Title

The effect of the number of blades on a propeller on the force generated by the propeller.

Word Count: 2996

Introduction

Propellers are relevant in today's society as they are used in aeronautics and the development of model aircraft. Aeroplanes and other aircraft are used for cargo transportation, public transportation and other varieties of transportation. Propellers as a propulsion system in aeroplanes are commonly thought to be outdated because of the employment of newer jet engines on various vehicles. However there is still a market for propeller planes as they are used in slower long distance cargo planes such as the Antonov AN-22 plane.

Apart from large scale vehicles, propellers are also used in model aircraft. These are the most applicable use cases for this experiment as there is a direct correlation between the experiment and the building and design process of a model aircraft. This is because propellers more often than not are used in model aircraft because they are more energy efficient at lower speeds as well as cheaper than other alternatives such as EDFs. Model aircraft also use similar sized propellers as the ones used in the experiment. When designing model aircrafts the propellers are chosen based on the characteristics of the components as well as the purpose of the aircraft. This real world application led to the research question: Will an increase in the amount of propellers lead to an increase in force generated by a propeller system?

Research Question

Will an increase in the amount of propellers lead to an increase in force generated by a propeller system?

Background science:

The basis of the propulsion system is to use the force generated by the displacement of the fluid to move the vehicle. Generally the more fluid displaced the more force generated which can lead to a faster speed, a further range or a higher load capacity. So the amount of fluid displaced has to be maximised in accordance to the force exerted by the motor to achieve an engineer's goal. Now there are various ways to displace fluids shown in vehicles such as fighter jets, cargo planes, boats and even hovercrafts.

Theory

When an airfoil moves through air a force is generated at either side of the airfoil due to a difference in pressure. Hence, a propeller made up of airfoils that is rotating at high speeds leads to a large volume of air being displaced. Through the use of airfoil[2] theory it is know that a spinning propeller displacing a large volume of air, creates an area of pressure lower than the free stream (free stream is the air that has not interacted with the propulsion system yet) in front of the propeller and an area of pressure higher than the freestream behind the propeller. This leads to a force being generated propelling the propulsion system in the direction of lower pressure; this force generated is denoted as thrust, F.

The basis of the calculation of thrust can be derived from the fundamental equation,

$$F = ma \tag{1}$$

Where $F = Force\ (N)$, $m = mass(g)$ and $a = acceleration\ (m/s^2)$.

This has to be altered to apply to the context of fluid motion in air so the force generated by the propeller can be theoretically calculated.

$$m = mass\ flow\ rate\ (g/s) = \dot{m} \tag{2}$$

It is known that acceleration is the rate of change in velocity,

$$v = u + at$$

Where $v = final\ velocity\ (m/s)$, $u = initial\ velocity\ (m/s)$, $a = acceleration\ (m/s^2)$ and $t = time(mins)$.

Therefore,

$$\frac{v-u}{t} = a \tag{3}$$

But time is constant in this application, so when the variables are substituted into equation 1 the basic thrust equation[1] is given,

$$F = (\dot{m} \times Ve) - (\dot{m} \times V0)$$
$$F = \dot{m}(Ve - v0) \tag{4}$$

Where, $Ve = exit\ velocity\ of\ air$ (m/s) and $V0 = free\ stream\ velocity$ (m/s)

But the mass flow rate can be broken down further into,

$$\dot{m} = r \times Vp \times A \tag{5}$$

Where $A = swept\ area\ (Area\ of\ air\ that\ interacts\ with\ the\ propeller)$, $r = density(kg/m^3)$ $V_p = velocity\ (m/s)$.

