A practical investigation of the factors affecting lift produced by multi-rotor aircraft

Aaron Bonnell-Kangas

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Introduction

Research question

What factors affect the lift generated by a multi-bladed rotary-wing aircraft?

Background

<blurb about importance and newness of multi-rotors>

Definitions

In the investigation of this question, some background information is useful:

Lift, in this investigation, is the static pressure that the aircraft generates on the ground, measured in millimeters of water. All of the craft tested generate this lift by employing rotating airfoils. When a flow of air exists over these airfoils, they generate a high-pressure zone below them and a low-pressure zone above them. While a full investigation of the properties of airfoils is outside the scope and means of this investigation, a few properties are considered to be established:

Pitch, in a propeller or airscrew, is the forward distance that a theoretical rotor blade would travel in one rotation. A propeller with a 10 cm pitch would move an aircraft forward 10 cm every time it completed a rotation. Other factors affect rotor blades, so theoretical pitch is never achieved.

Feathering, in a fully articulated rotor system, is the ability of a rotor blade to rotate on its longitudinal axis in order to alter its angle of attack.

Flapping, in a fully articulated rotor system, is the ability of a rotor blade to move up and down in the vertical plane, independent of other rotor blades or the aircraft.

Leading and **lagging**, in a fully articulated rotor system, refer to the ability of a blade to alter its angle relative to the other blades and the aircraft.

A **stall**, in an airfoil, is a condition where the airfoil generates drastically reduced lift or no lift at all, despite having air passing over it. Stalls occur when laminar flow over the top surface of an airfoil is interrupted.[1] Some conditions that might induce a stall include insufficient rotor speed and excessive angle of attack.

In most full-scale modern helicopters, one large main rotor is used to generate lift. Because of the torque required to turn the main rotor blades of the helicopter, another, smaller rotor is installed on the tail of the aircraft in order to counteract the tendency of the craft to yaw. This smaller rotor will be referred to as a **counter-torque rotor**, and these aircraft **single-rotor** helicopters. Single-rotor helicopters achieve directional thrust and aircraft control by altering the lift generated by each rotor blade in sequence as it passes by a specific point around the aircraft. For example, in order to roll the helicopter left, a pilot would command each rotor blade to increase its angle of attack as it passes the rightmost point in its rotation, and decrease its angle of attack as it passes the leftmost point in its rotation, thereby creating more lift on the right side of the craft and rolling it left. This is known as cyclic thrust control.

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[1] FAA Aircraft Handbook, page 4-3

Multi-rotor rotary-wing aircraft, in general, use more than one set of rotor blades to generate lift. Usually, these rotor blades are installed in pairs, so that the torque of one set of rotor blades acts to cancel out the torque generated by another. When a multi-rotor helicopter has two sets of blades, sharing an axis of rotation, they will be referred to as **coaxial** helicopters. Coaxial helicopters achieve control by the same cyclic pitch control used in single-rotor helicopters.

When a multi-rotor helicopter uses four sets of rotor blades for lift, with one rotor blade at each vertice of an imaginary square in the horizontal plane (figure 1-1), it will be referred to as a **quadrocopter** or a **quad-rotor**. While quadrocopters might be able to achieve control using multiple cyclic pitch-control systems, most quadrocopters use thrust vectoring instead. In order to roll left, as the single-rotor craft above, a quadrocopter would increase the rotational speed of its right rotor disc and decrease the rotational speed of its left rotor disc, therefore creating a difference in lift and rolling left. Note that all control in a quadrocopter—both lift and directional thrust—is achieved by varying the speed of the rotor discs individually. In cyclic pitch-control systems, additional servos and/or linkages are required to control the blades.

