Propeller Performance and Design

1. Propeller Design for Constant Pitch

The combination of Momentum Theory and Blade Element Analysis allows for some basic design parameters to be determined.

Recall that the **geometric pitch** $\boldsymbol{P}$ is the axial displacement of the propeller prescribed by the physical shape of the blades. The angle $(\boldsymbol{\beta})$ is the angle of the blade to the plane of rotation and for all blade radial locations to have the same value $\boldsymbol{P}$ then:

$$\tan \boldsymbol{\beta} = \frac{\boldsymbol{P}}{2\boldsymbol{\pi r}}$$

Similarly, the effective **pitch** $\boldsymbol{E}$ is the axial displacement of the propeller relative to the general air mass (i.e. the progress of the aircraft). The angle $(\boldsymbol{\phi})$ is the angle of the resultant airflow to the plane of rotation and since all blade radial locations must have the same value $\boldsymbol{E}$ then:

$$\tan \boldsymbol{\phi} = \frac{\boldsymbol{E}}{2\boldsymbol{\pi r}}$$

but since this is not a static condition ($\boldsymbol{E}$ depends on flow speed $\boldsymbol{V}$), it is more convenient to replace $\boldsymbol{E}$ with $\boldsymbol{V}$ and modify the rotational displacement accordingly then:

$$\tan\phi = \frac{V}{2\pi\, rn} \quad \left(= \frac{V}{2\pi\, rn}\frac{D}{D} = \frac{JD}{2\pi\, r} \right)$$

Where $\boldsymbol{J}$ is the advance ration given by $J = \frac{V}{nD}$

Now since the angle of incidence $\boldsymbol{\alpha} = \boldsymbol{\beta} - \boldsymbol{\phi}$, then:

$$\boldsymbol{\alpha} = \textbf{arc tan}\ \frac{\boldsymbol{P}}{2\boldsymbol{\pi r}} - \textbf{arc tan}\ \frac{\boldsymbol{JD}}{2\boldsymbol{\pi r}}$$

It can be seen that when $P = JD \ \left(\text{ie. when } \ J = \frac{P}{D} \right)$ then the incidence along the entire blade is zero and hence there will be no thrust.

Example:

If $\boldsymbol{P}$=*5m* and $\boldsymbol{D}$=*2m*, the angle of incidence ($\boldsymbol{\alpha}$) can be determined over a range of velocities (shown as values of $\boldsymbol{J}$). The values for $\boldsymbol{P}$ and $\boldsymbol{D}$ were chosen to give an angle of incidence of 6 degrees for $\boldsymbol{J}$=2 at $\boldsymbol{\beta}$ 0.75. This angle of incidence is typical of that for best lift/drag of an aerofoil section.

