Propellers and Ducted Fans

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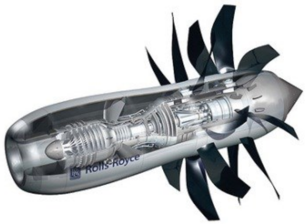
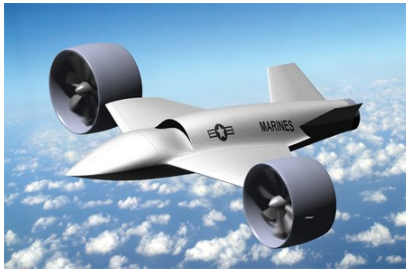
Room 2.40 QB





Propeller Performance and Design

Lecture 3

Notes in Blackboard: https://www.ole.bris.ac.uk

Propeller Design

Momentum Theory

+

Blade Element Analysis

Propeller Design for

- Constant pitch
- Optimum angle of incidence

Propeller Performance

- Test rigs
- Empirical charts

Propeller re-design

PROPELLER DESIGN

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

For Constant Pitch Propeller

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

The Geometric Pitch (***P***) is the axial displacement of the propeller prescribed by the physical shape of the blades.

The angle (β) is the angle of the blade to the plane of

Since all blade radial locations must have the same value of ***E***, then:

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

The Effective Pitch (***E***) is the axial displacement of the propeller relative to the general air mass (i.e. the progress of the aircraft).

The angle (ϕ) is the angle of the resultant airflow to the plane of rotation.

But since this is not a static condition, it is more convenient to replace ***E*** with V and modify the rotational displacement accordingly then:

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

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

$$\frac{5}{2\pi(0.75R)} = \frac{5}{4.7} = 1.06 --> 46.6 \text{ degs}$$

$$\boldsymbol{\alpha = \arctan \frac{P}{2\pi r} - \arctan \frac{JD}{2\pi r}}$$

$$\frac{2x2}{2\pi(0.75R)} = \frac{4}{4.7} = 0.848 --> 40.3 \text{ degs}$$

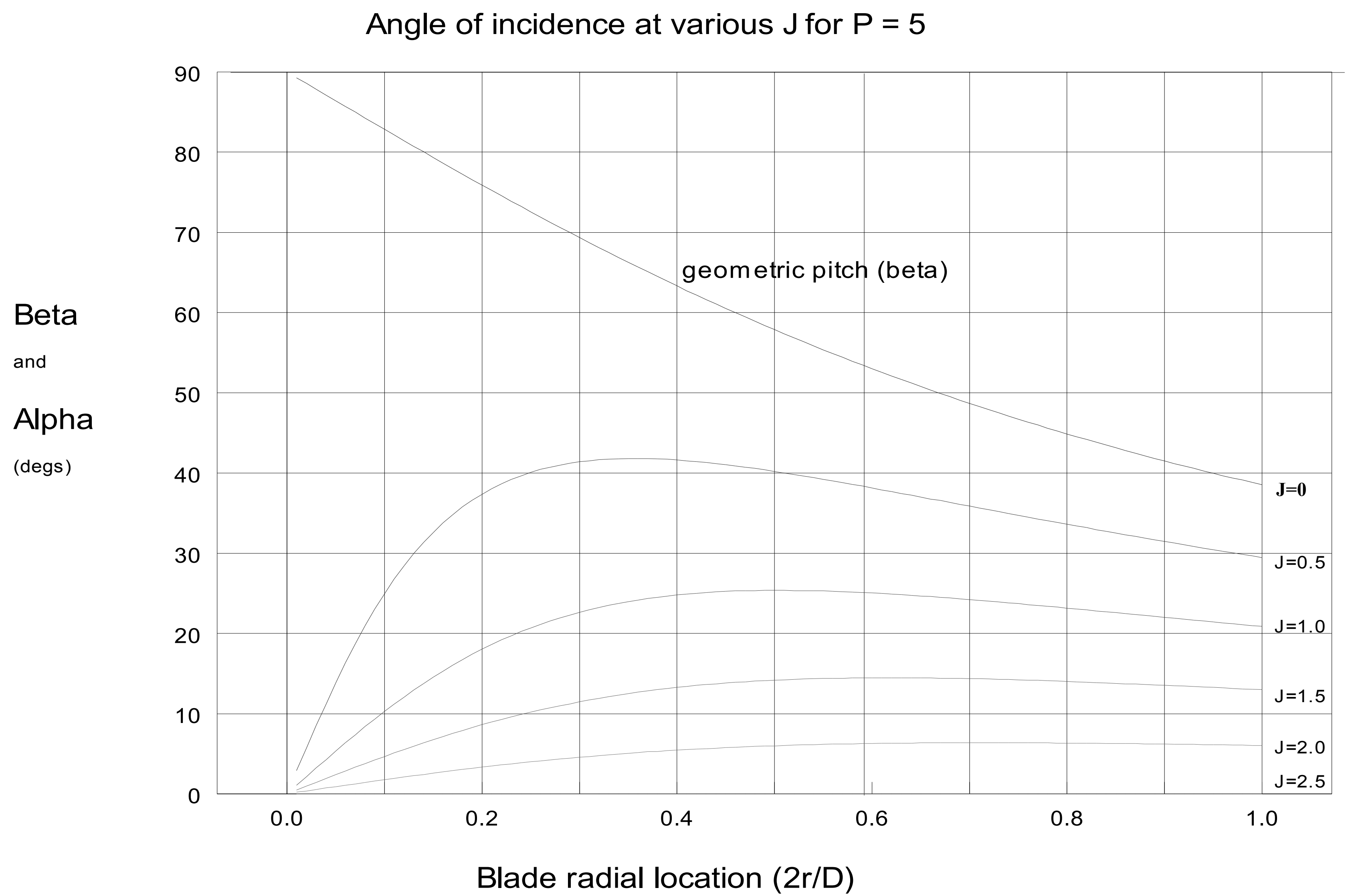
It can be seen that when $P = JD$ $\left(\text{ie. when } J = \dfrac{P}{D}\right)$ then the incidence along the entire blade is zero and the blade produces zero lift.

