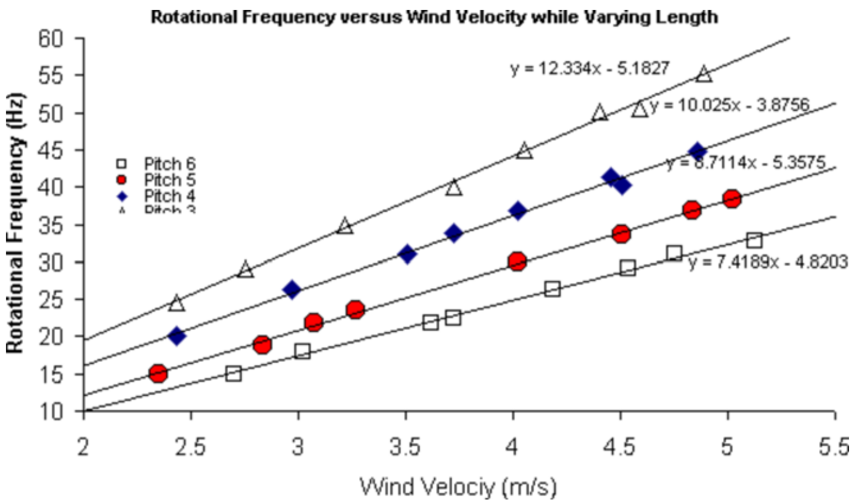

Figure (6): As in Figure (5) the rotational frequency is linearly related to the wind velocity. Notice that the frequency is dependent on pitch. The equations of the fits are also shown. Frictional forces are most likely the cause of the intercepts not being zero. This data was taken with the Master Airscrew propellers.

3.2 Drag Force vs. Pitch:

The data for the drag force versus pitch were taken using the Master Airscrew set of propellers. The wind velocity was held constant at about 5 m/s. Figure (7) shows that the drag force decreases with an increase in pitch. It also shows that at lower pitches there is more drag on windmilling propellers and at higher pitches there is more drag on propellers held stationary. This crossover point occurs around a pitch of 4.5. The question of which has more drag now depends on at least the pitch of the propeller.

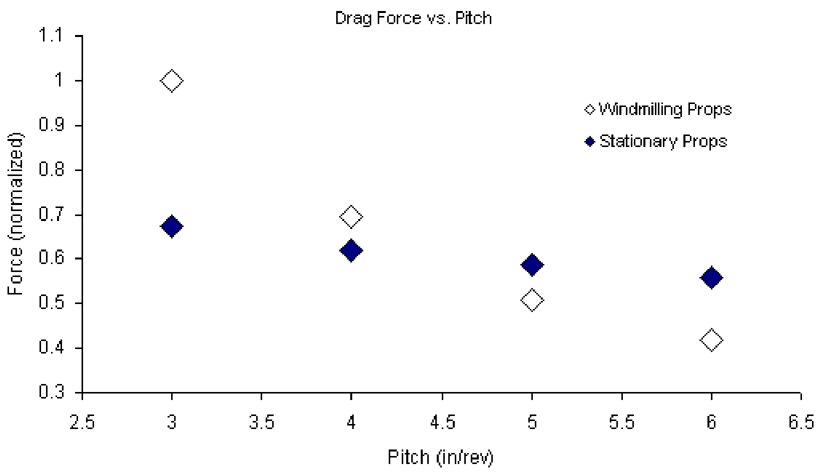

Figure (7): This data was taken using the Master Airscrew propellers and is normalized so that the force of the windmilling propeller with pitch 3 has a force of one. The key element shown here is that for lower pitches, the drag force on a stationary propeller is less than one that is allowed to windmill, but at higher pitches it is reversed.

