Introduction to Aerospace Propulsion

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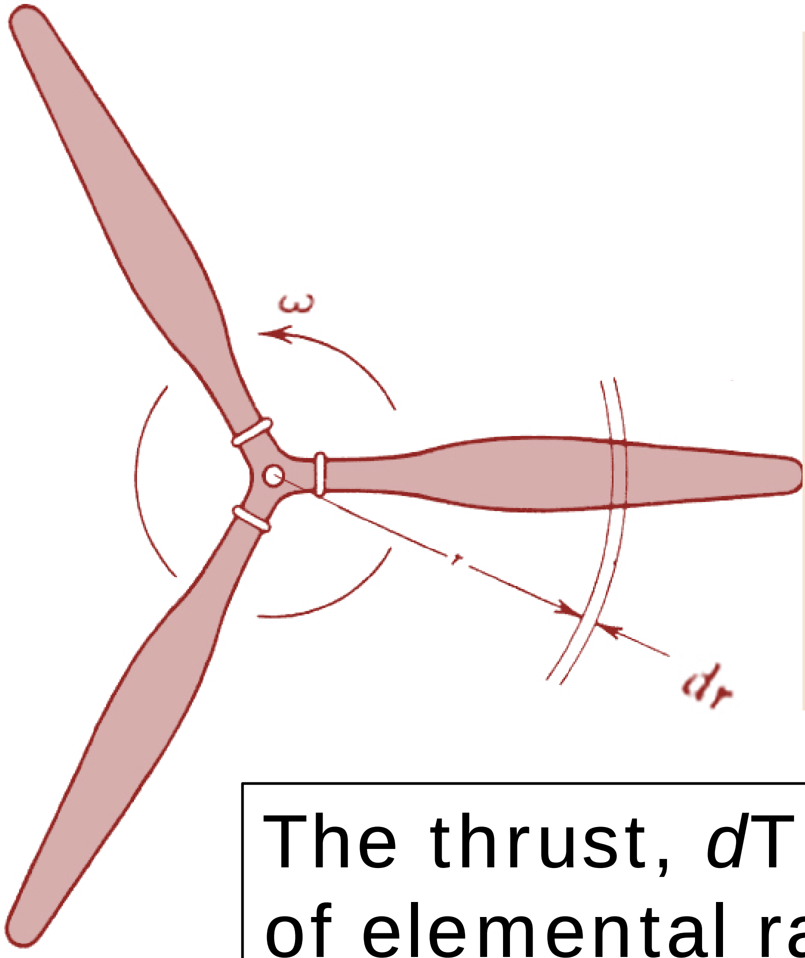
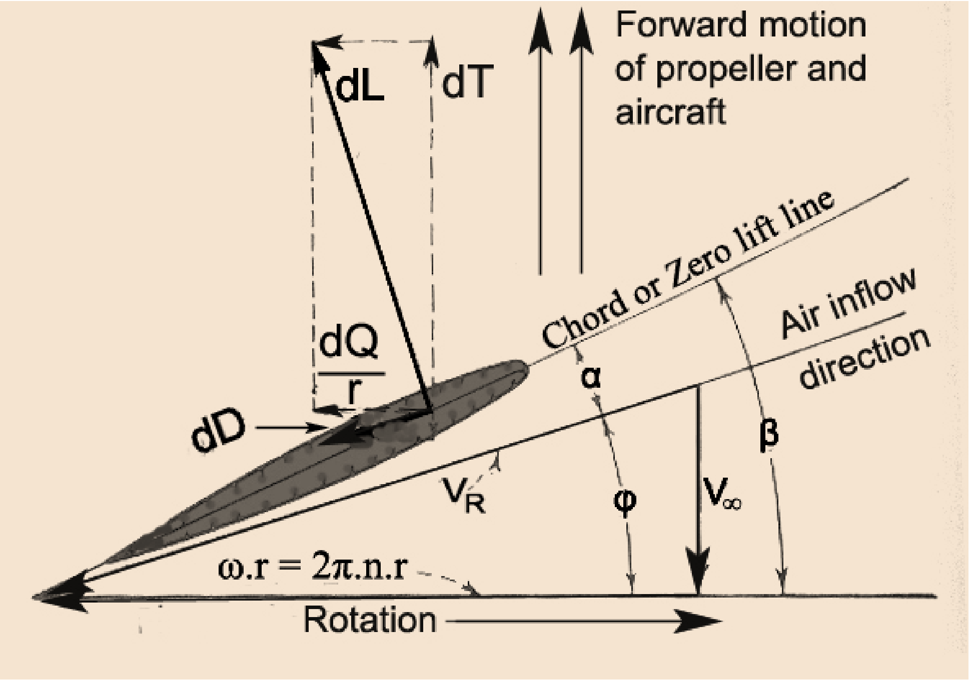
Lecture No - 30