N.B. - In practice it is unusual for all the radial locations of a blade to have the same pitch (referred to as Constant Pitch).

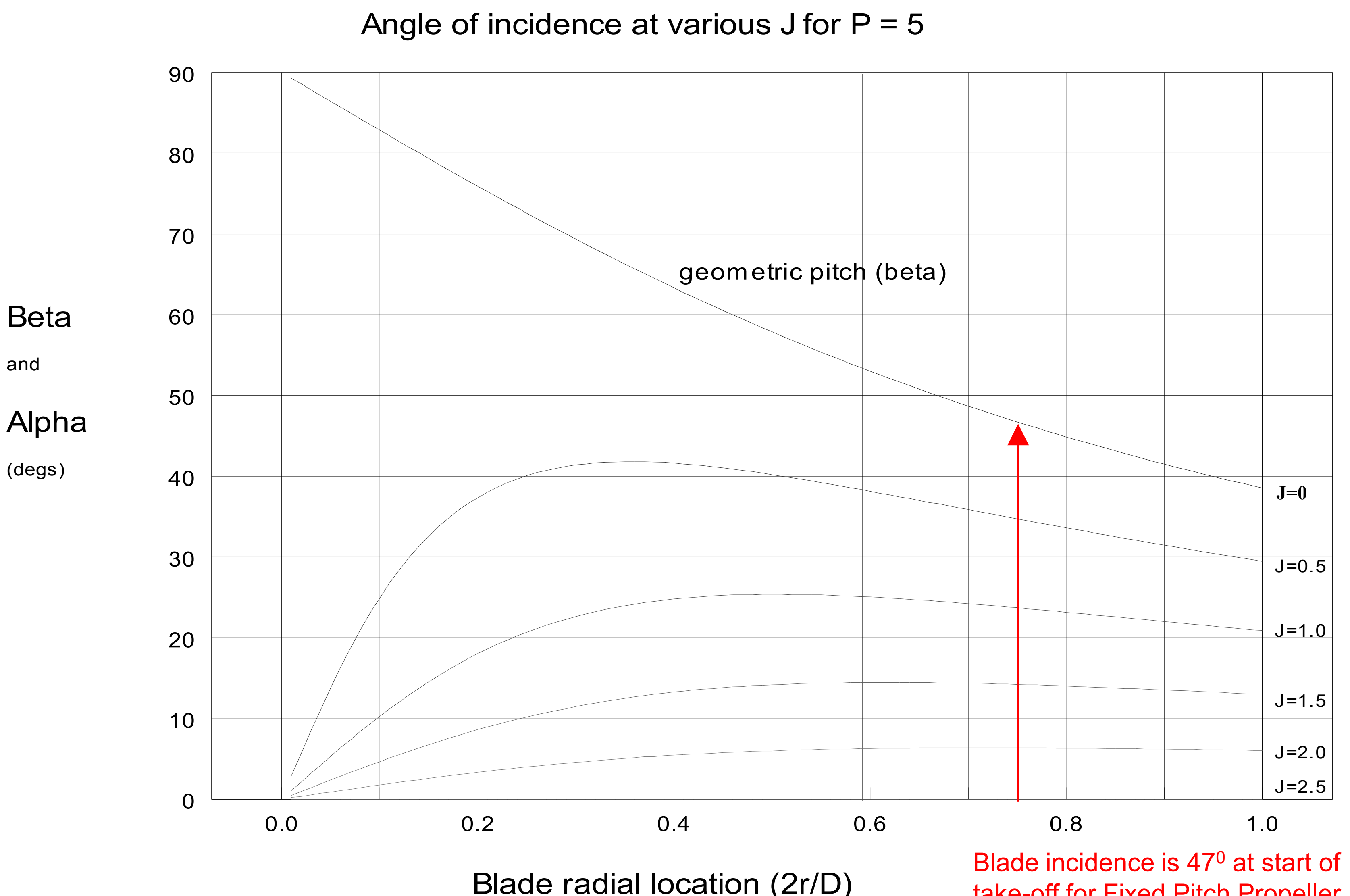
For example; If $\boldsymbol{P}=5m$ and $\boldsymbol{D}=2m$, the angle of incidence (α) can be determined over a range of velocities (shown as values of $\boldsymbol{J}$). What about $\boldsymbol{J}$=2?

The values for $\boldsymbol{P}$ and $\boldsymbol{D}$ were chosen to give an angle of incidence of 6 degrees at $\boldsymbol{\beta}_{0.75}$ (at J=2). This angle of incidence is typical of that for best lift/drag of an aerofoil section.