$$Vp = velocity = \frac{1}{2}(Ve + V0) \tag{6}$$

Hence,

$$F = r \times Vp \times A \times (Ve - V0) \tag{7}$$

Then the Bernoulli's equation is used which equates pressure and velocity[2] to derive the equation,

$$\Delta p = \frac{1}{2} \times r \times (Ve^2 - V0^2) \tag{8}$$

The force on the propeller with relation to pressure is,

$$F = \Delta p \times A \tag{9}$$

Through the substitution of Bernoulli's equation into the simple momentum theory[2]:

$$F = \frac{1}{2}\ r\ \times A \times (Ve^2 - V0^2) \tag{10}$$

The simple momentum theory would only be used in the preliminary design of a propeller because it does not account for the many losses that occur, this is evident through the use of swept area rather than total blade area which would require more complex geometrical calculation which would be too complex to calculate by hand. Therefore the results of this calculation is an ideal number that is an overestimate of the actual number. However it can still be used to get a general relationship between the basic components of a propeller.

<u>Hypothesis</u>

Based on the equation:

$$F = \frac{1}{2} \times r \times A \times (Ve^2 - V0^2)$$

It is reasonable to assume that an increase in area will lead to an increase in the force generated. This is because assuming all other factors are constant an increase in area will lead to a larger volume of air being moved as the mass aspect of F=ma increases. Leading to a larger force being generated. So with the essay investigation, investigating the effect of the number of blades on the force generated, the hypothesis is that as the number of blades on the propeller increase the amount of force generated will increase up until a certain point; where other factors will come into play such as the strength of the material and the design of propeller. But most importantly the torque of the motor which would most likely be the limiting factor of the propulsion system.

So the hypothesis is that

$$F \propto A$$

Up until a certain point as based on fluid behaviours the graph should increase until a peak after which it will then start to decrease. This is because as the number of blades increases the amount of drag also increases[9] as there will be more turbulence.

Methodology

Preliminary experiment

With an investigation of this nature a preliminary experiment was done to ensure that a force was produced and that different forces were produced for the different amounts of blades used. Initially a motor was used and the motor was powered via a 9v battery. Through the experiment it was made apparent that the motor was not powerful enough so the experiment motor was changed to a motor with gears that would provide enough torque to turn the turbines quick enough to generate a force. To power the new motor the prior 9v battery could not be used, so a power pack was used instead. Another fatal flaw of the experiment is the fact that the motor was moving around a lot creating large vibrations. This led to highly unreliable results as the mass could not be measured effectively. This was solved through the use of plasticine. The motor was attached to the mass balance through the use of plasticine as seen in figure 2. The use of plasticine decreased the large movements leading to more tangible results because the plasticine acted as a dampener for the motor.

Variables

Independent Variable

The independent variable in this experiment is the number of blades ranging from 1 blade to 6 blades.

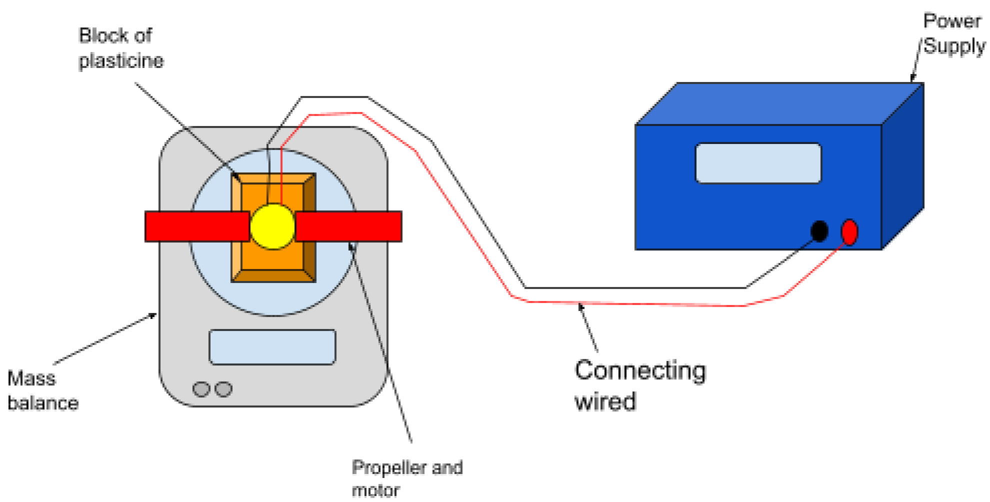
Dependent variable

The dependent variable in this experiment is the force generated measured via a change in mass of a mass balance (g).