Propeller theories

Blade element theory

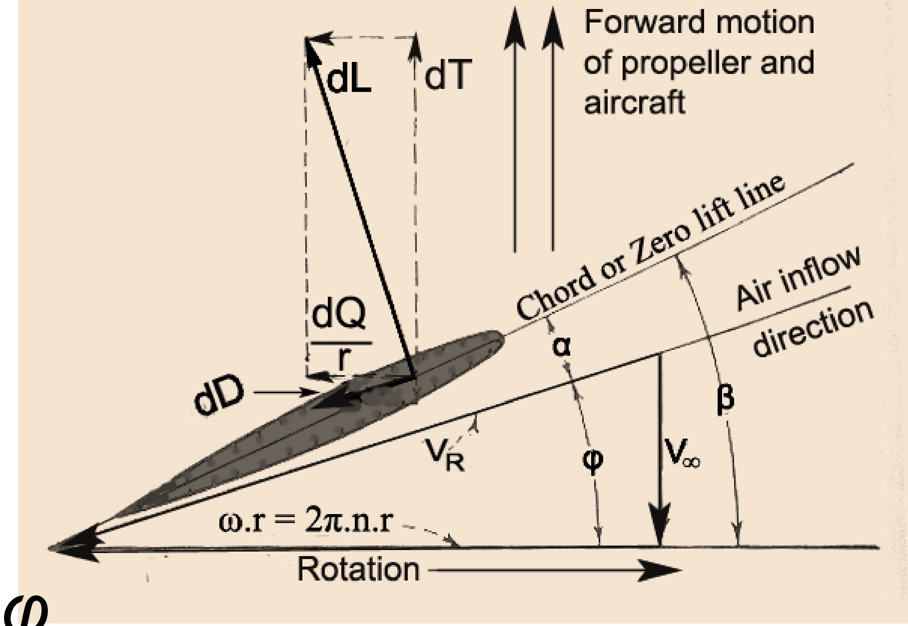
- The blade elements are assumed to be made up of airfoil shapes of known lift, C_l and drag, C_d characteristics.
- In practice a large number of different airfoils are used to make up one propeller blade.
- Each of these elements shall have its own lift, C_l and drag, C_d coefficient characteristics.





The thrust, *d*T created by an element of elemental radial length *d*r is created with contributions from the airfoil with lift, *d*L and drag, *d*D

Using the blade elemental lift and drag characteristics the working capacity of the blade element may be found as :



Thrust produced,

$$dT = dL\,.\cos\varphi - dD\,.\sin\varphi$$

$$= \tfrac{1}{2}\,.\rho\,.V_R^2\,.c.dr.\,(C_l\cos\varphi - C_d\sin\varphi)$$

Torque to be supplied ,

$$dQ = (dL\,.\sin\varphi + dD\,.\cos\varphi).\,r$$

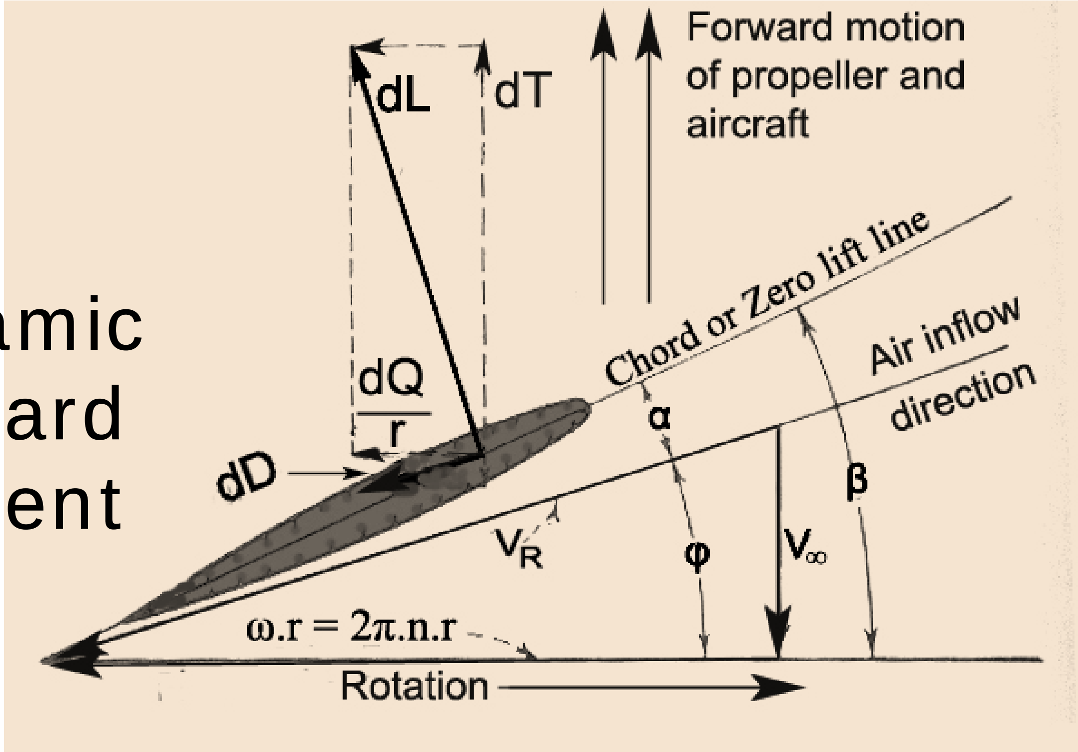
$$= \tfrac{1}{2}\,.\rho.V_R^2\,.c.dr.(C_l\,.\sin\varphi + C_d\,.\cos\varphi)$$

Substituting for Resultant inflow velocity Incident and aligned to the blade element,

