Propellers

1. System
2. Theory
3. Design
4. Selection

Supplement 4A: Propellers

Module #1

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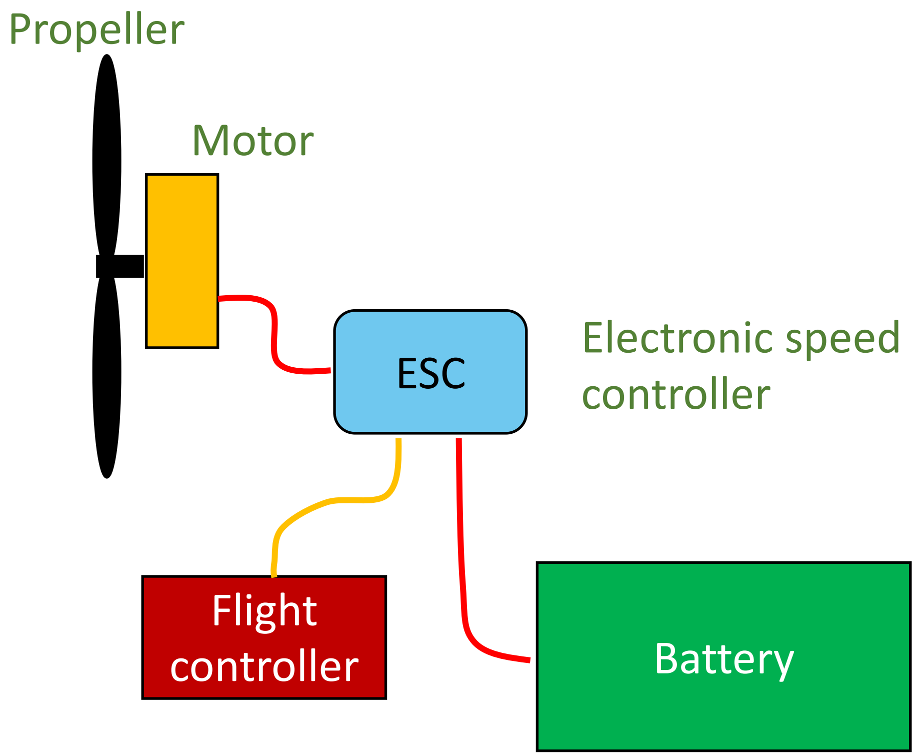
In this lecture you will learn:

- The fundamentals of converting stored energy into thrust
- The elements of a propulsion system

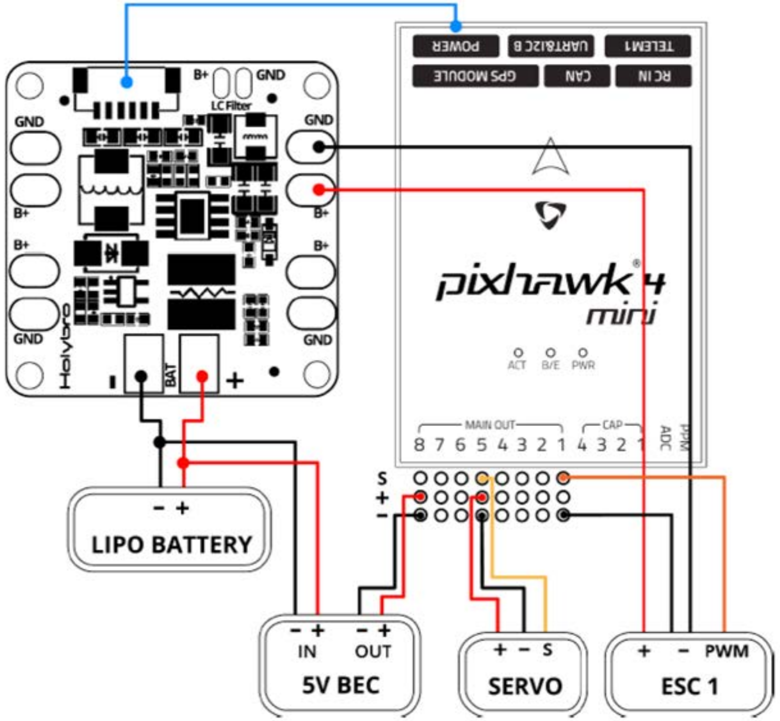
Most propulsion system for drones are based on lithium polymer battery technology

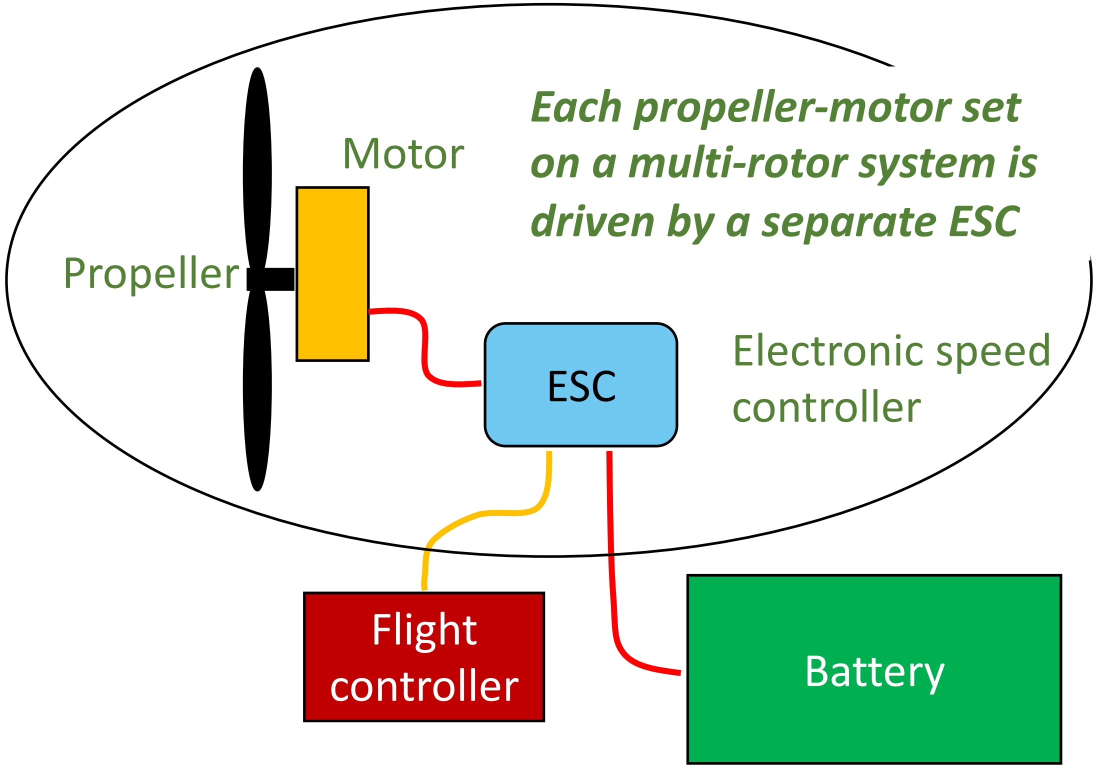
- The main elements of a propulsion system include:
  - Propellers
  - Motors
  - Speed controllers
  - Batteries
  - Sensors (feedback and health monitoring)