Control variables

Control	Reasoning and Solution
Blade pitch	The blade pitch affects the amount of air that the propellers interact with, which would in turn affect the value for the force given. To combat this the blade pitch is kept at 30^{o} through the use of a protractor throughout the experiment as blade pitch affects force generated.
Individual Propeller blade area	An increased area is what is being measured so it has to be accurate which is why Individual propeller blades were kept approximately the same so that the change in the surface area when changing the independent variable is kept the same.
Voltage	The voltage going to the motor must be kept the same because a change in voltage would lead to a change in rpm and torque subsequently affecting the force generated.

Figure 1 - Improved setup



Risk assessment

Risk	Cause	Solution
Cut	The first moving blade can lead to cuts if the user touches them because they are fast moving and sharp	Keep out of the way of the blades when the fan is moving.
Burns	When the motor is left on for prolonged stretches of time it heats up	Not leaving the motor on for too long and letting it cool down after.

There are no ethical or environmental implications from this experiment.

Method

Initially, whilst the power supply is off, the power supply is connected to the motor using connecting wires. The modular hub is then pushed on to the shaft of the motor. After this the required amount of blades is connected to the hub (Starting with the configuration with the least amount of blades) and the blades are tilted at 30^{o} to the same direction. The mass balance is then turned on and zeroed. Then the motor is placed on the mass balance and the base of the motor is surrounded by plasticine and the plasticine is molded to the pan of the mass balance and the motor. The mass shown is then recorded as the starting mass. The power supply is then turned on at the correct voltage for the motor, once the motor has started to spin at what appears to be a constant speed then the mass displayed on the mass balance is then recorded every 10 seconds, in a 30 second interval as your final masses. Then the power supply is turned off allowing for the next configuration of blades to be added and the motor to cool down.

Raw data

Table 1 – The raw data from all the propeller systems

Number of blades	Mass $\pm\ 0.01$/ grams						Average results of mass / grams		Error in mass g
	Trial 1		Trial 2		Trial 3				
	Starting mass	Final mass	Starting mass	Final mass	Starting mass	Final mass	Starting mass	Final mass	
1	284.85	271.80	284.85	271.60	284.85	271.30	284.85	271.57	0.25
2	287.24	272.30	287.24	272.90	287.24	272.70	287.24	272.63	0.30
3	289.91	274.10	289.91	274.70	289.91	274.60	289.91	274.47	0.30
4	292.53	276.30	292.53	276.80	292.53	276.80	292.53	276.63	0.25
5	295.62	280.40	295.62	280.60	295.62	280.60	295.62	280.60	0.10
6	299.14	284.50	299.14	284.40	299.14	284.90	299.14	284.60	0.25

The largest value for 2 blades on the propeller is 272.9g the smallest is 272.3g so the difference is 0.6 g when divided by 2 this gives an uncertainty of 0.3g . The data processing was done by subtracting the final mass from the starting mass. With a 2 bladed propeller that would be $287.24 - 272.63 = 14.61g$. To convert this to a force the value was then divided by 100 converting the value from grams to newtons.