$V_R = V_\infty / \sin\varphi$,

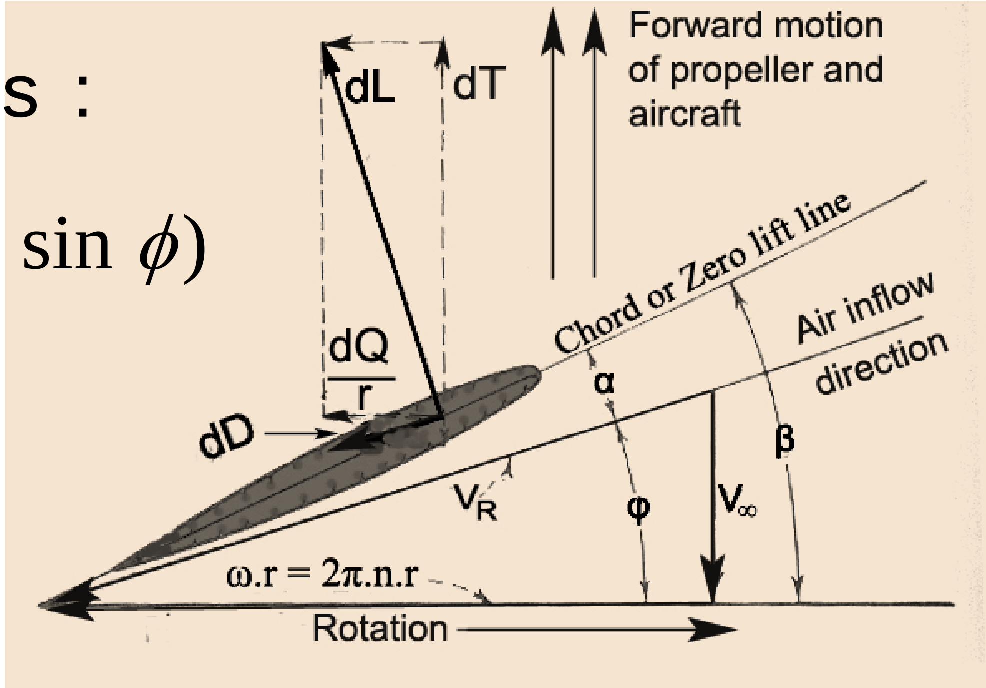
and for Incoming flow Dynamic head based on forward velocity of the element

$q = \frac{1}{2} \rho V_\infty^2$



The elemental thrust is :

$$dT = \frac{q.c.dr}{\sin^2 \phi}\left(C_l \cos \phi - C_d \sin \phi\right)$$



and

The elemental torque is :

$$dQ = \frac{q.c.r.dr}{\sin^2 \phi}\left(C_l \sin \phi + C_d \cos \phi\right)$$

Propeller thrust and torque are now computed by integrating from the root to the tip of the blade and for number of blades, B

$$T = q.B.\int_0^R \frac{c.dr}{\sin^2 \phi}(\mathrm{C_l} \cos \phi - \mathrm{C_d} \sin \phi)$$

$$Q = q.B\int_0^R \frac{c.r.dr}{\sin^2 \phi}(\mathrm{C_l} \sin \phi + \mathrm{C_d} \cos \phi)$$

- Thus, the net thrust and the torque are seen to be directly proportional to the number of blades, B and the chord, c.
- *This is not quite true in practice*, as more is the number of blades and wider the blade chord - it shall result in more surface area, more flow blockage and higher consequent aerodynamic losses.
- The optimum number of blades need to be found separately and not from the blade element theory.

The blade element efficiency,

$$\eta_{el} = \frac{\text{Thrust power produced}}{\text{Torque power supplied}}$$

In terms of elemental airfoil characteristics C_l and C_d , blade efficiency is :

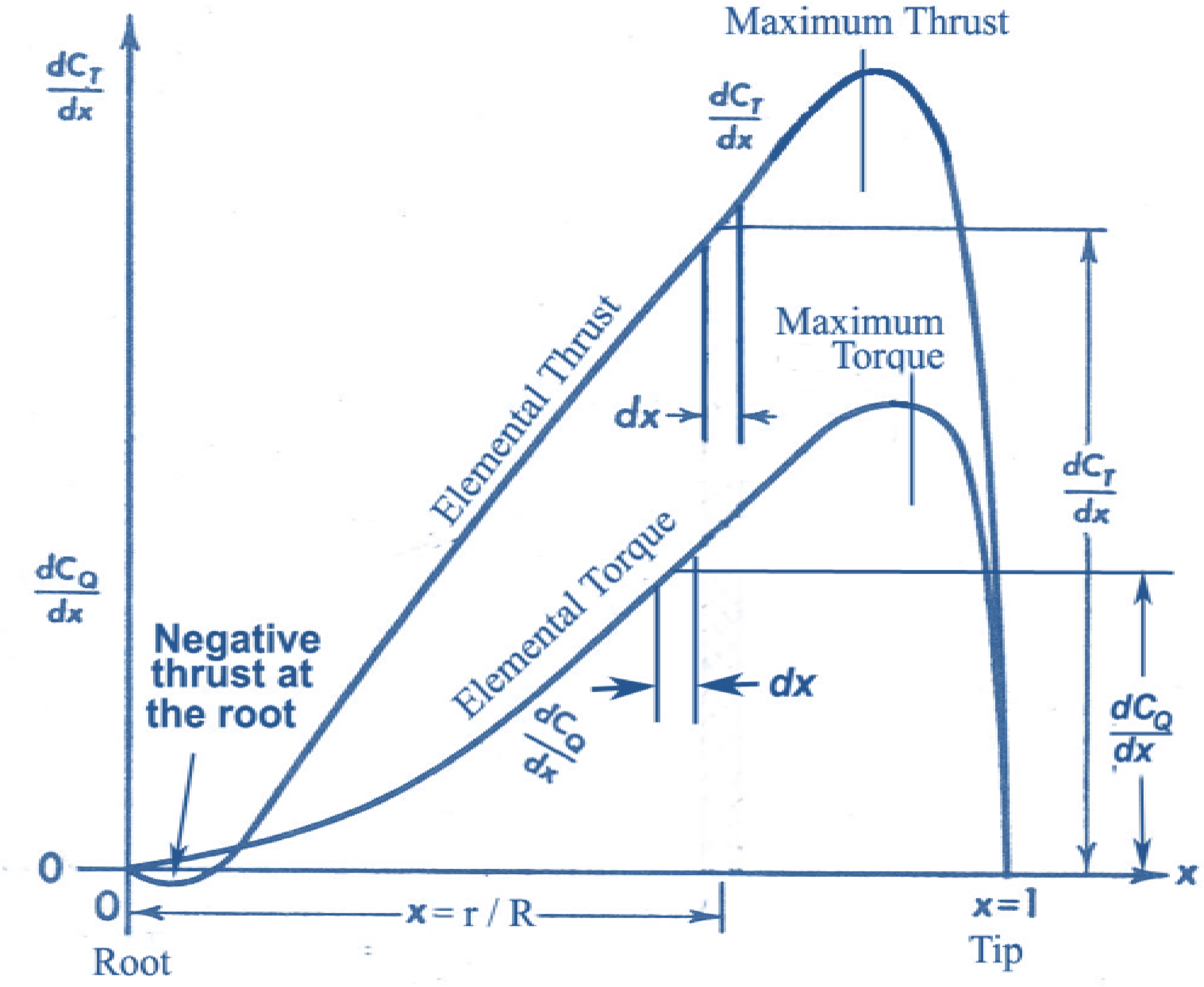
$$\eta_{el} = \frac{v.dT}{2\pi n.dQ} = \frac{V}{2\pi nr}.\frac{C_l \cos\phi - C_d \sin\phi}{C_l \sin\phi + C_d \cos\phi} = \frac{C_l \cos\phi - C_d \sin\phi}{C_l \sin\phi + C_d \cos\phi}.\tan\phi$$