VTOL aircraft can be analyzed as a system of three components: **structure, propulsion, control**

- The propulsion systems on VTOL aircraft require a flight controller that accepts a variety of motor/prop configurations



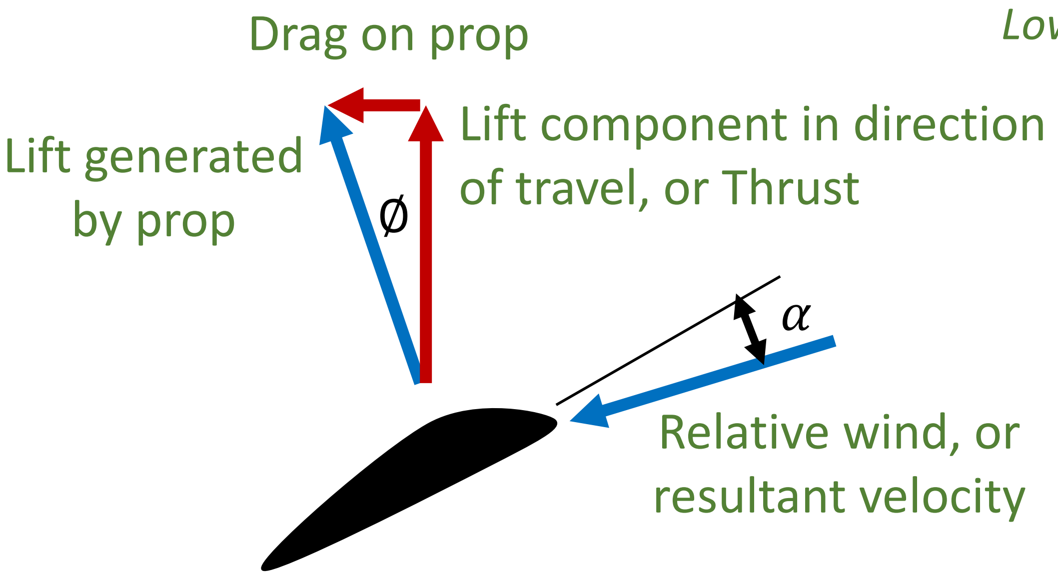


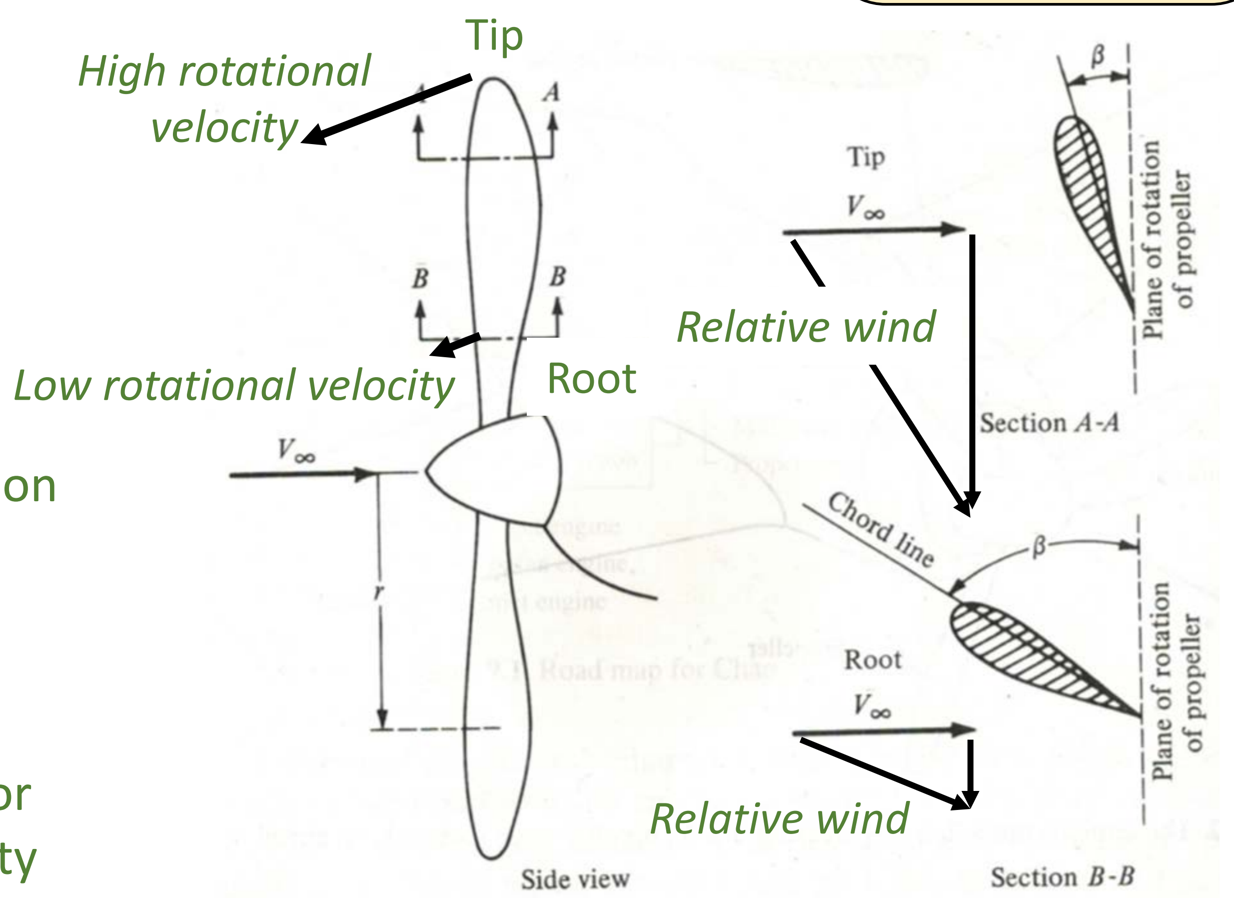
The design of a correctly functioning propeller requires a knowledge of propeller operation

- Propeller theory is based on two sub-theories about the function of a propeller
  - *The first is called blade-element theory*
  - *The second is called momentum theory*
- The convergence of these theories explains how propellers work and how they can be designed

A propeller typically has twist and functions as a rotating wing

- The twist that is built into a propeller keeps the angle of attack on the blade constant from root to tip