Example

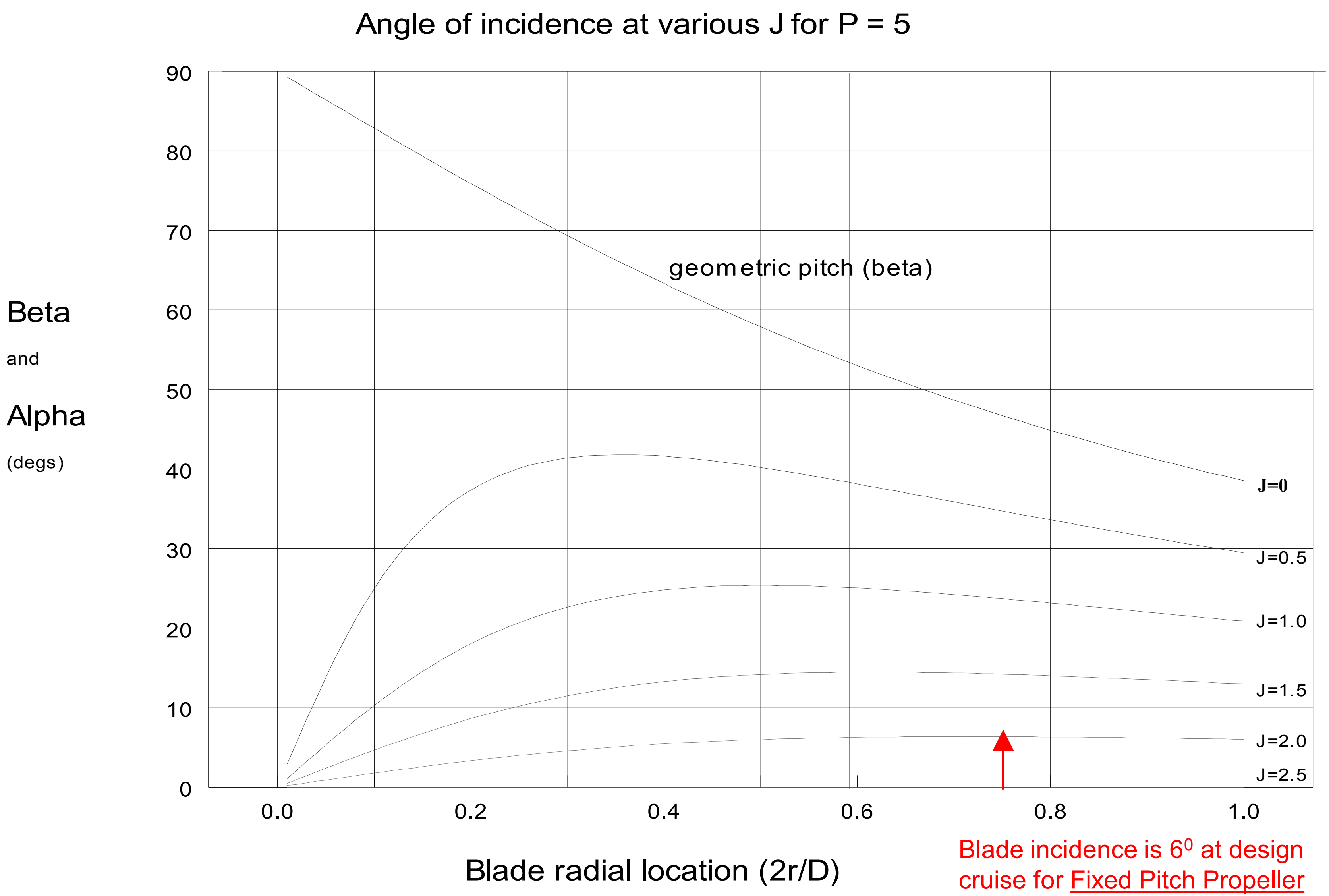

Angle of incidence at various J for P = 5
Beta
and
Alpha
(degs)
90
80
70
60
50
40
30
20
10
0
geometric pitch (beta)
J=0
J=0.5
J=1.0
J=1.5
J=2.0
J=2.5
0.0
0.2
0.4
0.6
0.8
1.0
Blade radial location (2r/D)