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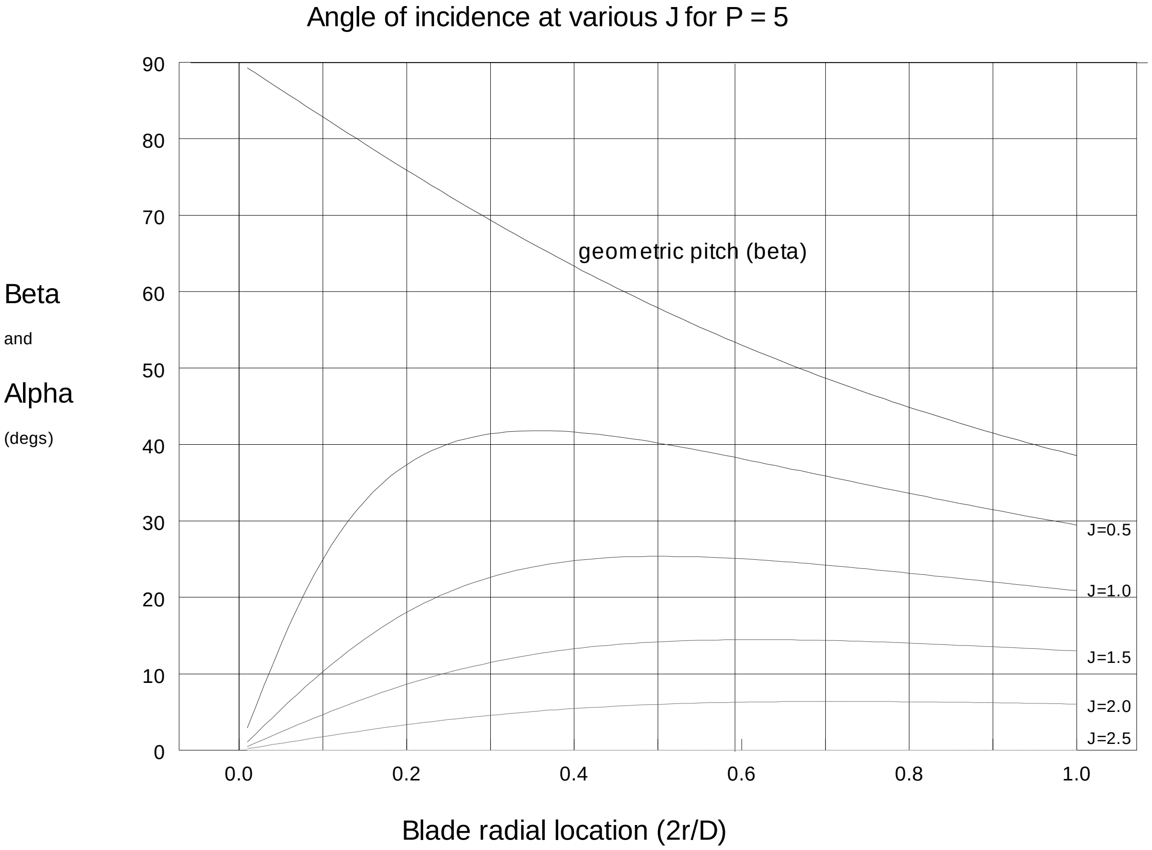

Whilst it can be seen that the angle of incidence is not constant along the entire length of the blade it is relatively constant in the region of $\mathbf{0.75}\boldsymbol{R}$, particularly at the higher advance ratios.

It can also be seen that for a fixed pitch propeller the angle of incidence for the best L/D will only be available at one value of the advance ratio $\boldsymbol{J}$.

In practice, it is unusual for all the radial locations of a blade to have the same pitch (that is why it is only quoted for one location, $\mathbf{0.75}\boldsymbol{R}$). In theory, the radial twist of the blade can be such that the angle of incidence is constant along its length (for a particular $\boldsymbol{J}$) so that the entire blade can operate at its best L/D.

2. Propeller Design for Optimum Incidence

For the incidence to remain constant along the length of the blade, the geometric blade pitch angle for each radial station can be determined as follows:

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$$\beta = \alpha + \phi \ ,$$