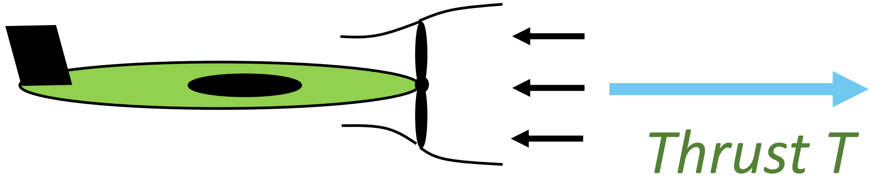




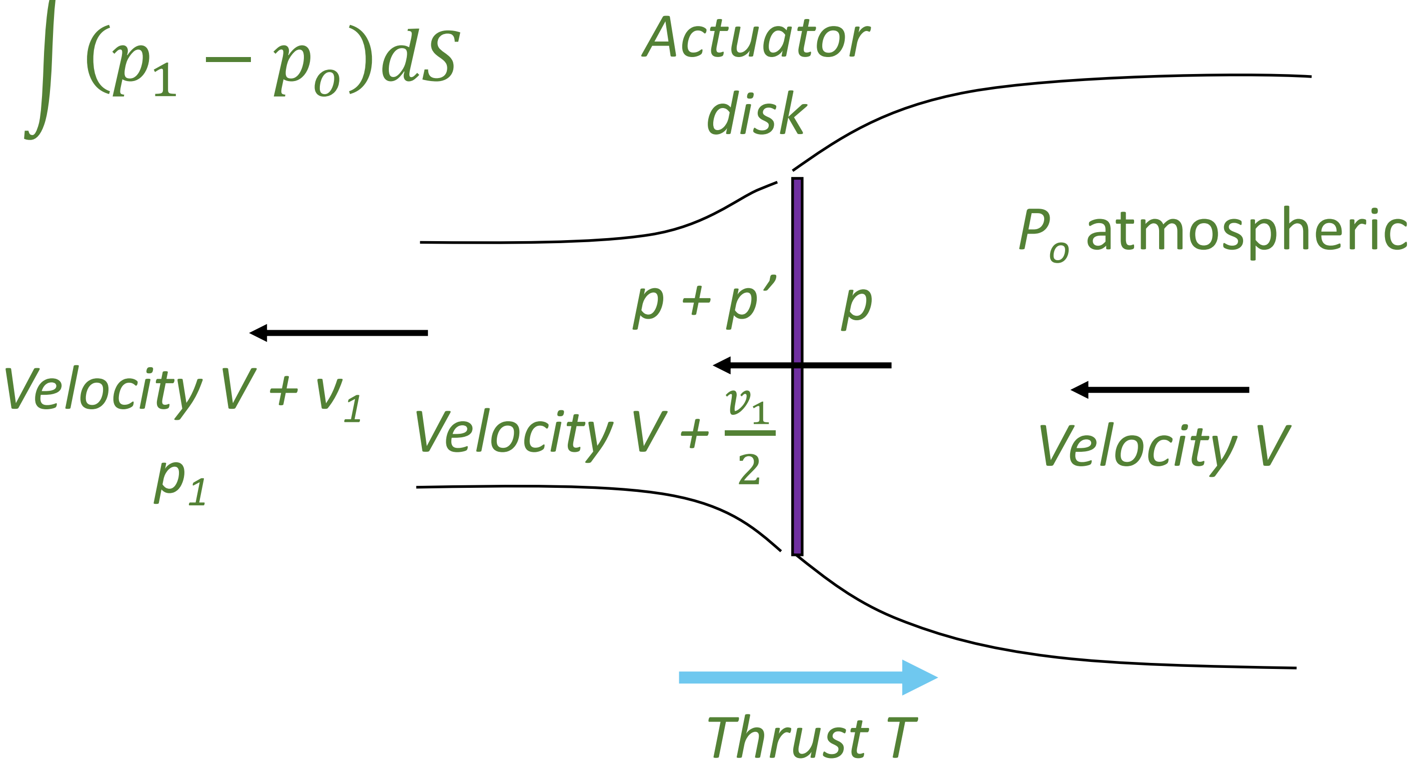
The propeller acts as an actuating disk that accelerates the airflow and increases the downstream velocity and pressure

Momentum theory describes the thrust generated by the accelerated airflow:

$$T = \rho \int v_1 \left(V + \frac{v_1}{2}\right) dS + \int (p_1 - p_o) dS$$



Propeller in tractor (nose) configuration



In addition to the analysis of the disk actuator, we need to consider the interaction of the air with the blade

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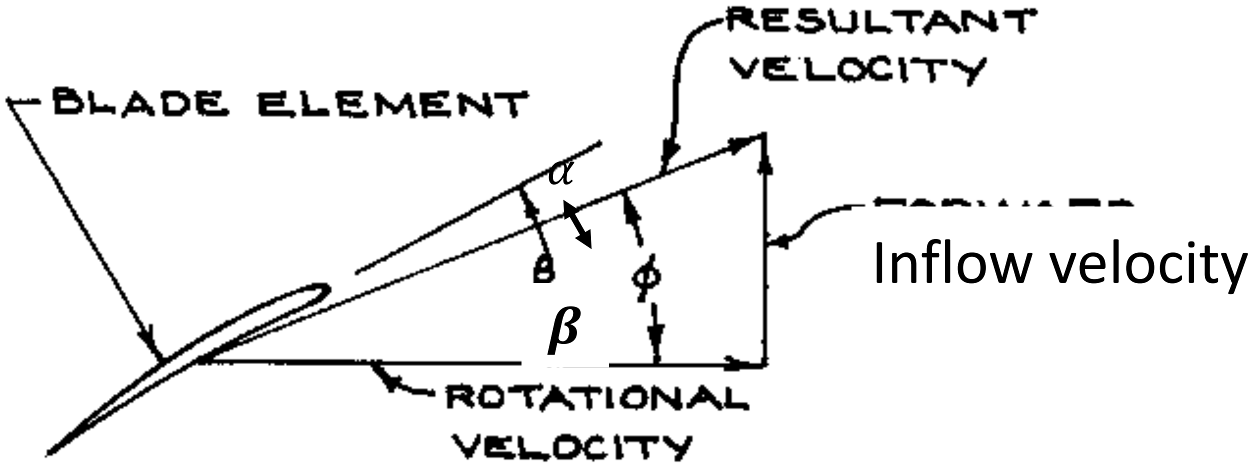
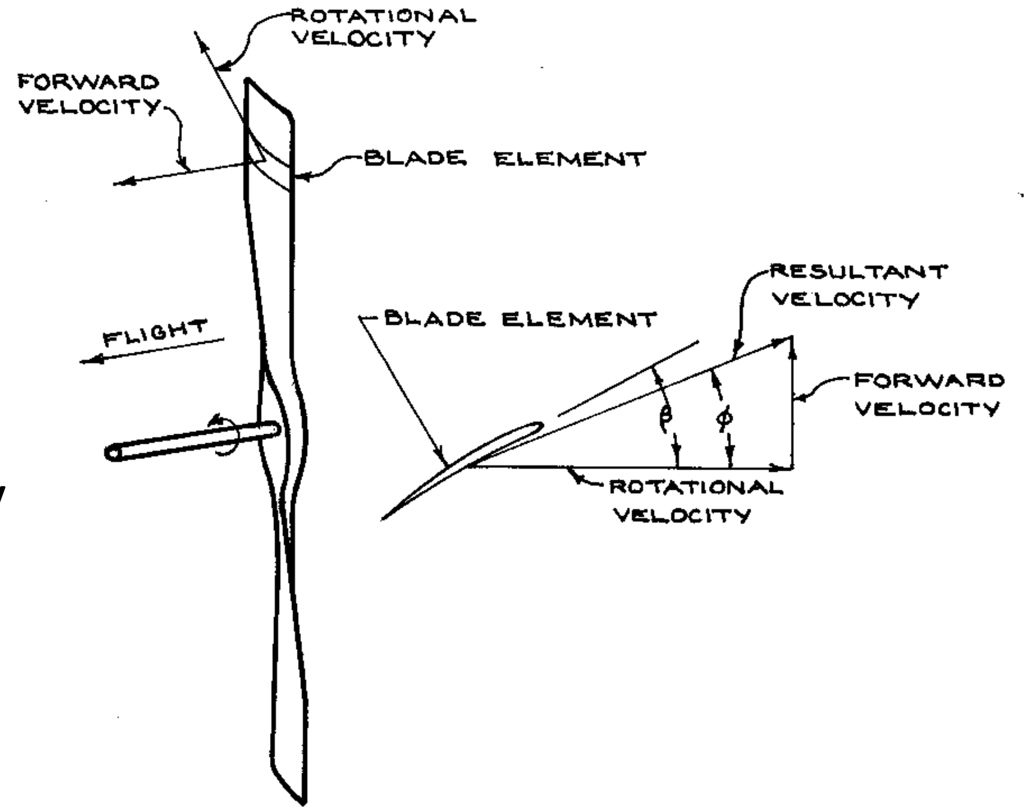
- The propeller blades can be broken into elements which are analyzed individually