The effects of the small range of data are most evident in Figure (7). Previous empirical data show that for a stationary propeller the function for drag force with respect to the average angle is

$$F = a + b\cos^2 q \qquad \text{(Hoerner 13-21) (2)}$$

Figure (8) shows my data plotted with this curve. Instead of using the pitch units of inches per revolution, the units of average angle are used. A propeller was made out of balsa wood with pitch 0 to determine a starting point. The balsa propeller was made to resemble the other propellers but it was impossible to precisely duplicate the shape. This propeller was also much thinner and lighter than the Master Airscrew propellers used. The measurement at 90^0 was made using only a hub and spinner. I assumed that a propeller with blades parallel to the direction of flow has no drag. This graph brings into question any attempts of extrapolation of any of the data presented. Even though the data may look linear or quadratic, that may not be the case.

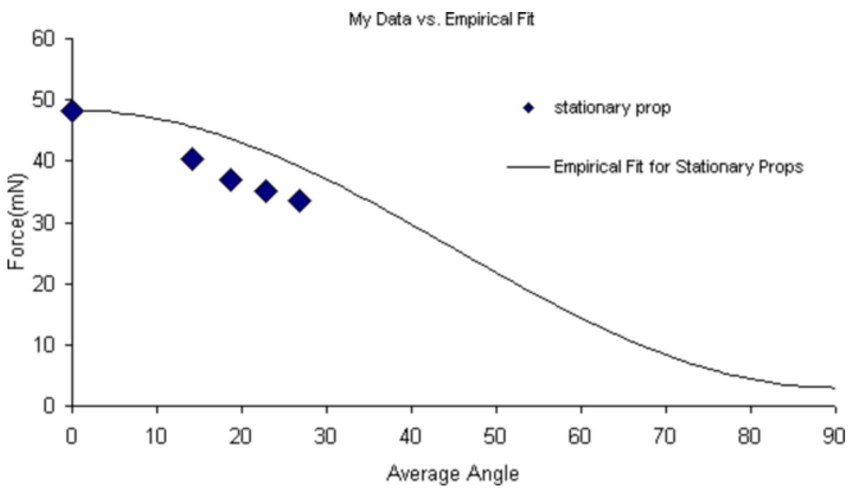

Figure (8): My data is superimposed over a line determined by an empirical fit. The general equation of the line is $F = a + b\cos^2 q$. The constant *a* was determined by making a propeller of pitch zero and the *b* was determined by assuming that the force due to a blade at 90^o is zero and measuring the force on only the hub.

3.3 Drag Force vs. Wind Velocity

Propeller drag force increases with wind velocity when it is allowed to windmill and when being held stationary as seen in Figures (9 & 10). These data were taken with a calibrated apparatus holding the length and pitch constant and changing only the wind velocity. The Tornado 13.7 cm, pitch 3 propeller; the Master Airscrew 13.5 cm, pitch 5 propeller; and the Tornado 13.8 cm, pitch 8 propeller were used. Frictional forces became apparent at low wind velocities, preventing data from being taken much below 1.5 m/s. When comparing the different propellers, it should be noted that each has a different surface area. That is, Figure (8) does not demonstrate that a stationary propeller of Pitch 8 has more drag than a stationary propeller than Pitch 3. They are nearly the same because the surface area of the Pitch 8 propeller is larger than that of the Pitch 3 propeller. With the small range of data collected it is impossible to make a prediction as to the nature of the curve, both linear and quadratic fits of the data are acceptable.

In Figures (11, 12, and 13) the windmilling and stationary data for each propeller is shown. Each graph is normalized to the stationary drag force at the highest wind velocity. Notice that the same pattern holds as discussed before regarding the pitch, as the pitch increases past a certain point, there is more drag on a stationary propeller than there is on a windmilling one. These data were taken at a high wind velocity (about 5m/s). Notice that for the pitch 5 and pitch 8 propellers, at lower wind velocities there is more drag on a windmilling propeller than on one held stationary. A separate experiment was performed that specifically considered this property and the data shown in Figure (14) resulted. This data show that there is *no* dependence on the wind velocity. If there were a dependence on wind velocity, it would be expected that the ratios at higher wind velocities would be different than those at lower wind velocities. A wider range of data would easily solve this problem.