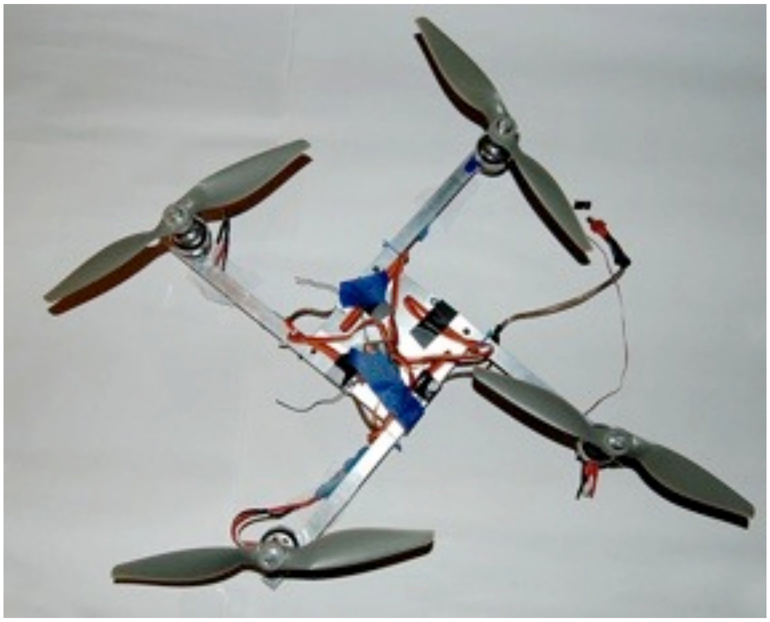

Figure 1-1: Quadrocopter

Procedure

Overview

Full-size rotary-wing aircraft are expensive to purchase and maintain, making an investigation of a full-scale aircraft impractical at this level. For that reason, the investigation uses scale model aircraft and airframes.

Testing is performed in a controlled environment: a Lexan container measuring approximately 60 cm x 60 cm x 30 cm. The craft were mounted to a Lexan substrate, in which holes were drilled along the radius of the rotor disc of each craft. These holes were used to measure the static pressure generated by the craft. (Figure 2-1)

Because many of the defining theories of helicopter aerodynamics have already been established, and because this investigation focuses on applications in multi-rotor aircraft, an experimental approach was selected that emphasized the differences between single- and multi-rotor craft. The following craft were tested:

	Type	Rotor disc area[1]	Lift-producing rotor discs	Total lift-producing rotor disc area	Rotor blade pitch [2]
Single-rotor 1	Single-rotor	2081.142 cm^2	1	2081.142 cm^2	
Coaxial 1	Coaxial	984.291 cm^2	2	1968.582 cm^2	
Quadrocopter 1	Quad-rotor	506.707 cm^2	2	1013.414 cm^2	15.24 cm
Single-rotor 2	Single-rotor	2081.142 cm^2	1	2081.142 cm^2	
Quadrocopter 2	Quad-rotor	324.293 cm^2	4	1297.172 cm^2	11.43 cm

Table 2-1: Blade Areas And Pitches

For all craft, the following measurements were taken:
- revolutions per minute (RPM) of the rotor disc(s)
- voltage of power source during testing
- current draw (A) of craft during testing
- static pressure (cm. H_2O)

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[2] Link to measurement procedures in some appendix

[3] Dude who told me I could assume things

The experimental procedure was as follows:

Single-rotor

1. A Hall effect sensor was permanently installed onto the frame of the craft in order to measure the RPM of the rotor disc. Magnets were installed onto the craft to activate the Hall effect sensors. Two magnets were installed on the bottom face of the main gear, which is directly attached to the rotor blades, in order to measure rotor RPM. (Figure 2-2)
2. The main rotor blades were balanced to minimize vibrations from rotor blade inertia. In order to balance the blades, each blade was weighed on a triple-beam balance. Clear, thin packing tape was applied to the lighter blade over the blade's center of gravity.
3. The lead-lag hinges were tensioned by tightening or loosening the bolts that attach the blades to the blade grips. To achieve this, the lead-lag hinge bolts were tightened until the blades would remain parallel to the ground when the craft was held sideways. The hinges were then loosened until a slight tap would cause the blades to angle towards the ground while the craft was held sideways.
4. The data logger was connected to the monitoring computer with its USB cable.
5. The craft was placed into the testing box diagonally, as shown in figure figure. Clear packing tape was used to hold the craft to the floor of the testing box: one 8" piece of packing tape was placed across each landing skid. A narrower 8" strip of clear packing tape was placed through the lower opening in the vertical stabilizer to secure the tail boom. (Figure 2-3)
6. The Hall effect sensor was connected to the data logger in the appropriate port.
7. The data logging software was launched on the monitoring computer and "Live mode" was enabled, with the option to save recorded data enabled.
8. The hose leading to the static pressure measuring tool was inserted into the static pressure measurement point in the floor