$$\beta = Blade\ angle,\ \alpha = Angle\ of\ attack$$
$$\phi = Incident\ angle\ of\ airflow\ on\ blade$$



The analysis of the blade element tells us how blade lift is generated

- For each element of the propeller, the lift generated is:

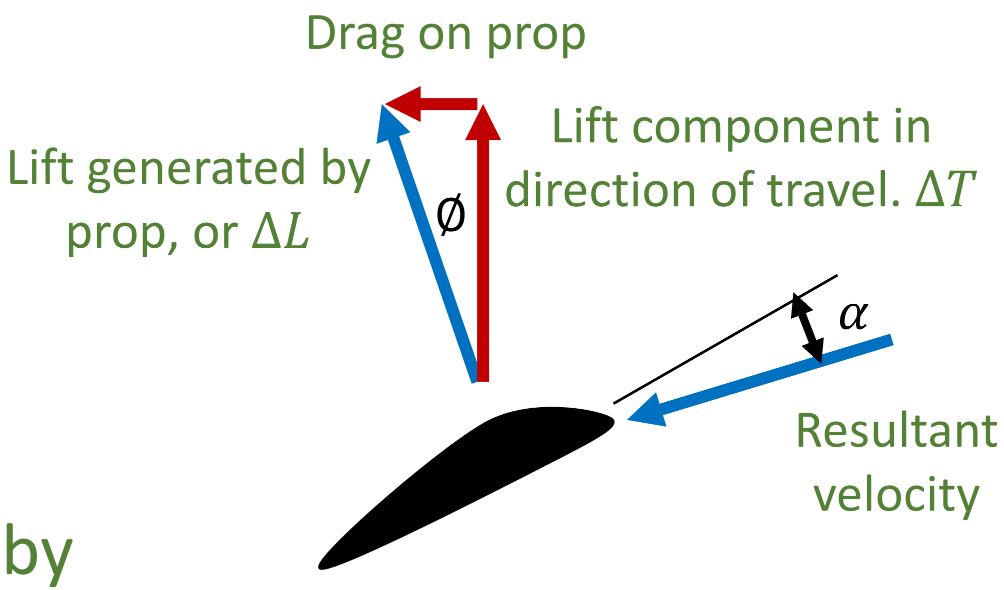
$$L = \frac{1}{2}\rho V^2 S C_L$$

$$\Delta L = \frac{1}{2}\rho(r\omega)^2 \Delta r c C_L$$

r = radius to blade element

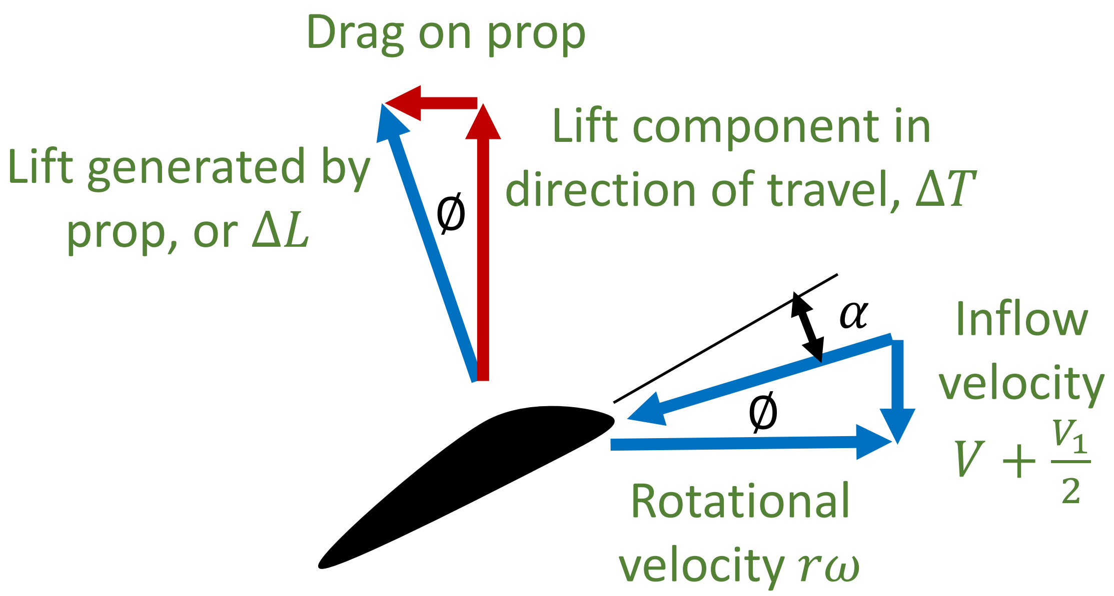
c = chord length of blade element

The thrust of the prop can be computed by summing all blade elements $T = \sum \Delta L cos\emptyset$



Putting momentum theory and blade element theory together allows us to solve for the incident angles of velocity

- The inflow velocity at the blade is $\mathrm{V} + \frac{v_1}{2}$, and combined with the blade rotational speed we can determine the angle of attack on the blade
    - This is used to determine the lift coefficient C_L on the blade element



$$\Delta T = \frac{1}{2}\rho(r\omega)^2 \Delta r c C_L$$

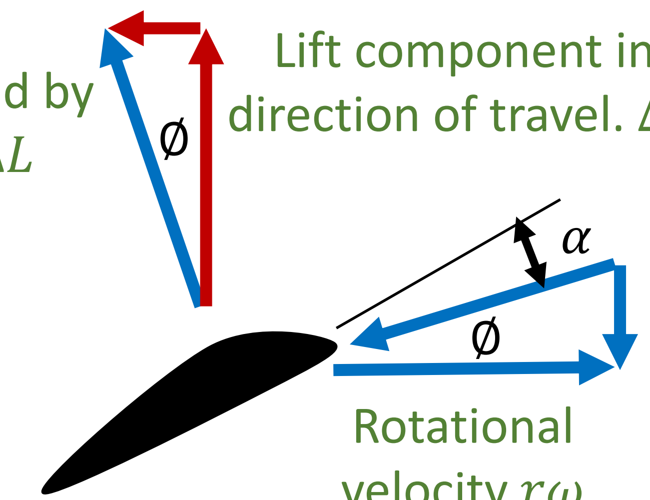
One blade element

$$T = \frac{1}{2}\rho \sum_i (r_i\omega)^2 \Delta r_i c_i C_{Li} \cos\emptyset_i$$