Applying maxima condition it can be shown that maximum efficiency, $\eta_{el\text{-}max}$ occurs at

$$\phi = \frac{\pi}{4} - \frac{C_d}{2.C_l}$$

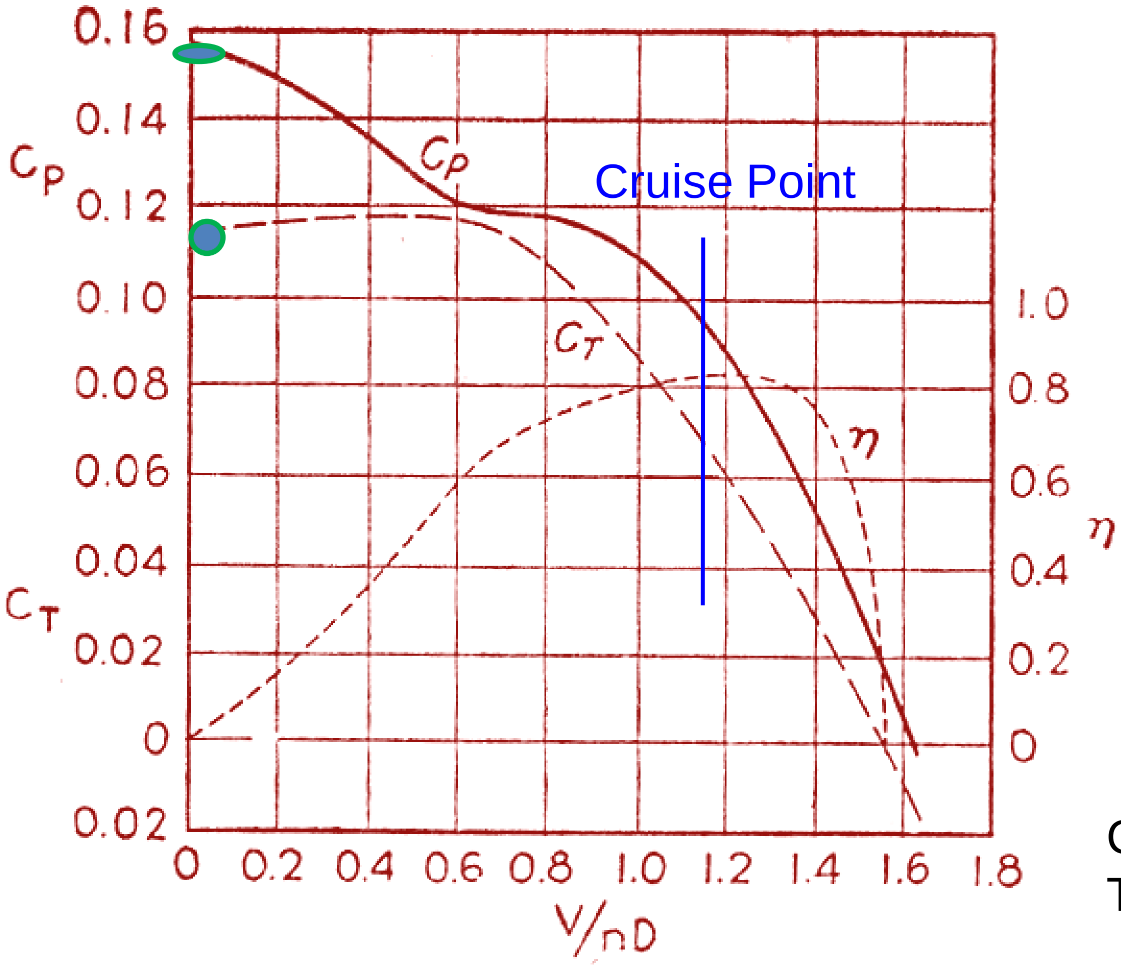
for a blade element airfoil characterized by its C_d & C_l

The estimations from blade element theory is within 10% of the actually obtained results.