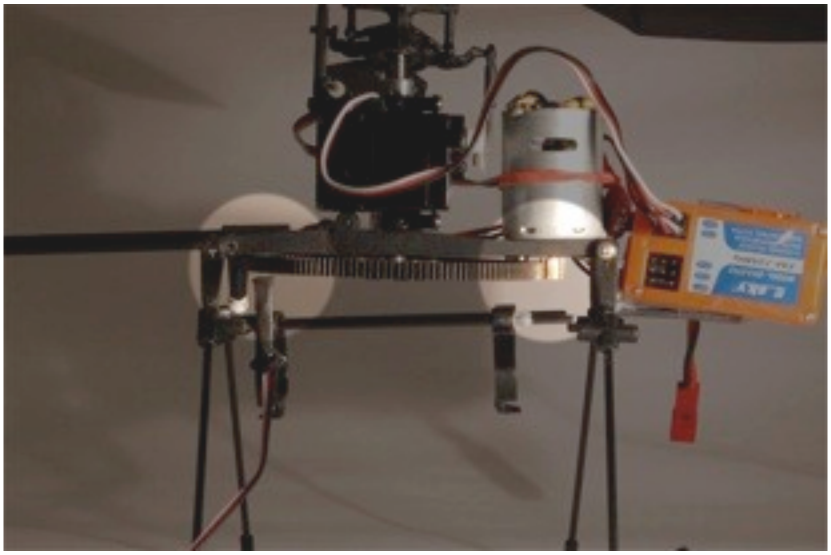

Figure 2-2: Placement of main gear magnets

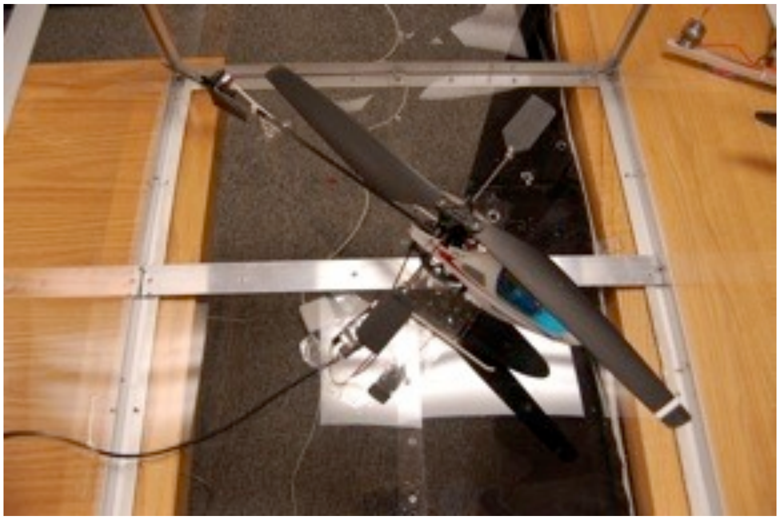

Figure 2-3: Placement of single-rotor craft

of the testing box marked "100% FP". Other measurement points marked “FP” were plugged from the bottom of the enclosure.. All other static pressure measurement points were plugged from the inside of the testing box.

9. Power to the radio transmitter was turned on, and the throttle stick was moved to the 0% position.
10. Power from the power supply was connected to the data logger, and nominal voltage was verified on the monitoring computer (between 8 and 11 volts). The craft's power supply cable was then connected to the port marked "TO ESC" on the data logger.
11. The throttle stick on the radio transmitter was moved to the 100% position over the course of about ten seconds.
12. Static pressure was recorded at the measurement point marked "100% FP" after the craft had been at 100% throttle for about 15 seconds.
13. The measurement tube was removed from the measurement point marked "100% FP". The measurement point marked "75% FP" was unplugged, and its plug was inserted into the measurement point marked "100% FP". The measurement tube was inserted into the measurement point marked "75% FP".
14. Static pressure was recorded after the measurement tube had been installed for 15 seconds.
15. The measurement tube was inserted into the measurement point marked "25% FP", and the previous measurement point was plugged, as before.
16. Static pressure was recorded after the measurement tube had been installed for 15 seconds.
17. The throttle stick on the radio transmitter was moved to the 0% position. Power was removed from the craft after the blades had come to a complete stop.