For the entire blade

Putting momentum theory and blade element theory together allows us to solve for the incident angles of velocity

- The thrust equation from blade element theory and the thrust from momentum theory must be equal
  - The inflow velocity is estimated which allows us to calculate the section lift coefficient C_{li} and the resulting thrust. The thrust must be the same using both theories

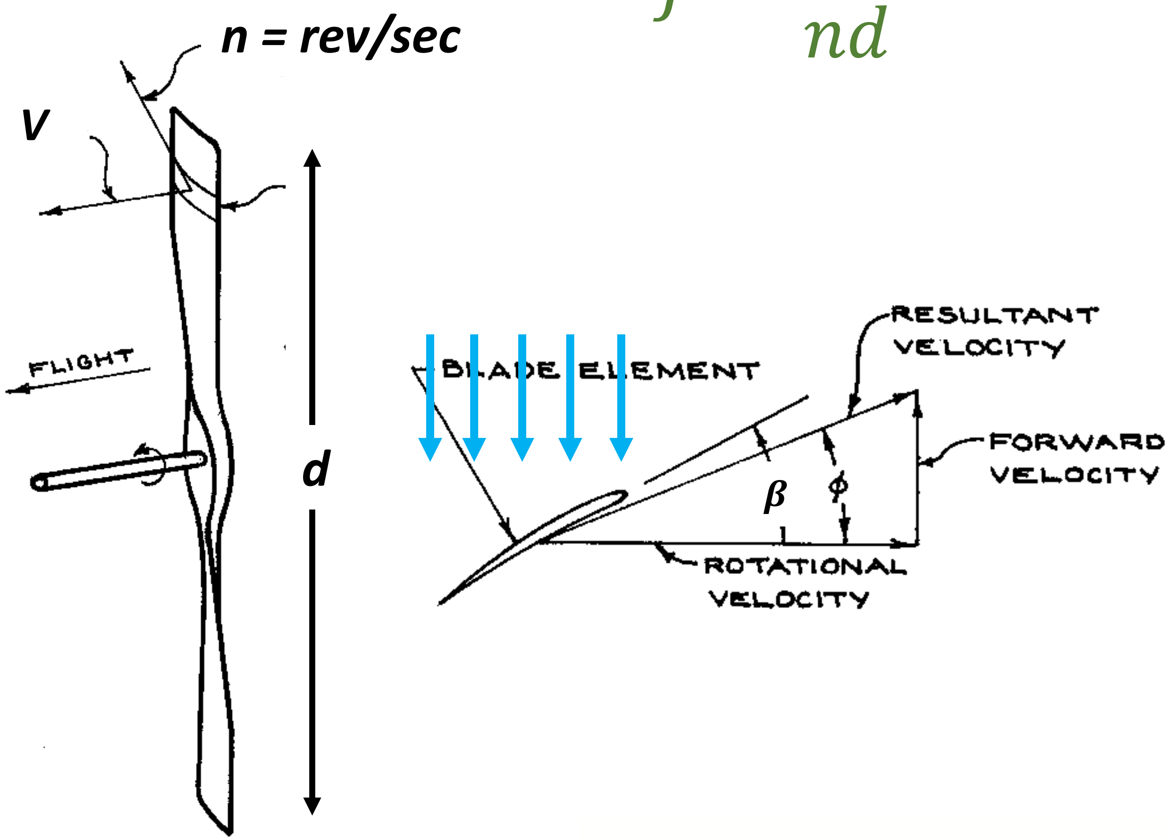


$$T = \frac{1}{2}\rho \sum_i (r_i\omega)^2 \Delta r_i c_i C_{Li} \cos\varnothing_i \qquad T = \rho \int v_1\left(V + \frac{v_1}{2}\right) dS + \int (p_1 - p_o) dS$$

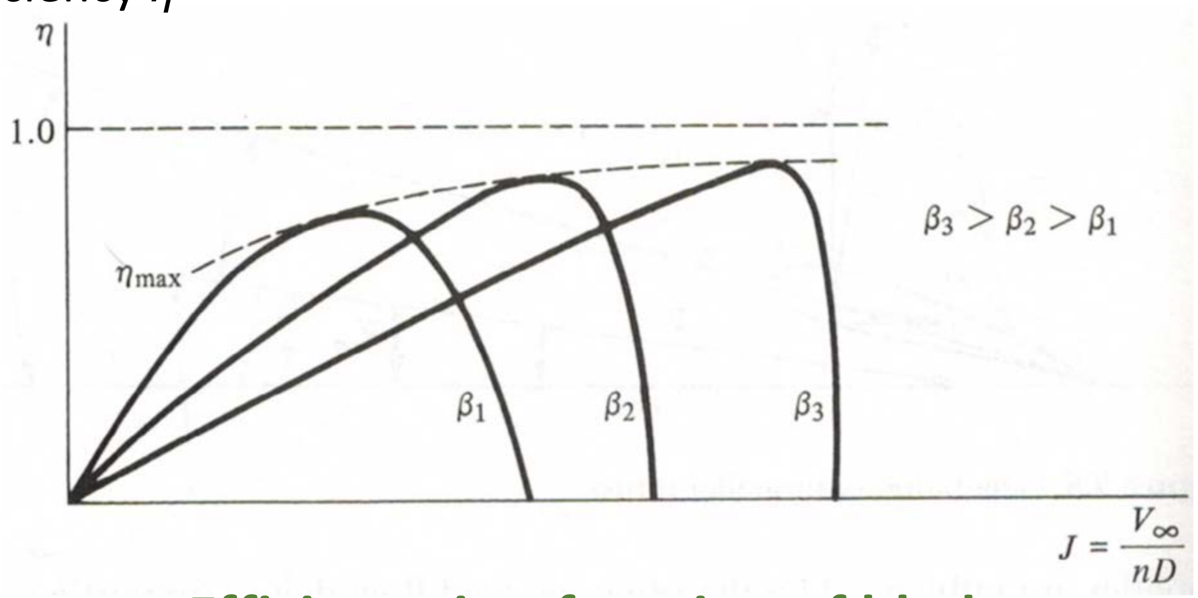
Blade element thrust = Momentum theory thrust

A convenient way to express prop performance is by using a non-dimensional quantity called the Advance Ratio, *J*

$$J = \frac{V}{nd}$$



Efficiency η



Efficiency is a function of blade angle and advance ratio

Experimentally, we can measure prop efficiency in a wind tunnel by changing the velocity of the wind