Example

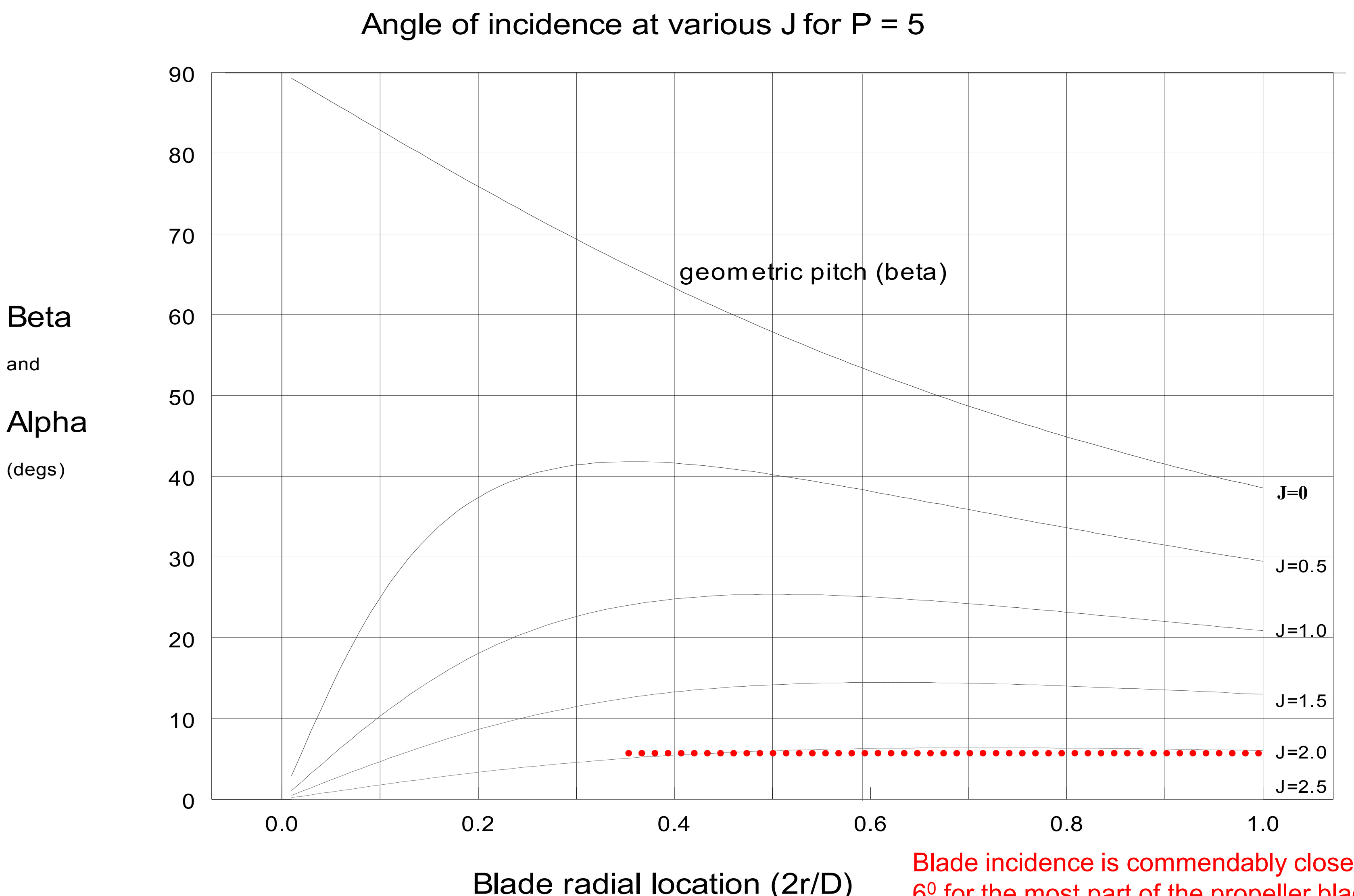


Blade incidence is 47^0 at start of take-off for Fixed Pitch Propeller

PROPELLER DESIGN – Example



PROPELLER DESIGN – Example



Blade incidence is commendably close to 6^0 for the most part of the propeller blade.

Design for Optimum Incidence

In practice, it is unusual for all the radial locations of a blade to have the same pitch (Constant Pitch).

In theory the radial twist of the blade can be such that the <u>angle of incidence is constant</u> along it's length (for a particular J) so that the entire blade can operate at it's best L/D.

For the incidence to remain constant along the length of the blade, the Geometric Blade Pitch Angle (β) for each radial station can be determined as follows:

$$\beta = \alpha + \phi \,, \qquad \tan\phi = \frac{V}{2\pi r n} = \frac{JnD}{2\pi r n} = \frac{JD}{2\pi r}$$

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

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

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

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

$$\left.\begin{array}{l}\text{P=15cms}\\ \text{D=28cms}\end{array}\right\}\frac{P}{D}=y=0.54$$

2-blade wood pusher

	INS	CM	SRP
5506650	7 X 4	18 X 10	£1.99
5506653	8 X 5	20 X 13	£2.49
5506654	8 X 6	20 X 15	£2.49
5506655	9 X 6	23 X 15	£2.59
5506657	10 X 6	25 X 15	£2.79
5506659	10 X 7	25 X 18	£2.79
5506664	11 X 6	28 X 15	£2.99
5506666	11 X 8	28 X 20	£2.99

2-blade glass filled

	INS	CM	SRP
5506801	6 X 2.5	15 X 6	£0.99
5506803	6 X 3	15 X 8	£0.99
5506805	7 X 4	18 X 10	£1.09
5506807	7 X 6	18 X 15	£1.09
5506811	8 X 4	20 X 10	£1.15
5506813	8 X 6	20 X 15	£1.15
5506817	9 X 4	23 X 10	£1.25
5506819	9 X 6	23 X 15	£1.25
5506823	10 X 4	25 X 10	£1.39
5506825	10 X 6	25 X 15	£1.39
5506829	11 X 7	28 X 18	£1.69
5506831	11 X 7.5	28 X 19	£1.69
5506835	12 X 6	30 X 15	£2.39

3-blade glass filled

	INS	CM	SRP
5506855	8 X 6	20 X 15	£2.89
5506859	9 X 6	23 X 15	£3.19
[illegible]	[illegible]	[illegible]	[illegible]