Single-rotor, with tightened lead-lag hinges

In order to test the effect of lead-lag hinge stiffness, this procedure was repeated, but with step (3) replaced with the following:

3. The lead-lag hinge bolts were tightened until they could no longer be easily tightened by hand.

Coaxial

1. A Hall effect sensor was permanently installed onto the frame of the craft in order to measure the RPM of the rotor disc. Magnets were installed onto the craft to activate the Hall effect sensors. One magnet were installed on the bottom face of the lower main gear, which is directly attached to the lower rotor blades, in order to measure rotor RPM. (Figure 2-4)
2. The main rotor blades were balanced to minimize vibrations from rotor blade inertia. In order to balance the blades, each blade was weighed on a triple-beam balance. Clear, thin packing tape was applied to the lighter blade over the blade's center of gravity.
3. The lead-lag hinges were tensioned by tightening or loosening the bolts that attach the blades to the blade grips. To

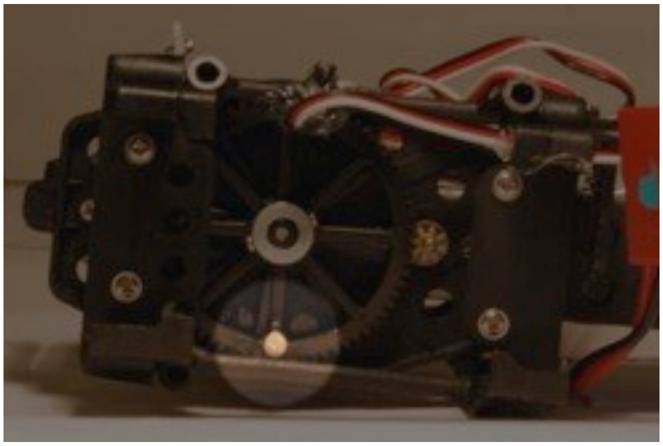

Figure 2-4: Magnet placement

achieve this, the lead-lag hinge bolts were tightened until the blades would remain parallel to the ground when the craft was held sideways. The hinges were then loosened until a slight tap would cause the blades to angle towards the ground while the craft was held sideways.

4. On the coaxial helicopter, the landing skids are friction-fit and therefore unable to withstand the forces of testing while the craft is held to the ground. To strengthen the skids, cyanoacrylate glue was added to the four sockets on the battery tray where the skids fit into the main frame. (Figure 2-5)
5. The data logger was connected to the monitoring computer with its USB cable.
6. The craft was placed in the center of the testing box. Clear packing tape was used to hold the craft to the floor of the testing box. One 8" strip of clear packing tape was placed across each landing skid to hold it to the floor of the testing box. (Figure 2-6)
7. The Hall effect sensor was connected to the data logger in the appropriate port.
8. The data logging software was launched on the monitoring computer and "Live mode" was enabled, with the option to save recorded data enabled.
9. The hose leading to the static pressure measuring tool was inserted into the static pressure measurement point in the floor of the testing box marked "100% LAMA". Other measurement points marked “LAMA” were plugged from the bottom of the enclosure.. All other static pressure measurement points were plugged from the inside of the testing box.