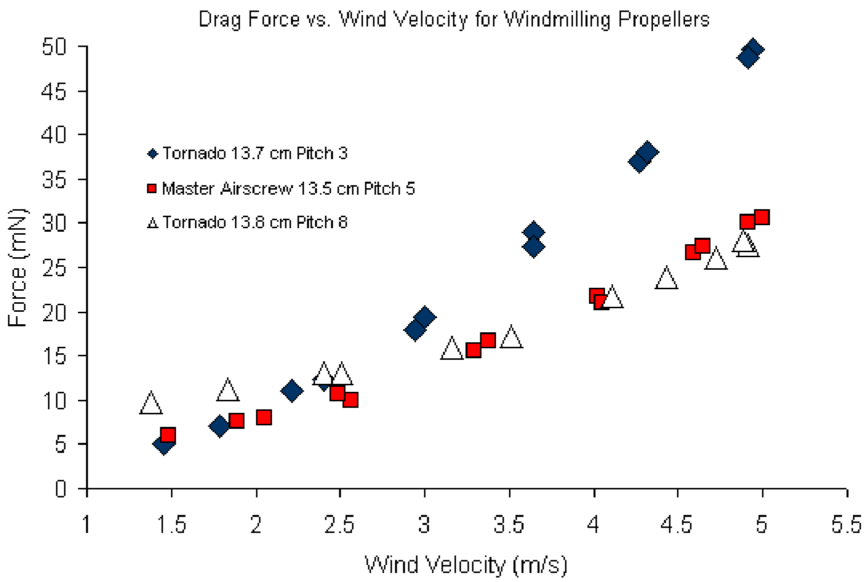

Figure (9): The force appears to increase quadradically with an increase in wind velocity. The values of the forces are actual values taken with a calibrated apparatus.

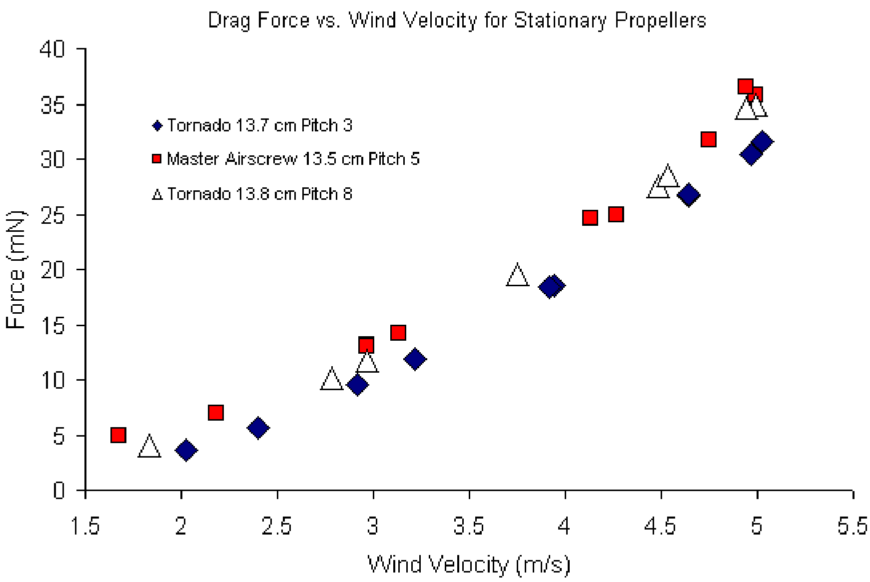

Figure (10): Similar to stationary propellers, the drag force also increases with wind velocity. It is not clear as to whether the increase in linear or quadratic.