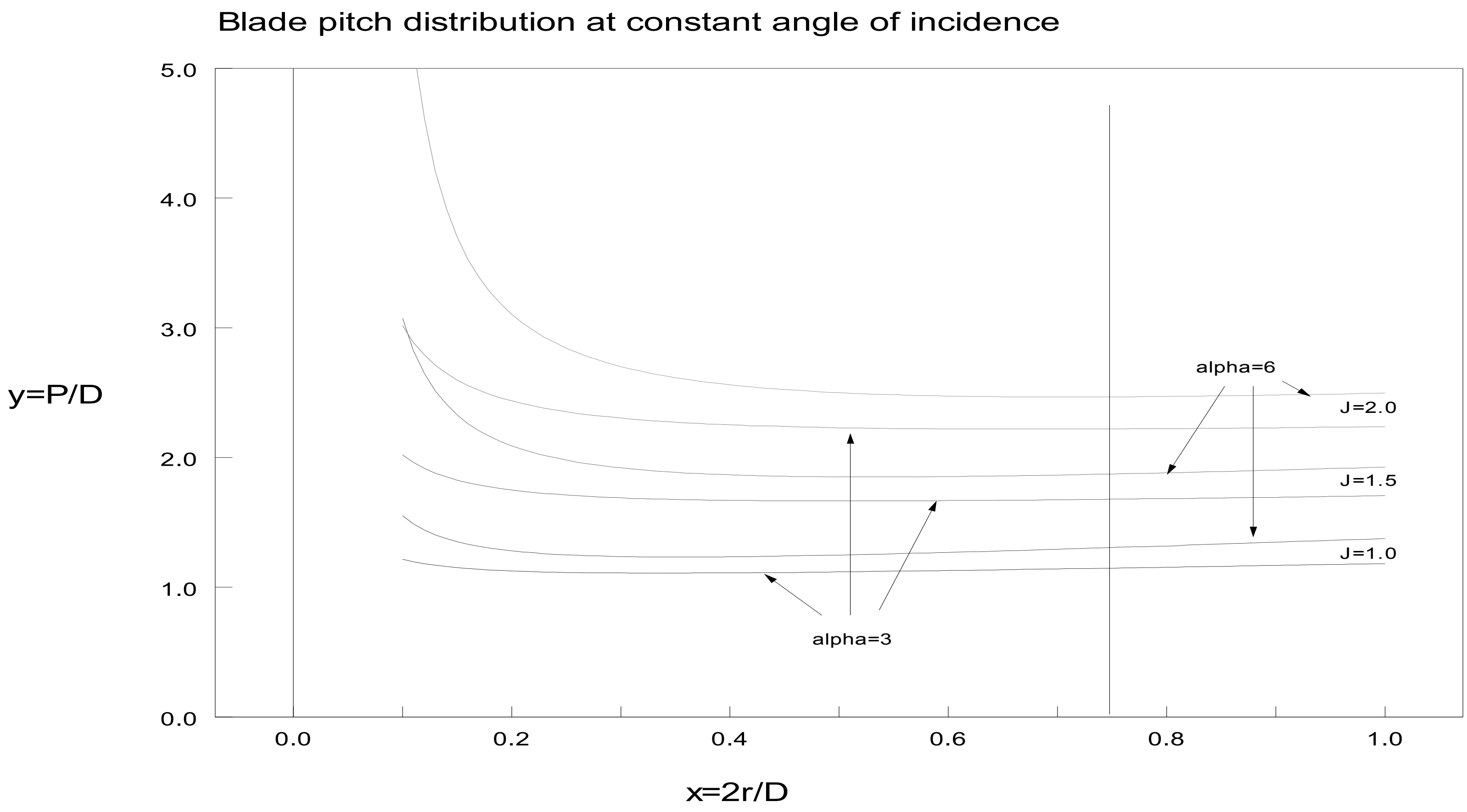
Zinger props

2-blade wood tractor

	INS	CM	SRP
5506580	7 X 4	18 X 10	£1.49
5506581	7.5 X 6	19 X 15	£1.59
5506582	8 X 4	20 X 10	£1.59
5506583	8 X 6	20 X 15	£1.59
5506584	8 X 7	20 X 18	£1.59
5506586	9 X 4	23 X 10	£1.85
5506587	9 X 5	23 X 13	£1.85
5506588	9 X 6	23 X 15	£1.85
5506589	9 X 7	23 X 18	£1.75
5506591	10 X 4	25 X 10	£1.99
5506592	10 X 5	25 X 13	£1.99
5506593	10 X 6	25 X 15	£1.99
5506594	10 X 7	25 X 18	£1.99
5506595	10 X 8	25 X 20	£1.99
5506596	11 X 5	28 X 13	£2.39
5506597	$\boxed{11 \text{ X } 6 \quad 28 \text{ X } 15}$		£2.39
5506602	11 X 7	28 X 18	£2.39
5506598	11 X 8	28 X 20	£2.39
5506599	11 X 9	28 X 23	£2.39
5506603	12 X 4	30 X 10	£2.99
5506601	12 X 5	30 X 13	£2.99
5506604	12 X 6	30 X 15	£2.99
5506605	12 X 8	30 X 20	£2.99
5506600	12 X 10	30 X 25	£2.99
5506606	13 X 5	33 X 13	£3.49
5506577	13 X 6	33 X 15	£3.49
5506607	13X6-10	33X15-25	£3.49
5506578	13 X 8	33 X 20	£3.49
5506579	13 X 10	33 X 25	£3.49
5506614	14 X 4	36 X 10	£4.69
5506608	14 X 5	36 X 13	£4.69
5506609	14 X 6	36 X 15	£4.69
5506610	14X6-10	36X15-25	£4.69
5506611	14 X 8	36 X 20	£4.69
5506612	14 X 10	36 X 25	£4.69
5506613	15 X 6	38 X 15	£6.95