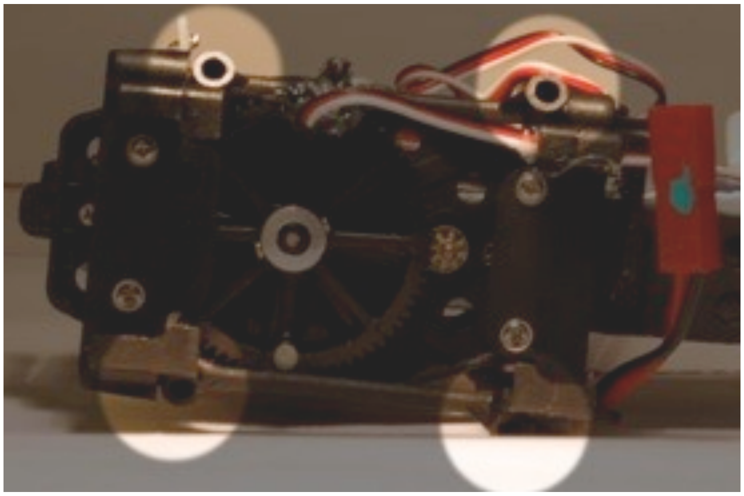

Figure 2-5: Skid reinforcement locations

Figure 2-6: Coaxial craft placement

10. Power to the radio transmitter was turned on, and the throttle stick was moved to the 0% position.
11. Power from the power supply was connected to the data logger, and nominal voltage was verified on the monitoring computer (between 8 and 11 volts). The craft's power supply cable was then connected to the port marked "TO ESC" on the data logger.
12. The throttle stick on the radio transmitter was moved to the 100% position over the course of about ten seconds.

13. Static pressure was recorded at the measurement point marked "100% LAMA" after the craft had been at 100% throttle for about 15 seconds.
14. The measurement tube was removed from the measurement point marked "100% LAMA". The measurement point marked "75% LAMA" was unplugged, and its plug was inserted into the measurement point marked "100% LAMA". The measurement tube was inserted into the measurement point marked "75% LAMA".
15. Static pressure was recorded after the measurement tube had been installed for 15 seconds.
16. The measurement tube was inserted into the measurement point marked "25% LAMA", and the previous measurement point was plugged, as before.
17. Static pressure was recorded after the measurement tube had been installed for 15 seconds.
18. The throttle stick on the radio transmitter was moved to the 0% position. Power was removed from the craft after the blades had come to a complete stop.

Quadrocopter

1. Two magnets were placed on one of the brushless motors on opposite sides of the motor housing. The Hall effect sensor was installed on the frame vertically. (Figure 2-7)
2. The data logger was connected to the monitoring computer with its USB cable.
3. The craft was placed in the center of the testing box, rotated so that its propellers would clear the walls of the testing box. It was secured to the floor of the testing box with clear tape by placing two 12" strips of clear packing tape across each arm of the main frame.
4. The Hall effect sensor was connected to the data logger in the appropriate port.

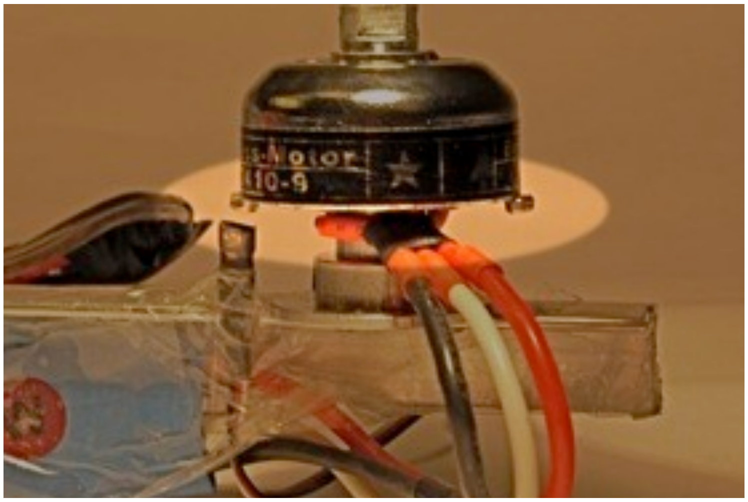

Figure 2-7: Quad-rotor magnet placement

5. The data logging software was launched on the monitoring computer and "Live mode" was enabled, with the option to save recorded data enabled.
6. The hose leading to the static pressure measuring tool was inserted into the static pressure measurement point in the floor of the testing box marked "100% QUAD". Other measurement points marked “QUAD” were plugged from the bottom of the enclosure. All other static pressure measurement points were plugged from the inside of the testing box.
7. Power to the radio transmitter was turned on, and the throttle stick was moved to the 0% position.
8. Power from the power supply was connected to the data logger, and nominal voltage was verified on the monitoring computer (between 8 and 11 volts). The craft's power supply cable was then connected to the port marked "TO ESC" on the data logger.
9. The throttle stick on the radio transmitter was moved to the 100% position over the course of about ten seconds.

10. Static pressure was recorded at the measurement point marked "100% QUAD" after the craft had been at 100% throttle for about 15 seconds.
11. The measurement tube was removed from the measurement point marked "100% QUAD". The measurement point marked "50% QUAD" was unplugged, and its plug was inserted into the measurement point marked "100% QUAD". The measurement tube was inserted into the measurement point marked "50% QUAD".
12. Static pressure was recorded after the measurement tube had been installed for 15 seconds.
13. The throttle stick on the radio transmitter was moved to the 0% position. Power was removed from the craft after the blades had come to a complete stop.