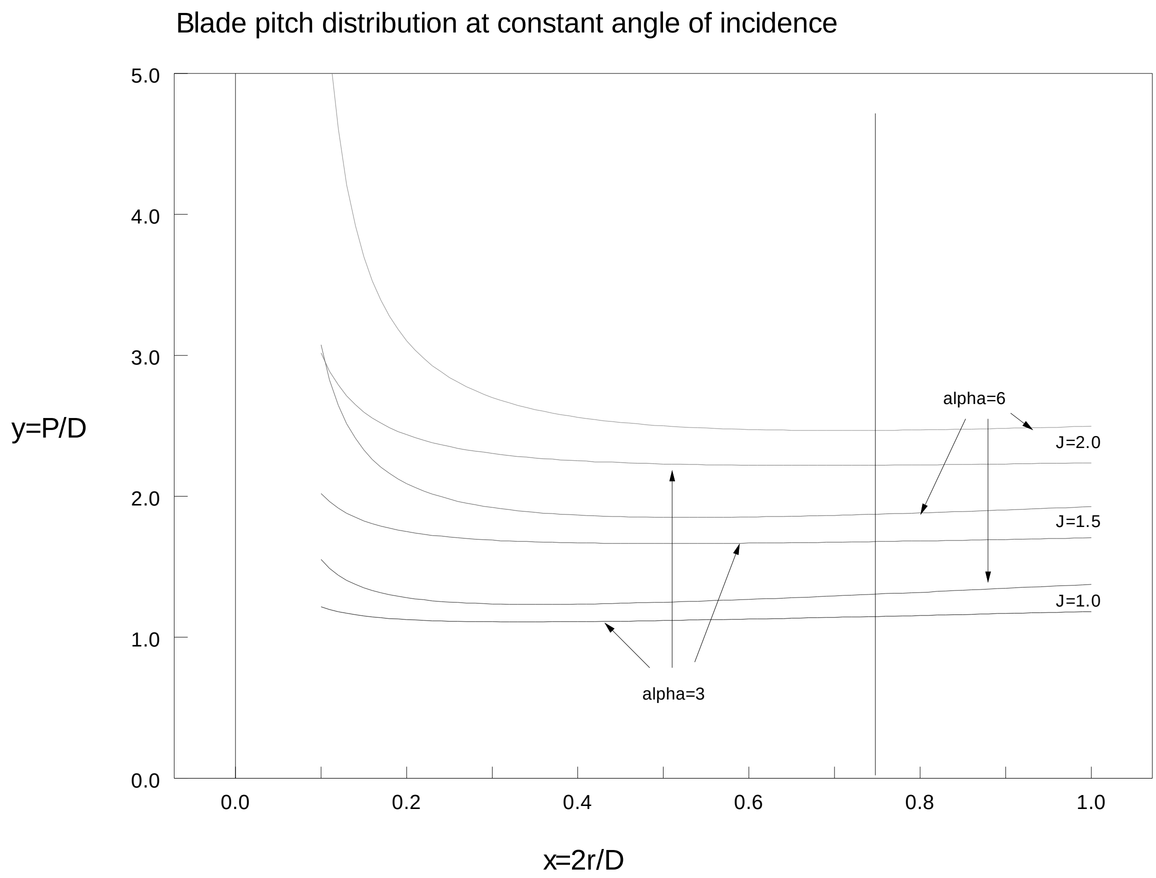
thus $$\tan\beta = \tan(\alpha + \phi) = \frac{\tan\alpha + \tan\phi}{1 - \tan\alpha\tan\phi}$$

but $\tan\beta = \dfrac{P}{2\pi r}$, so $$P = 2\pi r\,\frac{\tan\alpha + JD/2\pi r}{1 - (JD/2\pi r)\tan\alpha}$$

Using the dimensionless quantities $y = \dfrac{P}{D}$ and $x = \dfrac{2r}{D}$, then :

$$y = \pi x\,\frac{\tan\alpha + J/\pi x}{1 - J\tan\alpha/\pi x} = J\,\frac{1 + \pi x\tan\alpha/J}{1 - J\tan\alpha/\pi x}$$

This has been plotted for two angles of incidence, $\alpha = 3^0$ and $\alpha = 6^0$ and for three values of advance ratio, $J = 1.0$, $J = 1.5$ and $J = 2.0$ as shown below:



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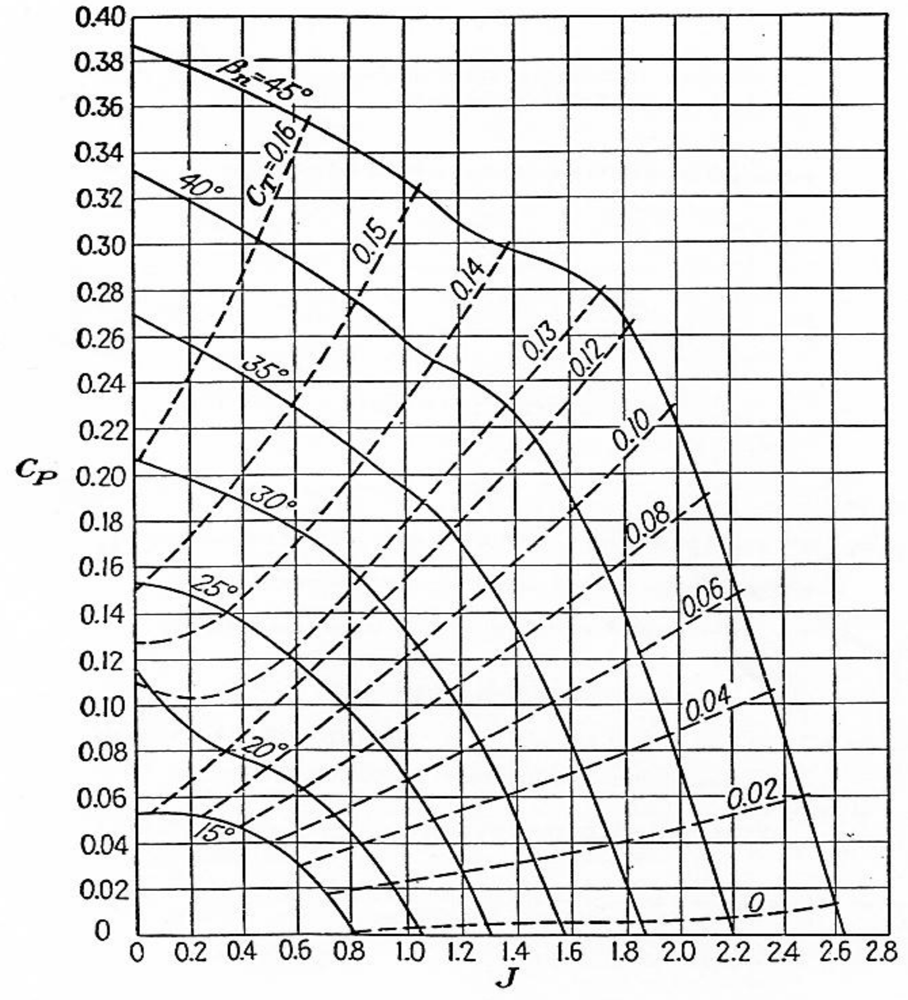
3. Propeller Performance Charts

The performance charts have a number of uses;

- Comparing the performance of commercially available propellers
- Choosing a propeller to suit a particular engine's power output characteristics
- Establishing the best blade pitch setting for a flight mission
- Determining the take-off or climb performance of an aircraft
- Providing a measure in the development of a new propeller design

The most common everyday use would be to determine an existing aircraft's performance. Consider an aircraft of known mass, drag and engine power. Provided the propeller's speed and diameter are also known (and this is most likely) then the surplus power to accelerate or climb can be determined from the charts. From a chart of $\boldsymbol{C_P}$ against $\boldsymbol{J}$, the blade pitch angle $\boldsymbol{\beta}$ can be found. This can then be used to determine efficiency η and therefore the available propeller thrust. The value of the excess thrust can then be used to calculate the available acceleration or climb rate of the aircraft.