Example

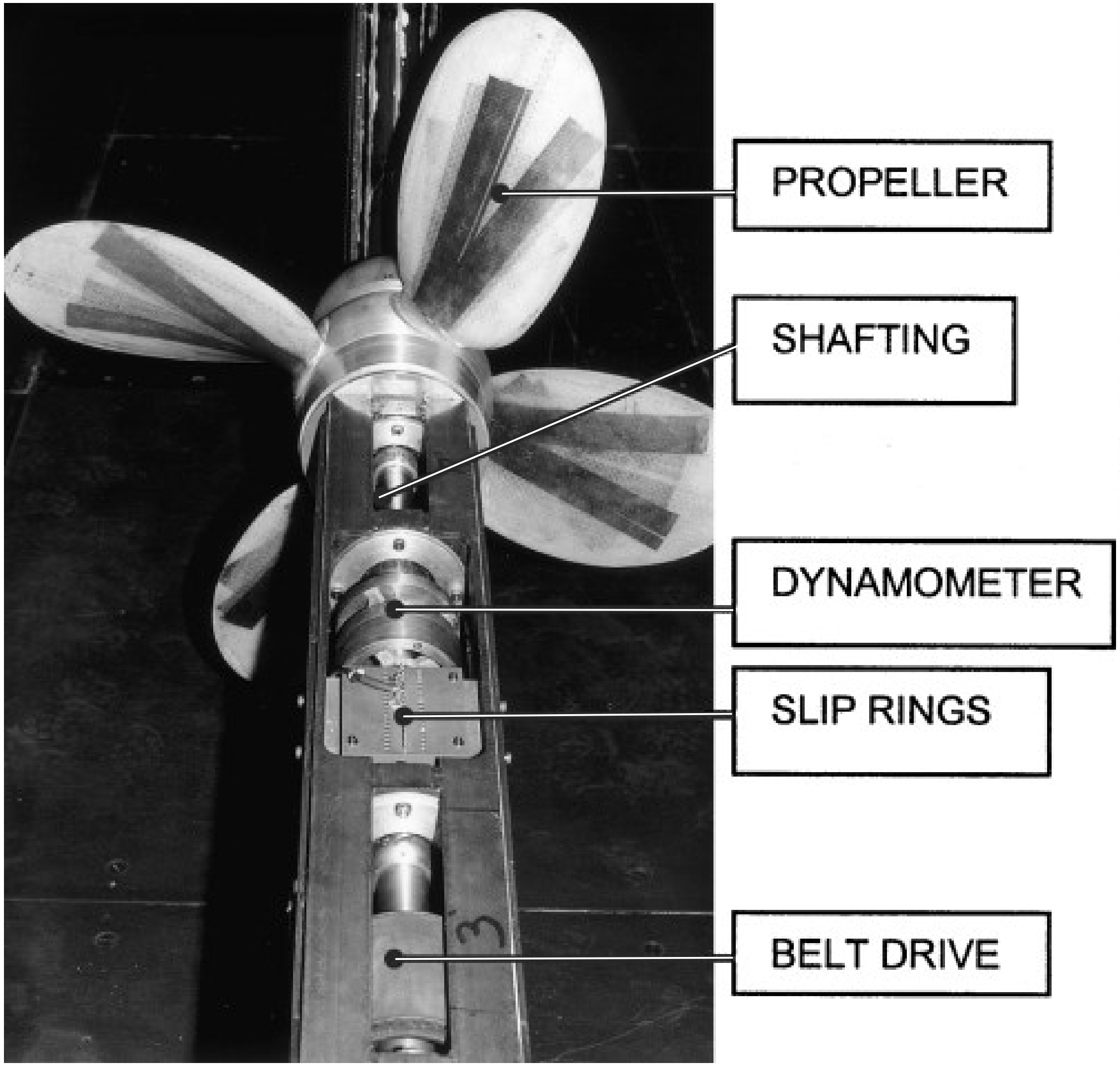
This has been plotted for two angles of incidence, $\alpha = 3^0$ and $\alpha = 6^0$ and for three values of advance ratio, $J = 1.0, J = 1.5$ and $J = 2.0$ and this is shown below:

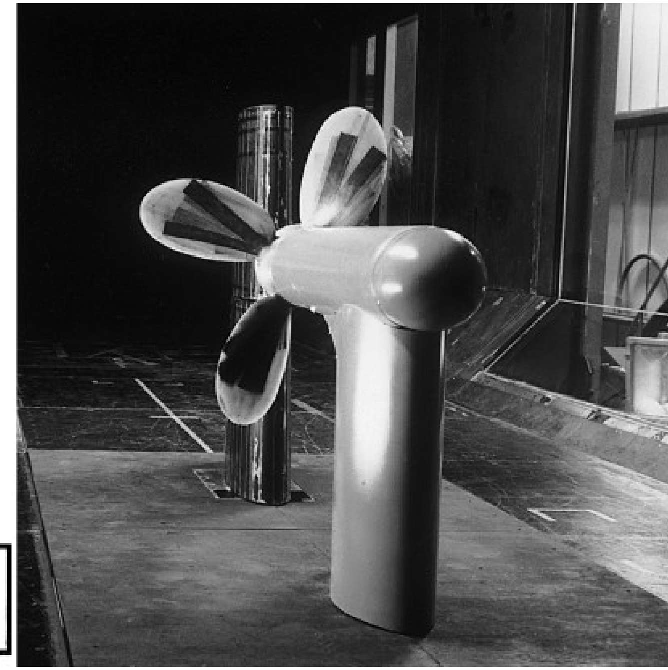


PROPELLER PERFORMANCE

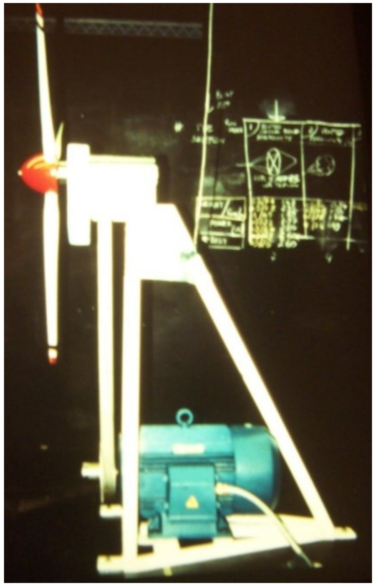
PROPELLER TESTING

Typical test rig





PROPELLER TESTING – Bristol University test rigs



▲ 11 kw High speed (8,000rpm) propeller test rig.