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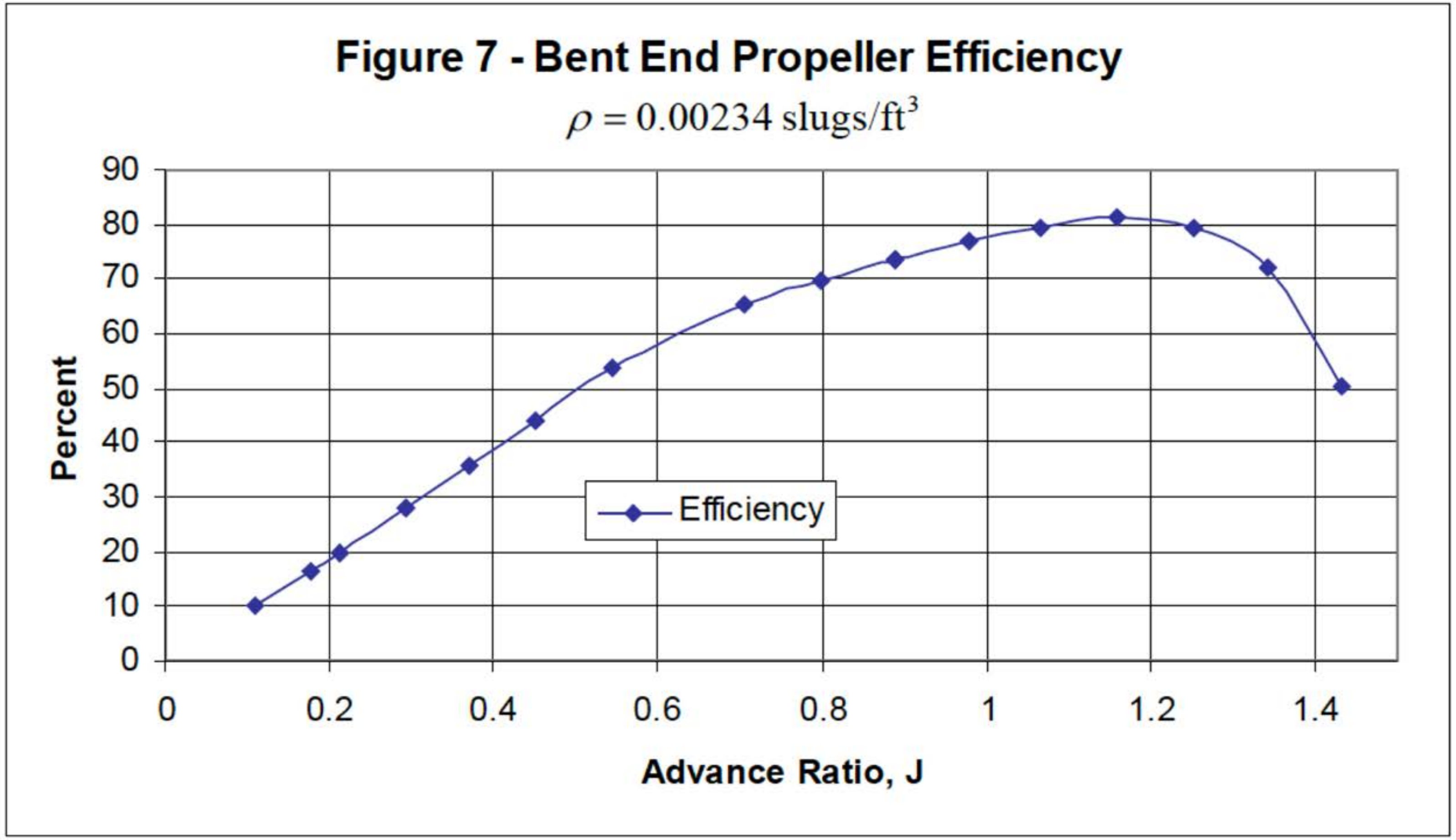
Test results of a Wright Model B propeller

Run	Velocity (ft./sec.)	Advance ratio (J)	Thrust (lbs.)	Ct	Power (HP)	Cp	Efficiency (%)
1	6.65244	0.1117258	127.8	0.21390	15.11	0.23190	10.2642
2	10.4426	0.1755473	124.5	0.20840	14.39	0.22370	16.3542
3	12.5982	0.2116839	121.6	0.20330	14.26	0.21830	19.7111
4	17.5043	0.2939805	117.4	0.19640	13.32	0.20700	27.8857
5	22.1058	0.3711723	113.8	0.19030	12.91	0.19820	35.6436
6	26.8601	0.4521839	110.9	0.18640	12.28	0.19170	43.9763
7	32.2532	0.5428457	110.5	0.18570	12.06	0.18790	53.6457
8	42.0518	0.7064167	99.1	0.16560	11.66	0.17920	65.2923
9	47.6267	0.7994974	91.1	0.15190	11.27	0.17440	69.6431
10	52.9691	0.8889666	82.7	0.13790	10.79	0.16680	73.4687
11	53.0516	0.8897176	82.1	0.13670	10.79	0.16580	73.3266

The plots provide a description of the propeller's performance



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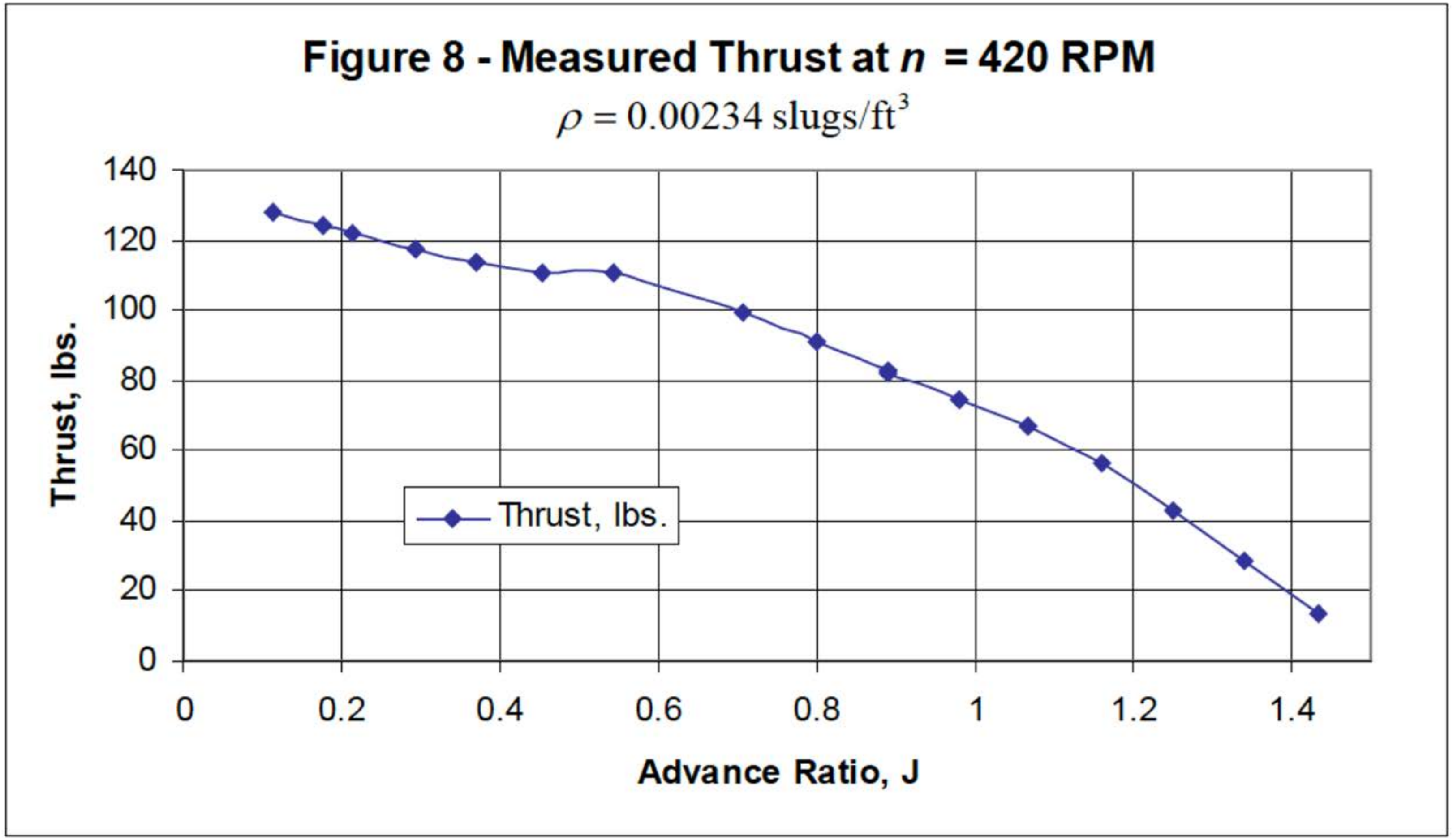