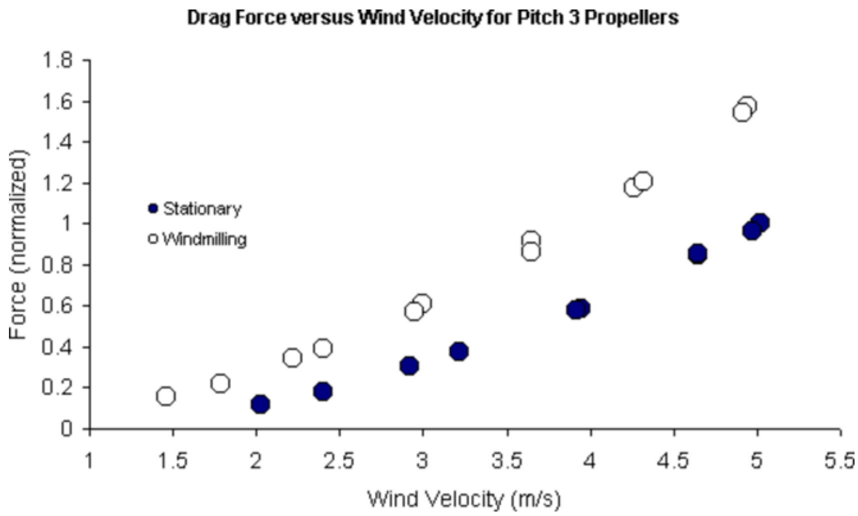

Figure (11): The data is normalized so that the largest value of the stationary data is one. Notice that the stationary drag force is never more than the windmilling drag force.

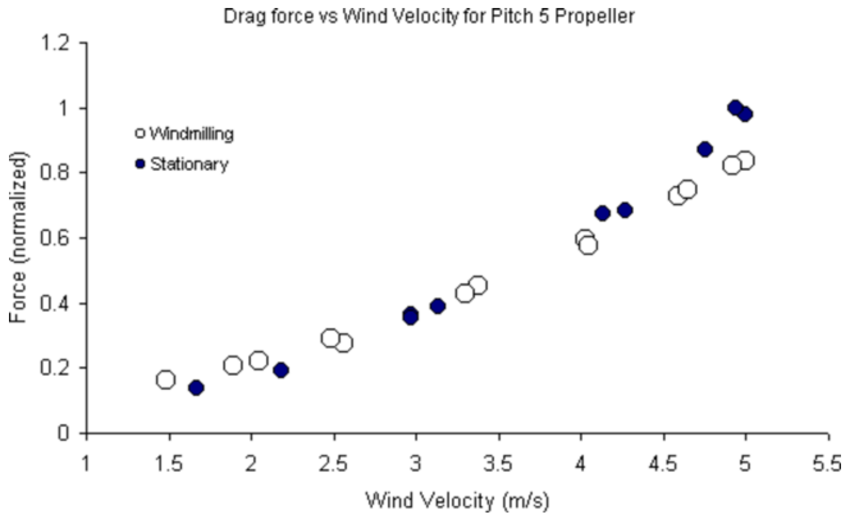

Figure (12): This data is normalized in the same manor as Figure (11), the largest value of the stationary data is one. From this graph it appears that at higher wind velocities there is more drag on a stationary propeller than on a windmilling one, but at lower wind velocities it is the other way around.

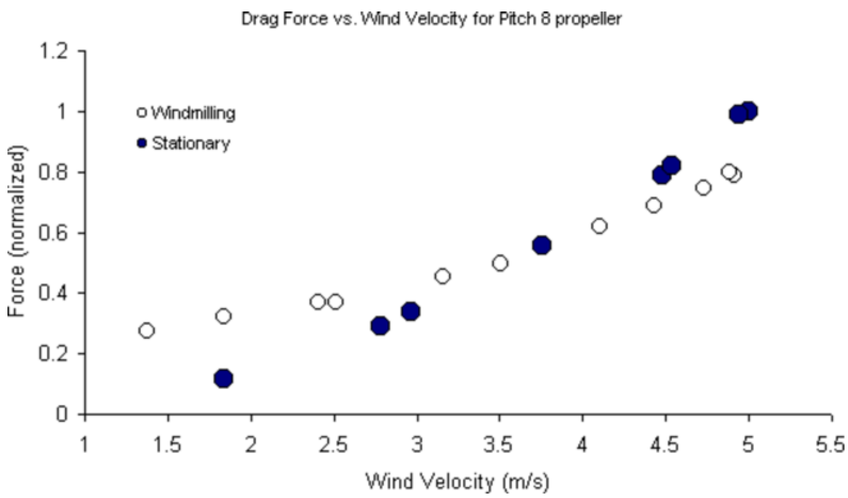

Figure (13): Normalized Drag Force versus Wind Velocity for a Pitch 8 Propeller. This data is normalized in the same manner as the previous two, the largest value of the stationary data is one. Similar to Figure (12) and more pronounced, it appears that at higher wind velocities there is more drag on a stationary propeller than on a windmilling one, but at lower wind velocities it is the other way around.