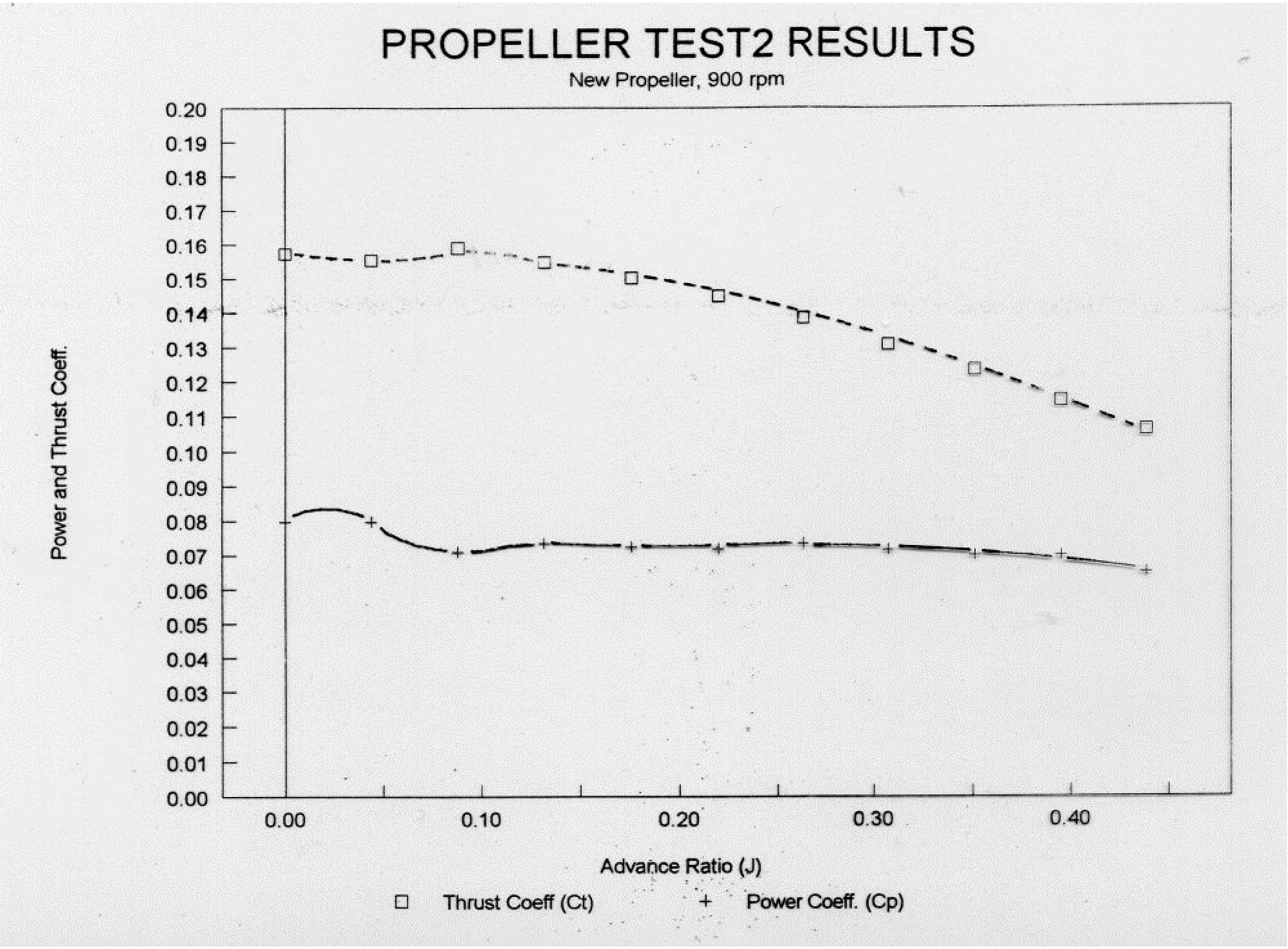
30 kw Ducted fan test rig (for tests commencing 2010).►

◄ 30 kw General purpose propeller test rig.

Applied Example

Aviation Enterprises "Chevvron" light aircraft

Applied Example



Propeller Performance

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 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

Propeller Performance

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

PROPELLER PERFORMANCE

Recalling the Coefficients used in the analysis of propeller performance

$$\boldsymbol{J} = \frac{\boldsymbol{V}}{\boldsymbol{nD}}$$ (where $\boldsymbol{J}$ in the Advance Ratio)

$$C_P = \frac{P}{\rho n^3 D^5}$$

$$C_T = \frac{T}{\rho n^2 D^4}$$

$$\eta_p = \frac{TV}{P} = \frac{C_T \rho n^2 D^4 V}{C_P \rho n^3 D^5} = \frac{C_T J}{C_P}$$

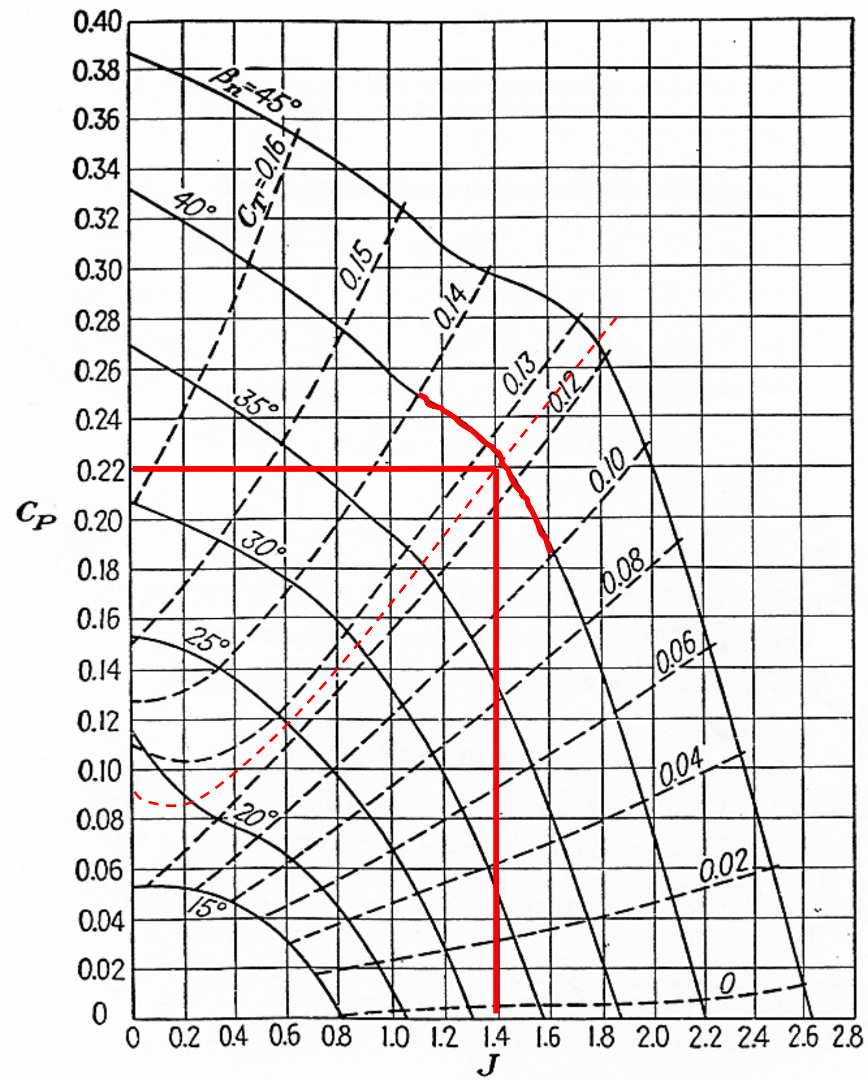
Where $\boldsymbol{\rho}$ = air density, $\boldsymbol{n}$ = propeller rotational speed (revs/sec), $\boldsymbol{D}$ = propeller diameter