Quadrocopter, with 8x6 GWS props

The procedures for “Quadrocopter” were repeated, but the craft was fitted with four 8x6 GWS props, as described in Table 1-1: “Quadrocopter 2”.

Results

Data

Trial	RPM	Pressure (25%)	Pressure (50%)	Pressure (75%)	Pressure (tip)
Single-rotor 1	1050	0.033		0.050	0.055
Coaxial 1	1200	0.077		0.095	0.091
Quad-rotor 1	4100		0.400		0.260
Single-rotor 2	1400				0.043
Quad-rotor 2	1450		0.055		0.002
Quad-rotor 3	3500		0.130		0.020

Table 3-1: Data Collected

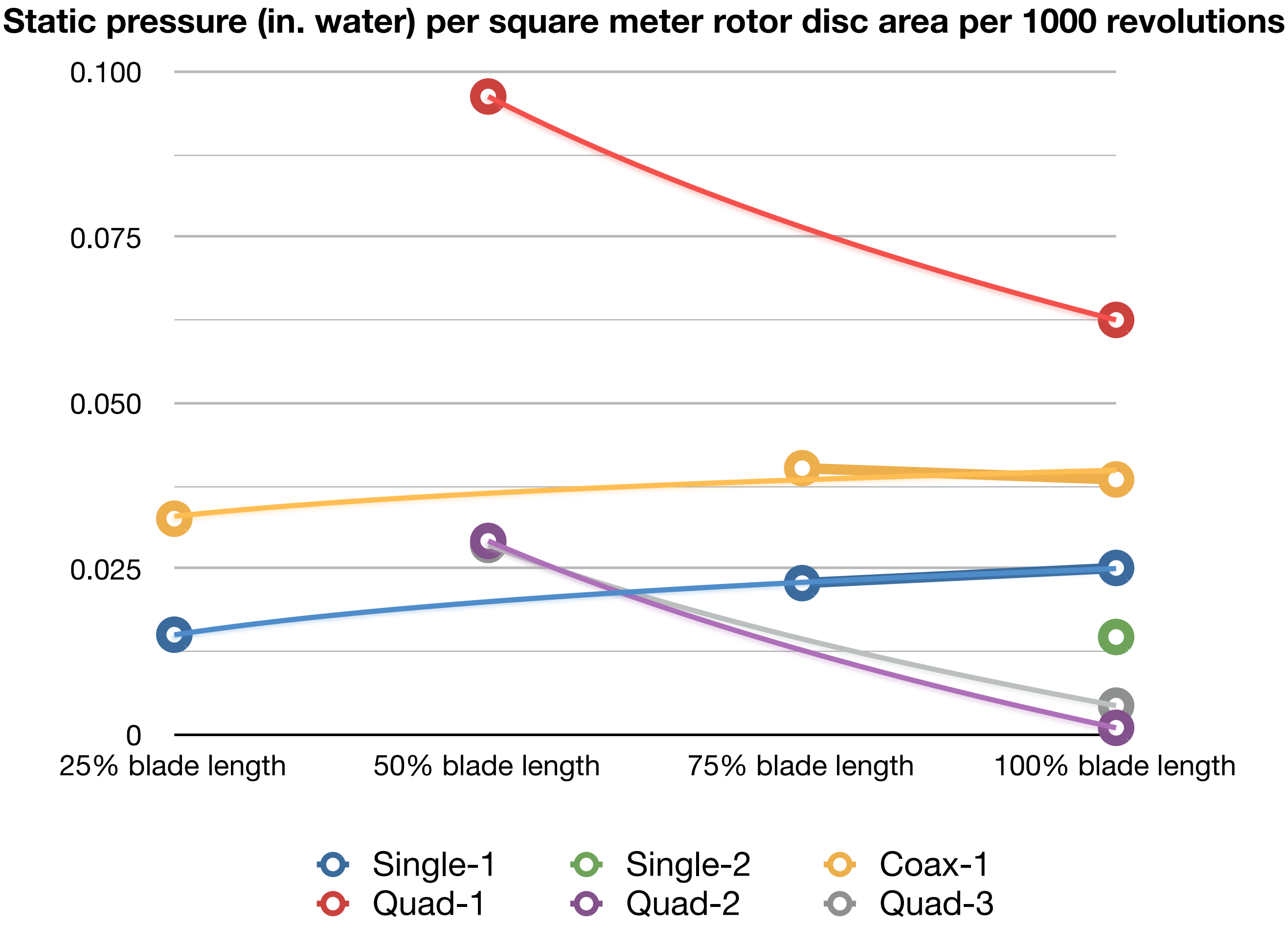

Chart 3-1: Blade Lift Profiles

Notes:
- During the trial “Single-rotor 2”, the lead-lag bolts were tightened as described in the section “Single-rotor, with tightened lead-lag hinges”. Only the 100% measurement was taken.
- During the trial “Quad-rotor 1”, only two blades, described in Table 2-1: “Quadrocopter 1” were installed on the craft.
- During the trial “Quad-rotor 2”, four blades, described in Table 2-1: “Quadrocopter 2” were installed on the craft. The throttle was not advanced to 100% during testing because of concerns that oscillatory forces would damage the airframe. Near the end of testing, one of the propeller mounts failed, sending the attached propeller into a safety shield. Extreme caution should be used during testing of propellers at high speeds.
- The “100%” hole used in trials “Quad-rotor 2” and “Quad-rotor 3” was the same hole used in “Quad-rotor 1”, although the props used in “Quad-rotor 1” were longer. The “100%” data point for trials 2 and 3 may be lower than actual.

Analysis

A few obvious trends are present in the data:

- Although the single-rotor helicopter was rotating at a higher RPM during the trial “Single-rotor 2” than during “Single-rotor 1”, it generated less lift (0.148 in. H_2O/cm^2 rotor disc area/ revolution vs. 0.252 in. H_2O/cm^2 rotor disc area/revolution)
- The more aggressively-pitched propellers tested in “Quad 2” and “Quad 3” generated less lift, at lower RPMs, than their more gently-pitched counterpart in “Quad 1”.
- The blades designed to be used in cyclic pitch-control helicopters had more steady pressure generation along their length, while the propellers generated much more lift at their center than at their tip.
- The coaxial helicopter generated slightly more lift than the single-rotor, but with a similar lift profile along the blade