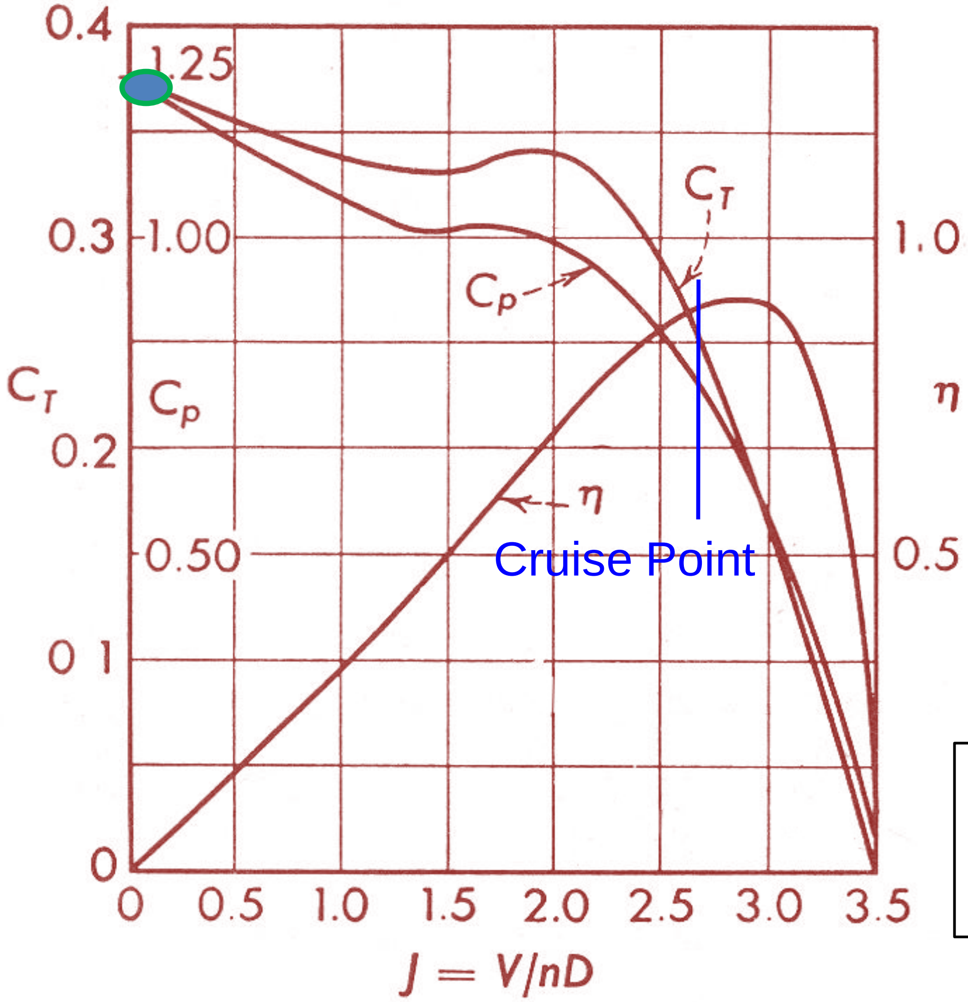
If the elemental performances are plotted in the form of dC_T /dX and dC_Q /dX variation in X, the span-wise direction of a blade (root to tip)