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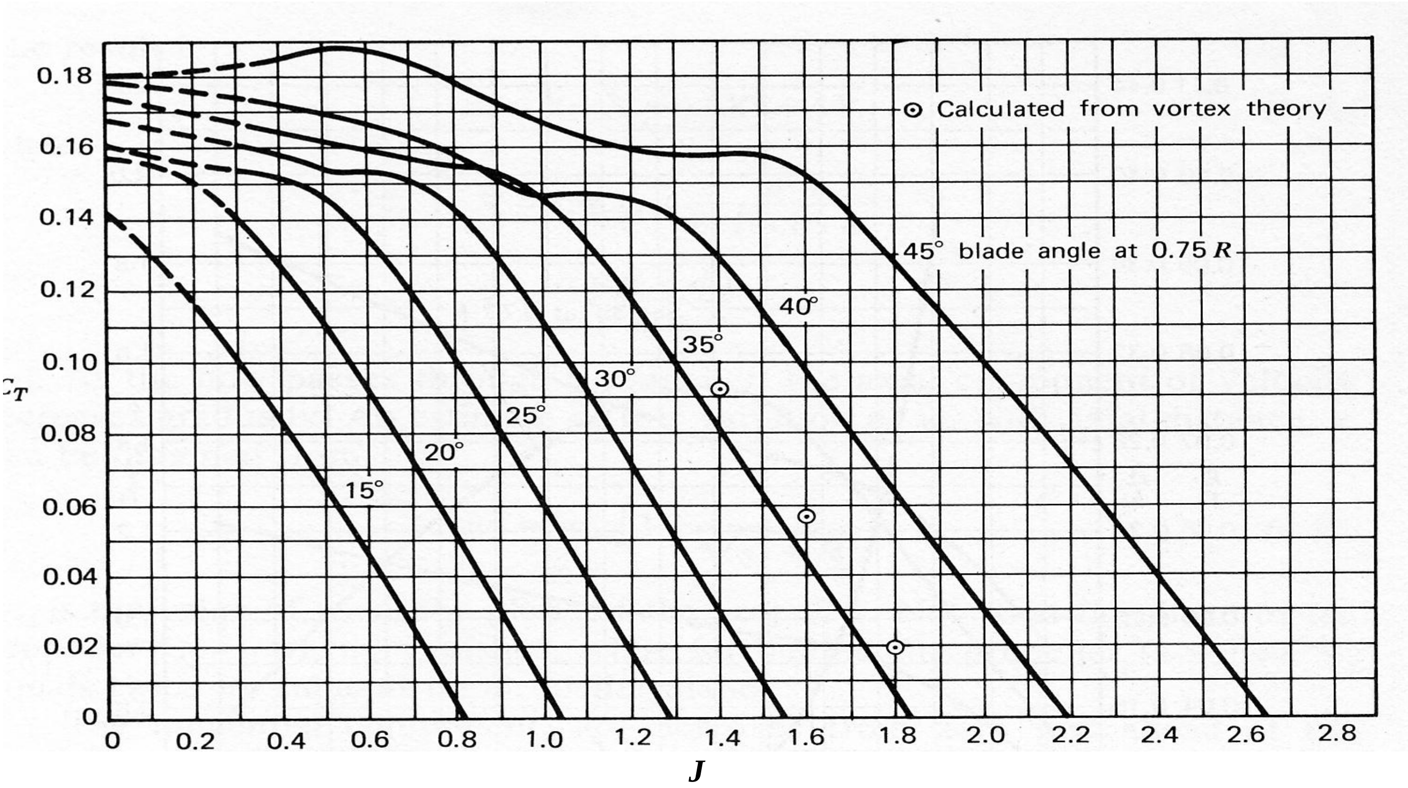

There are various forms of displaying empirical propeller performance data, often by separate charts for C_P , C_T and η_P

Inspection of the C_T against J chart reminds us of the basic flow vectors, namely that increasing J (and hence V) but holding β constant reduces the angle of incidence α (and hence C_T).

The methods of propeller analysis described aid the design of propellers and can give reasonable predictions of performance. Lifting line methods and CFD will give better results but at a cost in time and computation.

General Aviation (GA) propellers are purchased "off the shelf" to best match the engine and airframe characteristics. Such proprietary propellers are tested in controlled conditions over a range of advance ratios (J) and Performance Charts are issued for:

- single propellers– (fixed pitch)
- family of propellers (as above) of various pitches
- propellers that have 2 or 3 pitch settings – (adjustable)
- propellers with infinite pitch settings (including feathering) – controllable

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4. Propeller Design

Until now the propeller has been considered in isolation but this is rarely the case. It is usually situated in front of an engine cowling or the nose of the aircraft. Such an obstruction could generate significant blockage drag and for such a situation it would do well not to overload the propeller directly ahead of it. This can be taken account of in the blade analysis design phase. The engine characteristics also feature in the design of a suitable propeller. For cruise the propeller efficiency should be matched to the most economical engine operating speed. The Off-Design performance should also be considered particularly when the propeller has been extensively optimised for one design point.

5. Propeller Re-design: Absorbing More Power

There are a number of ways by which the propeller can be modified to convert additional power into useful thrust, mostly by increasing various parameters:

- Increase propeller diameter
- Increase propeller rotational speed
- Increase number of blades
- Increase blade chord
- Increase blade pitch

All have their advantages and disadvantages and the right choice depends upon the application.

Increase propeller diameter.