Conclusions

Rotary-wing aircraft have widely varying requirements for their airfoils and rotational speeds. Quad-rotor aircraft, for example, require relatively short, low-inertia propellers, because they need to be able to quickly vary the lift provided from each propeller. This imposes two requirements on propellers for quad-rotor aircraft:

- they must have a high pitch in order to generate the necessary lift
- they must rotate faster than the rotors of single-rotor aircraft, for the same reason

In the experimentation performed, it was clear that these higher-pitched props had a *much higher optimal rotational speed* than their finely-pitched counterparts.

Lead-lag hinges are necessary in single-rotor helicopters with fully-articulated rotor hubs because of the issue of dissymmetry of lift. When a single-rotor helicopter enters forward flight, airflow (and thus lift) over the advancing blade increases, as airflow over the retreating blade decreases. Lead-lag hinges help to mitigate this issue by allowing rotor blades to move back and forth in the horizontal plane.[4]

In the experimentation performed, it was observed that to interfere with this natural pattern of leading and lagging (by over-tightening the lead-lag hinges) reduces rotor efficiency, possibly by introducing excessive stresses onto the rotor hub.

Normally, propellers decrease in efficiency as the number of blades increases, due to increased tip-vortex losses.[5] When one contra-rotating propeller is placed directly behind another, however, efficiency can *increase* because the second propeller neutralizes the rotating flow produced by the first.[6]

In the experimentation performed, this was observed: the blades of the coaxial helicopter, pitched very similarly to those of the single-rotor, produced greater lift. The coaxial blades were pitched slightly more aggressively—the entire increase cannot be attributed to flow turning—but it is one possible explanation.

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[4] http://www.aviastar.org/theory/rotor.html

[5] http://www.stefanv.com/rcstuff/qf200203.html

[6] ftp://ftp.clarkson.edu/.depts/mae/public_html/papers/vanderover.pdf

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