Low speed aircraft propeller Characteristics

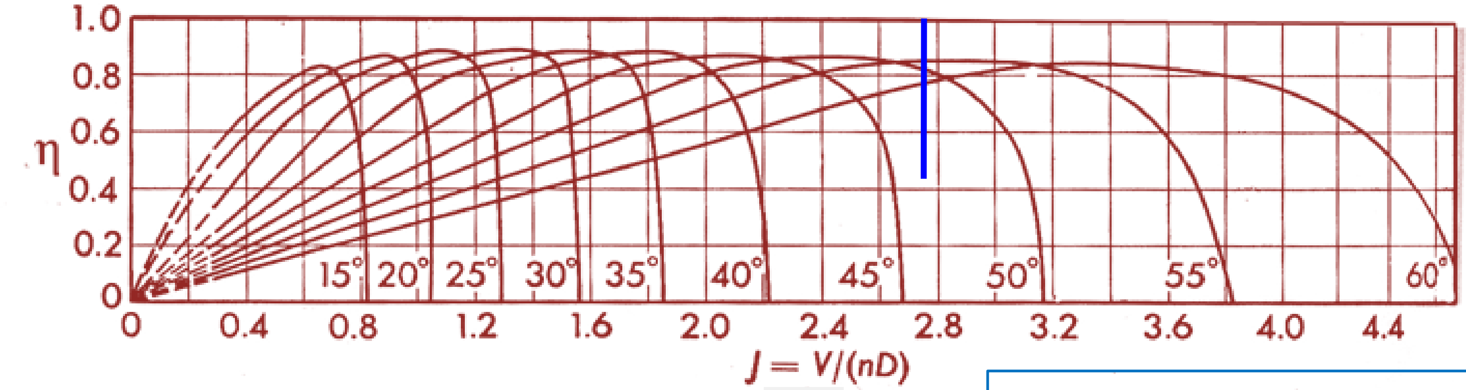


Courtesy:
Theodorsen, 1948

High speed aircraft propeller characteristics

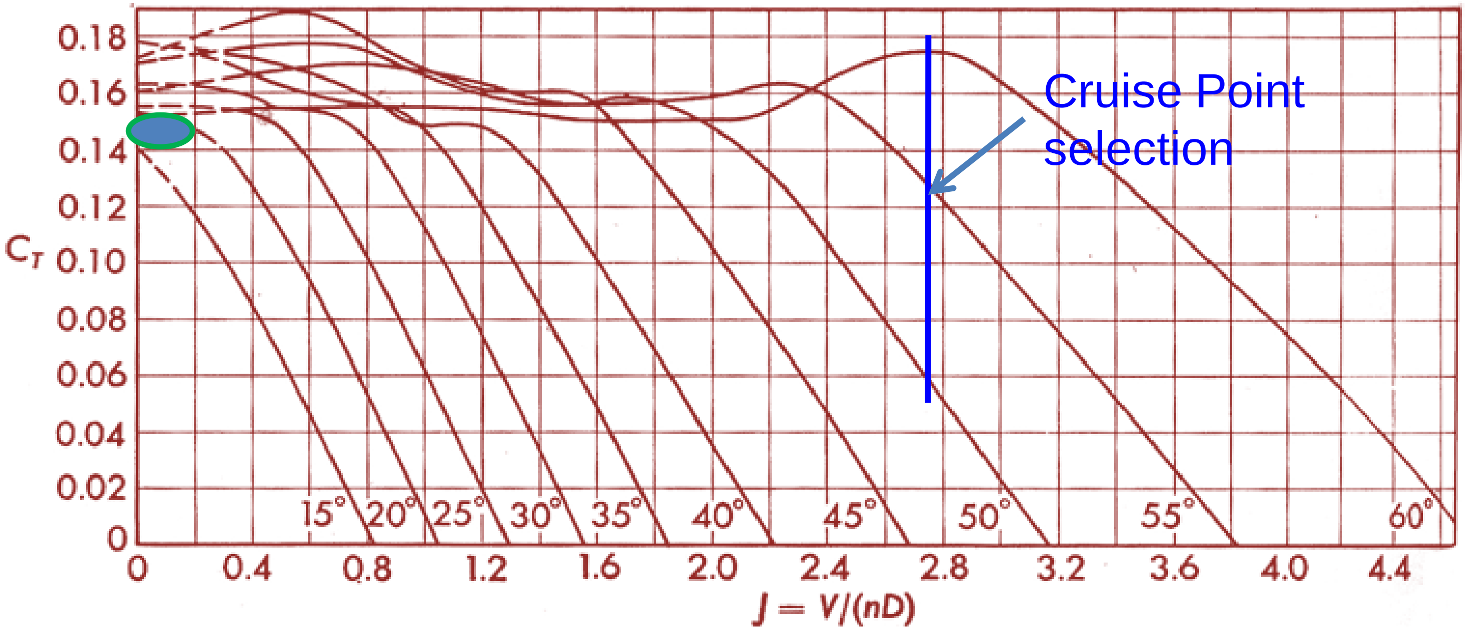


Courtesy: Dommasch et al., 1967



Efficiency of Propeller

Variable Pitch Propeller

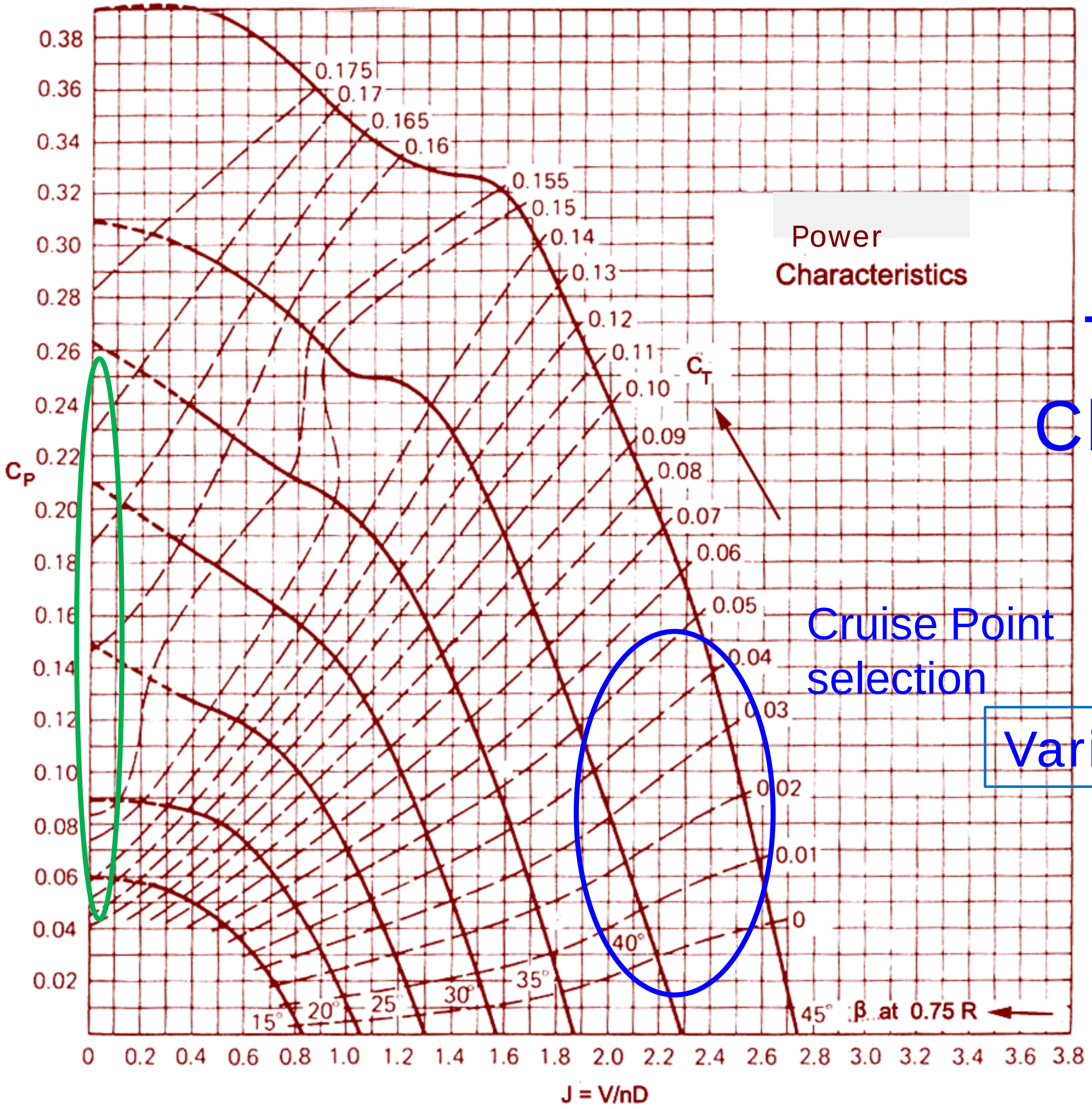


Cruise Point selection