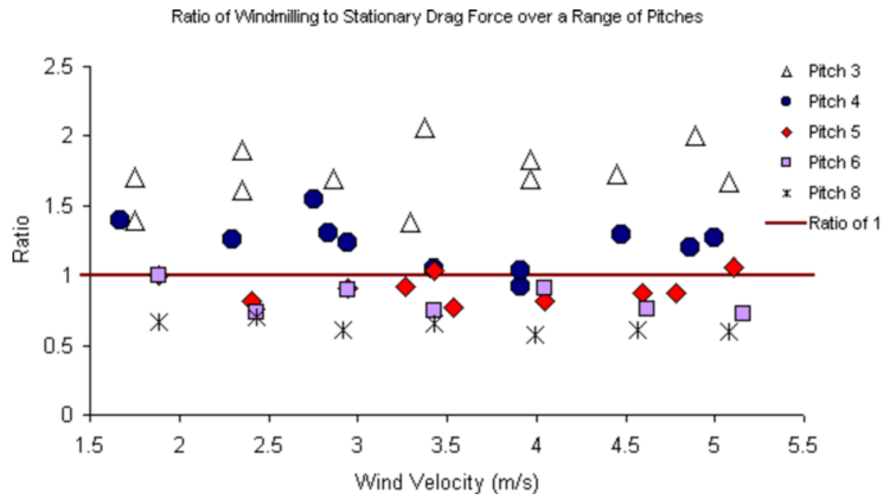

Figure (14): Here we see a general trend that is a repeat of Figure (7) in that as pitch increases the windmilling to stationary drag force ratio decreases. This figure contradicts Figures (12 and 13) because it shows that the ratio of windmilling to stationary drag is constant over the range of wind velocities. This data was taken looking specifically at this property.

3.4 Drag Force vs. Length

Figure (15) shows a graph of the drag force versus propeller length for both stationary and windmilling propellers. The set of Tornado Pitch 3 and Tornado Pitch 8 propellers were used for these measurements. As expected, the force increases with length but (once again) there are not enough data to tell what the shape of the curve should be. From this data we see that the crossover point is also dependent on length. This is best seen in Figure (16). Here we see that for the pitch 3 propeller there is more drag on a windmilling propeller than on the stationary as expected, but notice that the ratio increases as the length decreases. It appears that if a propeller with a length between 7 and 8 cm was tested, that the drag forces for the stationary and windmilling states would be the same. The pitch 8 propellers also show a dependence on length. As expected, there is more drag for the stationary propeller of length 14 cm but this ratio decreases with length unlike the pitch 3 propeller. It appears that the ratio is one around 11 cm.

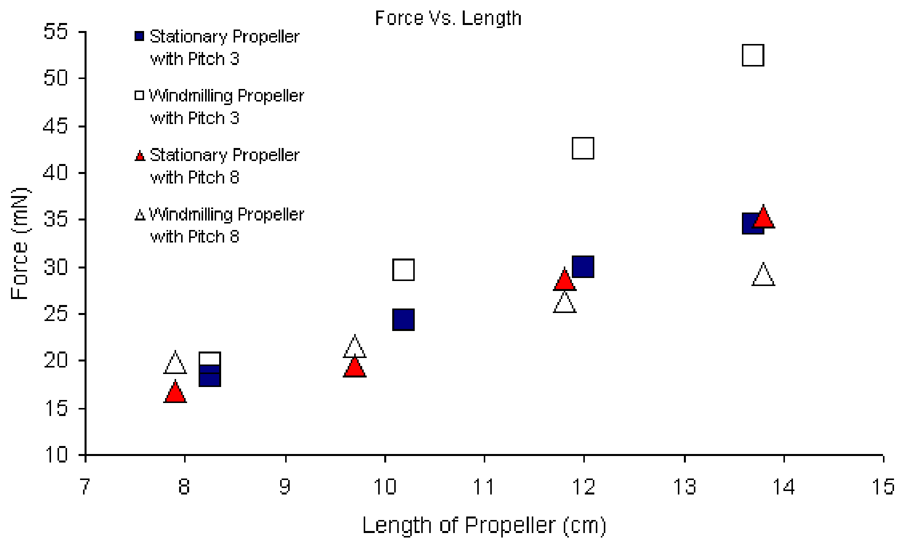

Figure (15): The drag force increases with length for both stationary and windmilling propellers. It is not possible to determine whether the increase is linear or quadratic.