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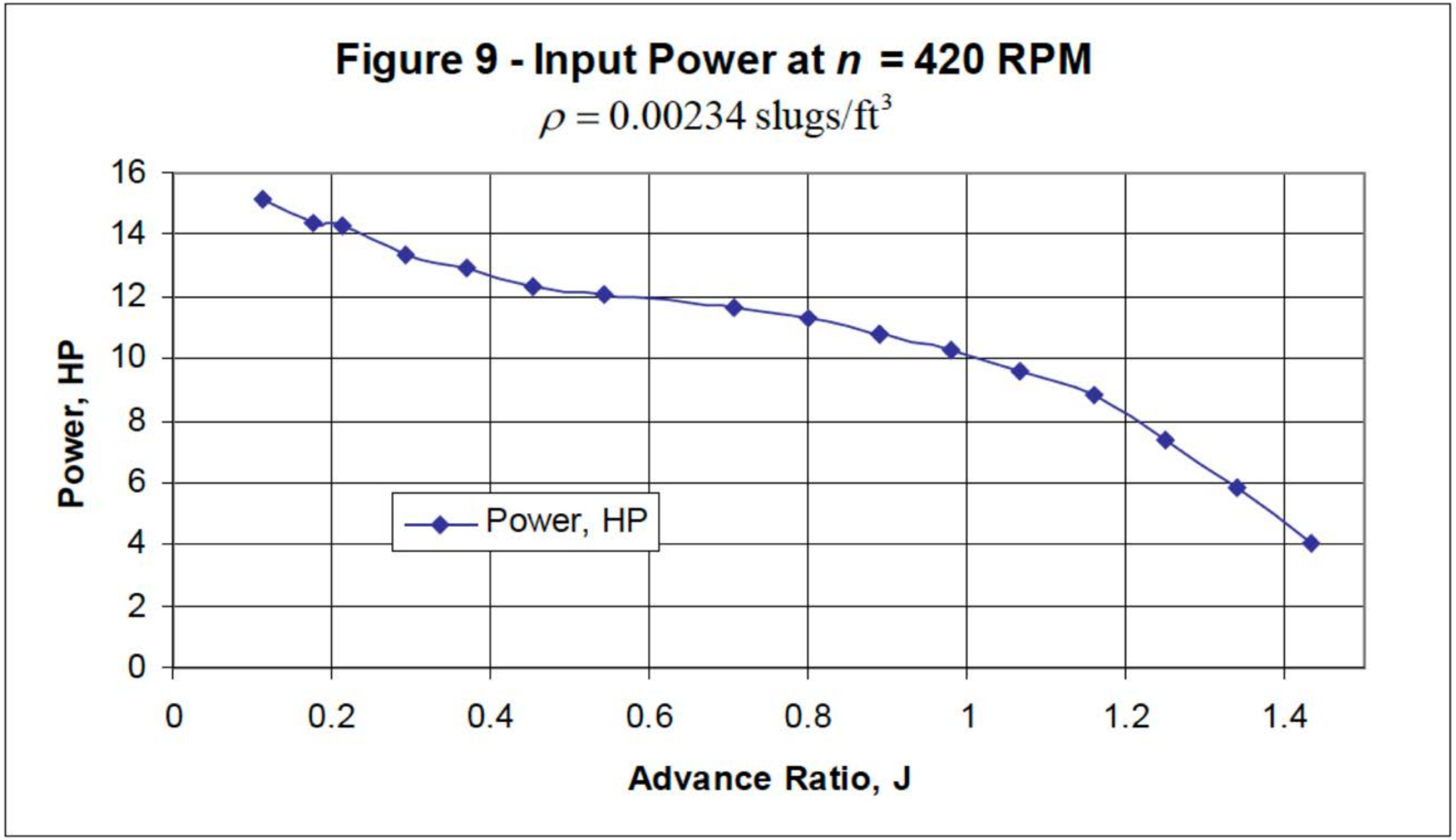

Review:

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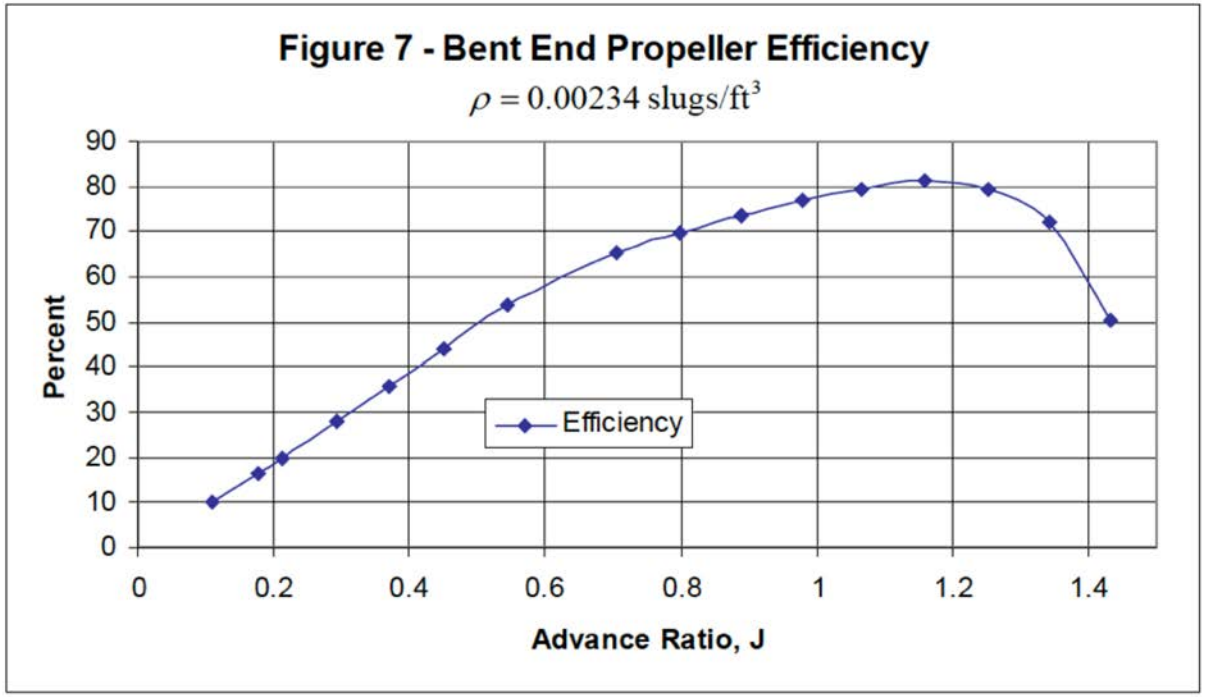
- At what speed does the Wright Model B propeller exhibit its maximum efficiency? The propeller diameter is d = 8.5 ft.