Advantages:

Operates on a greater mass of air, thus increasing efficiency

Easy retrofit if blades are detachable

Reduces tip losses for a given level of thrust

Disadvantages:

Reduces ground clearance, increasing stone/chip damage

Increases blade tip speed, possibly incurring wave drag and compressibility noise

May require reduction gearbox to reduce tip speed, thus cost and weight penalty

Higher gyroscopic forces may affect handling

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Increase propeller rotational speed

Advantages:

No large torque increase with higher power level

Usually conducive to engine power delivery

No design changes on propeller (assumed strong enough) or aircraft structure

Higher Reynolds number

Disadvantages:

Power is proportional to speed cubed, thrust is proportional to speed squared

Increases blade tip speed, possibly incurring wave drag and compressibility noise

Increase engine and transmission noise

Higher gyroscopic forces may affect handling

Increase number of propeller blades

Advantages:

Increases rotor solidity and therefore thrust generating potential

Can still operate at same Reynolds number and best L/D

Reduces tip losses for a given level of thrust

Improves vibration characteristics

Disadvantages:

Requires new hub assembly

Increases hub complexity, particularly for constant speed propellers

Expensive to modify and maintain

Increase propeller blade chord

Advantages:

Increases rotor solidity and therefore thrust generating potential

Easy retrofit if blades are detachable

Increases Reynolds number

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Disadvantages:

Increases the "**Propeller Moment**" and thus associated control loads **(see below)**

Reduces blade aspect ratio, increasing tip losses

May compromise aerofoil performance due to higher camber

Generally more expensive to manufacture

Increase propeller blade pitch

Advantages**:**

The easiest option, no modifications required

Disadvantages**:**

Operating off the design point for the blade aerofoil

General increase in vibration, due to localised stalling

Contra-Rotational Coaxial Propellers

Advantages**:**

Prevents T.O. yaw due to swirl effects.

Prevents T.O. yaw due to inclined propeller disk (tail draggers only).

Prevents T.O. yaw due to differential wheel drag.

Prevents a/c rotation induce yaw due to gyroscopic effects.

Prevents a/c rotation induce roll due to engine torque.

Aerodynamically more efficient.

Disadvantages**:**

Expensive initial costs and maintenance.

High weight penalty.

Complex pitch change mechanism.

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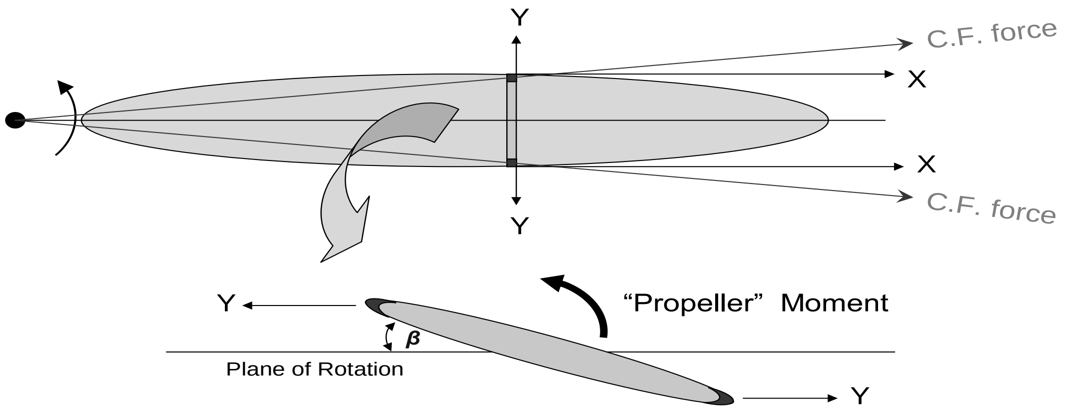
The "Propeller Effect" or Propeller Moment

Consider an elemental strip of propeller blade to be made up of discrete masses. The inertial forces (due to centrifugal forces) acting on these elemental masses in the leading and the trailing edge of the blade strip will have a components in the **Y** direction. These force components will create an inertial moments (called the "Propeller Moment") which tries to pitch the blade element down (leading edge down). An increase in blade will result in a higher propeller moment.



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