Thrust Co-efficient of Propeller

Courtesy:
NACA, USA

Typical Propeller Thrust-Power Characteristics using NACA airfoils



Cruise Point selection

Variable Pitch Propeller

Courtesy:
NACA, USA

C_s, the speed power coefficient, defined by,

$$Cs = (\rho.V^5 / P.n^2)^{1/5}$$

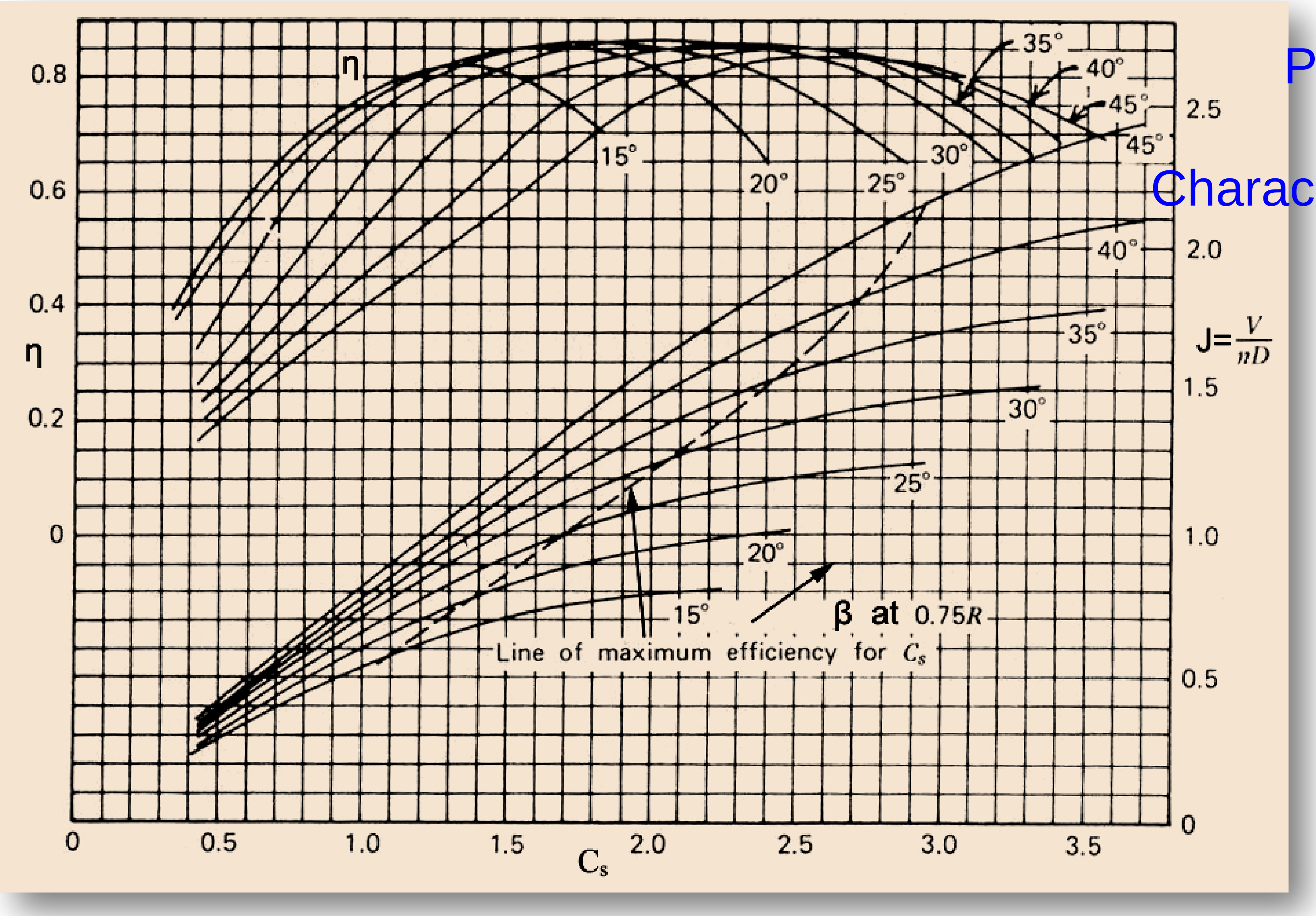
Is often used for design / selection of propeller