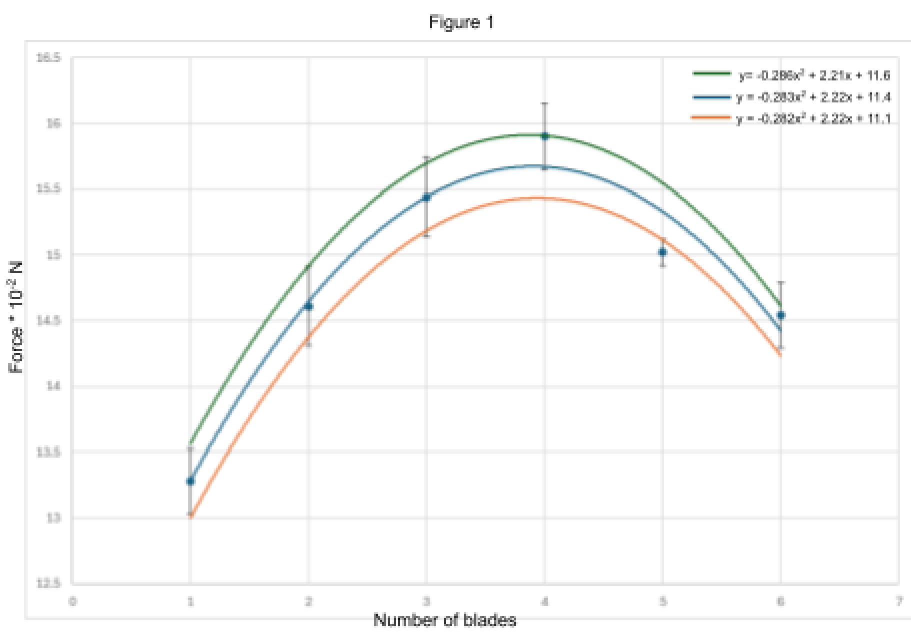
Processed data

Table 2 – Processed data for all propulsion systems

Number of blades	Difference between final mass and starting mass $\pm\ 0.01$/g	Force $\pm\ 0.0001$/N	Error in Force
1	13.28	0.1328	0.0025
2	14.61	0.1461	0.0030
3	15.44	0.1544	0.0030
4	15.90	0.1590	0.0025
5	15.02	0.1502	0.0010
6	14.54	0.1454	0.0025

Graph

Graph 1 – The Graph for the processed table with difference in mass on the y-axis and number of blade on the x-axis



Conclusion

The equation of the line of best fit is a negative quadratic:

$$-(0.28 \pm 0.0018)N^2 + (2.21 \mp 0.0061)N + (11.4 \pm 0.29) = T.$$

This corroborates the previous statement that the force generated by the propeller should increase up until a peak after which it will decrease. This is expected because as the surface area increases the mass flow rate [3] of the air moving increases. This leads to an increased force generated but a higher resistance as the more blades the more turbulence. A higher force will only be generated if the drag generated by the increase in surface area is able to be overcome by the force generated as a result of the increased area. But after a certain point, depending on various variables such as RPM and torque, the drag from the surface area overcomes the motor and does not increase the force. This causes the force generated by the propeller to decrease. Which leads to the shape of a negative quadratic. The highest point on the graph was when 4 propellers were used. 4 propellers generated 0.159 newtons of force. This means that the most efficient propeller system at generating an upwards force with this particular system is the 4 bladed propeller system.

Evaluation

This experiment gave the expected results based on similar experiments such as the effect of a change in propeller pitch[4]. This experiment had a different independent variable but the trend line generated would be similar[5]. This validates the experiment as it provided a template to cross reference the results obtained with. It also corresponds with the design of optimum propellers[9] which displays the effect of the number of blades as a negative quadratic. However, that being said, although the trend that was observed for this experiment was accurate the values however were not. As each propeller used had dimensions of approximately 10 cm by 4 cm the force generated was expected to be higher because of the large surface area of the blades. As using formula (10) the force generated for the 2 bladed propeller for example is meant to be:

$$F = \frac{1}{2} * d * A * (Ve^2 - V0^2) \tag{10}$$

$$F = \frac{1}{2} * 1.204 * 0.08 * (6.8^2 - 5.1^2)$$

$$F = 0.97N$$

Based on the average air density at sea level being 1.204 kg/m^3 and the air speed observed with an anemometer for the 2 bladed propeller being 6.8m/s→5.1m/s the theoretical possible force that could be generated from the 2 bladed system was 0.97N. This however was not the case and the force actually generated was 0.1461 which is 85% less this could be because of many individual factors that combined to have a large effect on the accuracy of the experiment.