Propeller design considerations: size

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- The size of a propeller is determined by many factors:
  - Dimension restrictions on the entire aircraft
  - The amount of weight that will be carried
  - The rotational speed of the propellers
- Larger diameter propellers turn slower because the tip speed of the propeller is $v_t = r\omega$, where r is the radius on the propeller and ω is the rotational speed.
- If we need to keep the tip speed below some maximum value, then the rotational speed must decrease as the diameter of the propeller increases
  - *Propeller tip speed that is too high results in more drag which in turn requires more power for the same thrust*

Propeller design considerations: size

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Low efficiency hover:
small diameter propeller

Mid-efficiency hover: Large hexacopter built by VT

High efficiency hover:
rotorcraft (Yamaha RMAX)

Transitional aircraft that both hover and fly forward are subject to inefficiencies both in hover and forward flight

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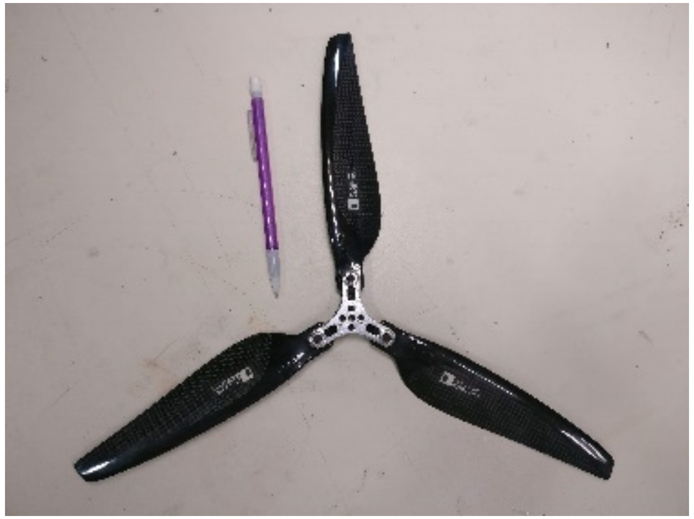
- These aircraft are a compromise and are never flying at an efficient design point

Quiz: *What compromises can you identify on this NASA aircraft design?*

In the selection of propellers, many factors are taken into consideration

- Carbon fiber propellers are strong and manufactured to tight tolerances, but they are expensive



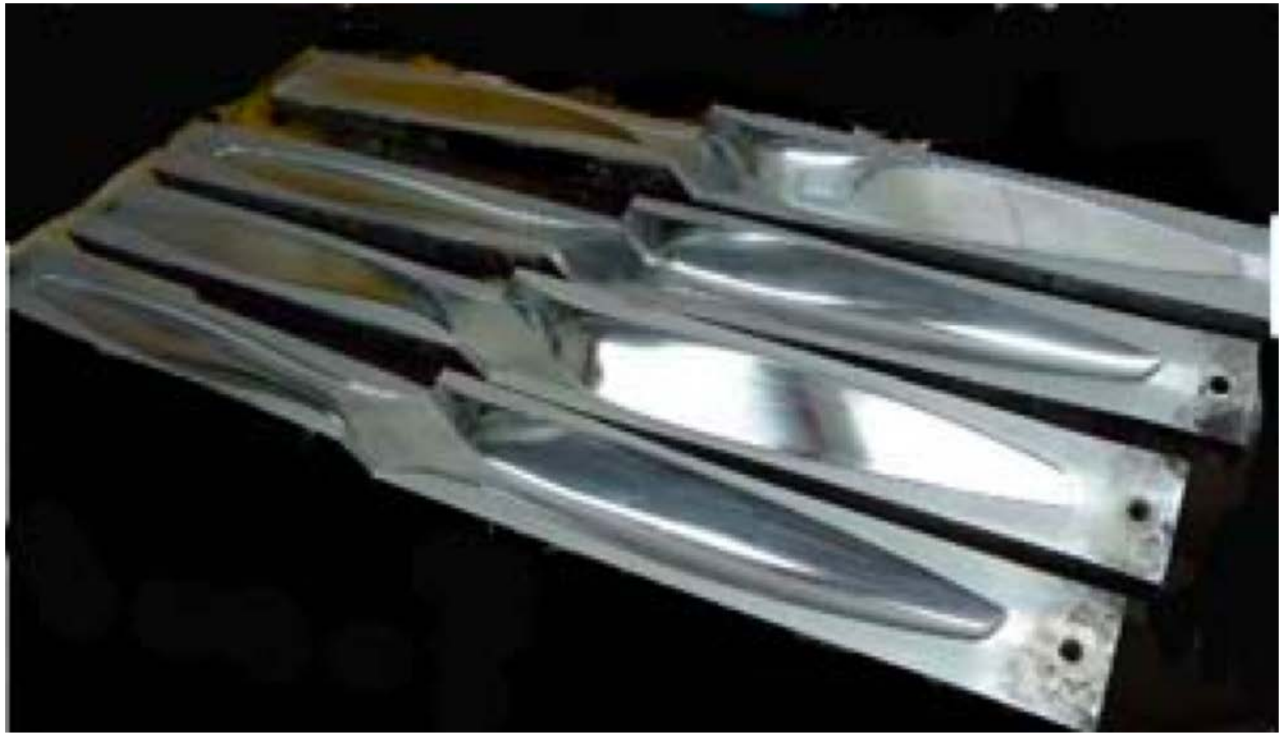
KDE propeller: $120

T-motor 26x8.5 props: $282/pair

In defining propellers, the first number is the diameter and the second number is the pitch. The pitch is the distance the propeller would move forward if there was no slip in air as it rotated

Carbon fiber propellers are usually manufactured by using a precision-machined mold to lay up the carbon epoxy material

- This is a good process for repeatability, but it still represents an expensive process because it cannot be fully automated



https://www.dolphinco.com.au/cabon-fiber-propeller/

In the selection of propellers, many factors are taken into consideration

- Plastic propellers are low-cost but not as efficient because their shape is not well controlled
- Wood propellers are able to hold better tolerance and still be low-cost

EcoSoar propellers, 9x5, 5 for $2.91

Gemfan 16x4.5, $7.50