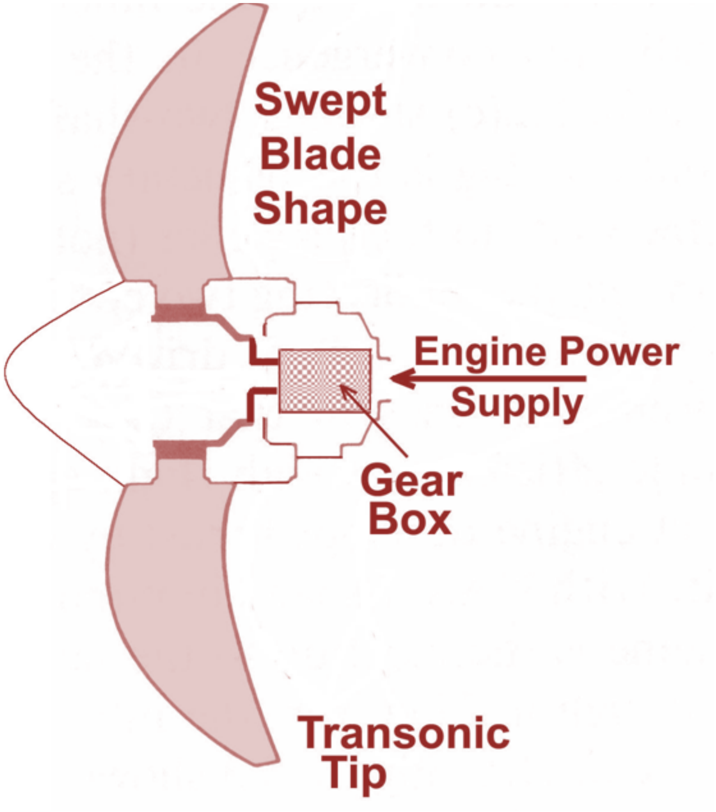
If coeff of power, Cp as a function of J, is known, Cs can be obtained from

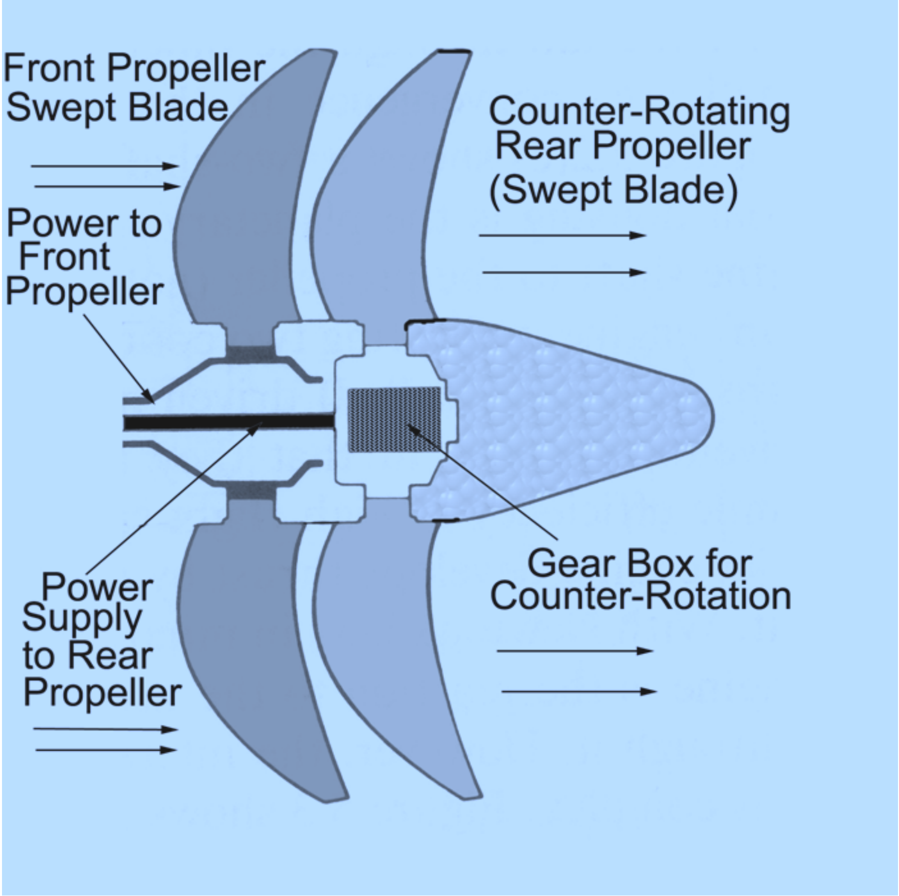
$$Cs = J / Cp^{1/5}$$

The *usefulness of C_s is in the process of defining it -- diameter was eliminated.* Thus the propeller design or selection related flow parameters may be estimated even before the propeller size is fixed.

Propeller Cs Characteristics







Transonic Swept bladed propellers

(a) Tractor ; (b) counter-rotating Pusher

In an aircraft application:

Propeller Power, $P_{prop} = P_{Engine} \cdot \eta_{shaft} \cdot \eta_{prop}$

Propeller Torque, $Q_{prop} = Q_{engine}$

Typically,

at Take off,

Q_{prop} is low, β is low, P_E is High, rpm is high

at Cruise ,

Q_{prop} is high, β is high, P_E is low, rpm is low

Next

Propeller Tutorial