Such factors are:

- The modular design of the propulsion system:

  The modular design of the experiment led to many limitations for the experiment. Such as the amount of blades that could be used in it. This is because the hub had predesignated spokes that the propeller blades would be attached to. This limited the amount of data that could be collected which could have led to a less accurate equation for the line of best fit even though the general shape was still accurate. This design did not also allow for equal spacing of the propeller blades for some configurations of the propeller system. The uneven spacing could have affected the results as it will lead to uneven pressure zones between propellers. If this non-uniformity is large enough it could have led to inaccurate data. The metal spokes on the hub could have also interfered with the experiment by creating more drag with little to no lift generated. This could be fixed with more specialised equipment made specifically for this experiment with individual propeller systems with different blades made.

- The method of propeller attachment:

  As the propellers were made of twin walled plastic sheets the propellers could be attached to the hub by pressing the steel spokes through one of the holes on the sheet. This creates a frictional force on the spoke which will combat the outwards force from the high angular velocity. However this limits the RPM of the motor that could be used without the propeller slipping from the spoke. This limits the amount of force that can be generated because of the low RPM. As well as possibly distorting the results as the propeller tilt might deviate from the 30^{o} as the air pressure on the propeller might rotate it. This could be fixed by making the propeller configurations out of a single piece of material. Preventing it from being able to turn keeping the angle constant.

- The hub to shaft attachment:

The hub was also attached to the shaft through the use of friction. However, The material that the hub was made of was less elastic than the material the propeller was made of as the hub was made of hard plastic. This led to a low frictional force being exerted on the shaft by the hub, allowing for the hub to shift during the experiment. This also means that the hub and propeller system were moving at a slower speed than the shaft because of slippage from a low frictional force between the hub and shaft. This would be fixed by using a more elastic material for the hub with a smaller hole as when the prongs are pushed in it would create a larger frictional force preventing the prongs from slipping.

- The gear alignment and material in the gearbox of the motor:

  The gears were poorly aligned and made of weak 3d-printing material. This means that overtime the gears would get worn out. This paired with the poor alignment means that the full force of the motor could not be fully transmitted through the gear box. This means that propeller systems that required a higher torque could not fully function at its full capacity because of the gears not transferring the force efficiently. A more durable metal gear box would have been better at maintaining the torque as it would have transmitted it more efficiently.

These issues individually might not have had as large of an effect on the value but combined they amplified each other leading to the value that was given in table 2. This would be solved by whole propeller configurations being 3d printed. This would guarantee that the blade pitch stays the same. It would allow for the motor to go to a higher RPM. It would not have spokes sticking out consistently creating drag. It could also be 3d printed with a material that was marginally more elastic that the previous hub. Which would allow for a more secure attachment to the shaft. This change would increase the validity of the experiment.bAs well as this if the gearbox was made of a more sturdy and durable material and used a different form of gears that would have a lower chance of slippage such as a herringbone gear; then the experiment might have a more accurate reading when compared to the theoretical value.

However the issue with comparing this experiment with the theoretical value is the limitation of the equation used to calculate the potential force. The equation is simplified by removing certain variables such as the propeller pitch and blade area. These variables are crucial [7] but are consistent within this experiment so most likely would not have altered the conclusion of 4 blades being the best choice for this configuration.

Extension

This experiment could lead to many more different experiments because of the sheer amount of variables that are at play. Such experiments could be “The best pitch for blade configurations of different amounts of blades”. This would be an insightful experiment as it is one of the variables that were kept constant throughout the experiment. This would allow for the effect of the blade pitch to be seen and used to see if the uncertainty in blade pitch[8] might have made a difference to this experiment.

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