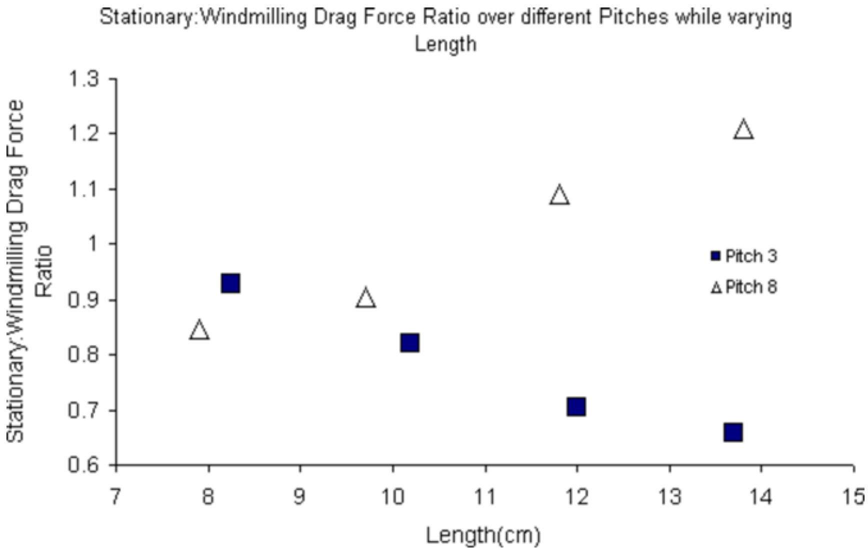

Figure (16): For a pitch 3 propeller as the length increases the ratio of stationary to windmilling drag increases but for a propeller with pitch 8 it is the other way around. This change in the ratio for both propellers suggests that the crossover point is also dependent on length.

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4. Conclusions:

From the experimental results reported here we can conclude what we could have figured out with a little thought: drag force increases with length and wind velocity, and decreases with pitch. What is less clear is *how* the drag force increases and decreases with these variables. Does it increase linearly or quadradically with length and wind velocity? When considering the pitch, does the windmilling drag force also follow a cosine-squared curve? More accurate data are needed to determine the characteristics of the crossover point. *Does* it depend on wind velocity? Arguments both for and against rely on data that could be drastically changed if just a couple of data points were moved. Further work in this topic should begin either with an increase in the range of the variables, or increasing the precision of the data. Improving either one of these will help answer *all* of the questions posed above.

The main goal of this investigation was simply to determine whether a stationary or a windmilling propeller has more drag. The answer is complicatedly simple: it depends. It is clear that it depends on the pitch and length of the propeller, and it is probably independent of the wind velocity. A crossover point was discovered where the drag forces for the windmilling and stationary states were the same. This crossover point is also dependent on the pitch, the length, and probably independent of the wind velocity.

Acknowledgements:

I want to thank Professors Carl S. Helrich and John Ross Buschert of Goshen College for all of their help. They helped in some way with every single aspect of this investigation. I would also like to thank Adam Scharf for getting me excited about this topic and then graciously graduating early so I could have the investigation all to myself.

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[1] One of my editors read an article in RPM magazine that said that model airplane propeller manufacturers sometimes fudge the pitch of the propellers. Apparently, a typical buyer, if having to choose between propellers of the same pitch, would rather buy a propeller with a higher R.P.M. But that buyer would compensate some R.P.M. for an increase in pitch. So the manufacturers will fudge the pitch and claim that it is higher than it really is in order to attract customers.