PROPELLER PERFORMANCE CHARTS

A typical performance chart for a controllable pitch propeller is shown here.

For example: If the pilot knows the available engine power (C_P=*0.22*) and the speed at which he/she wishes to fly (J=*1.4*), then propeller pitch (βn), should be set to 40^0 and the available thrust, from the $\boldsymbol{C_T}$ value, (=*0.125*) can be determined.

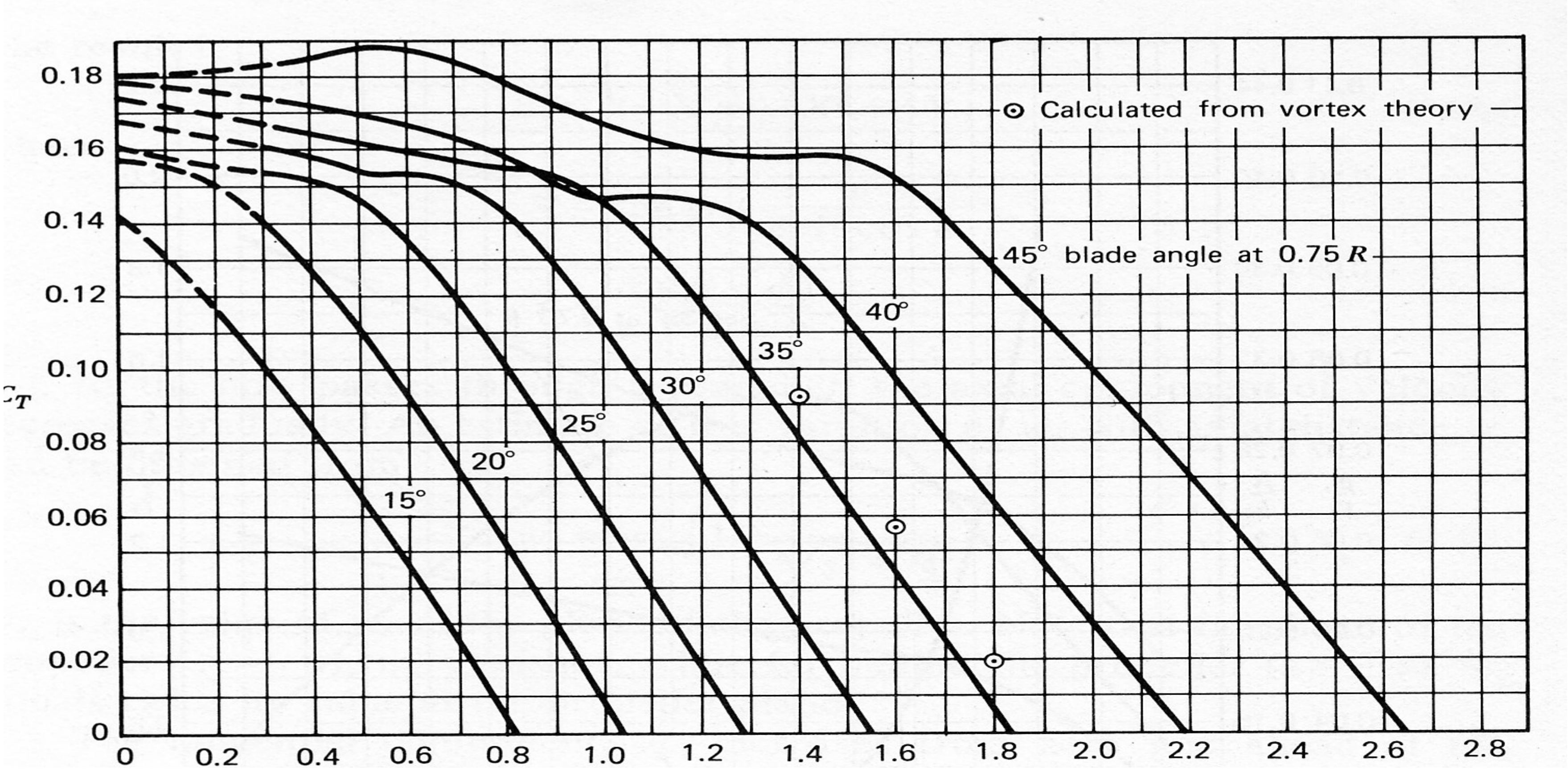
If the aircraft drag at this speed is known, then the rate of climb can also be calculated.



PROPELLER PERFORMANCE CHARTS continued

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

Inspection of the $\boldsymbol{C_T}$ 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.



PROPELLER PERFORMANCE CHARTS continued

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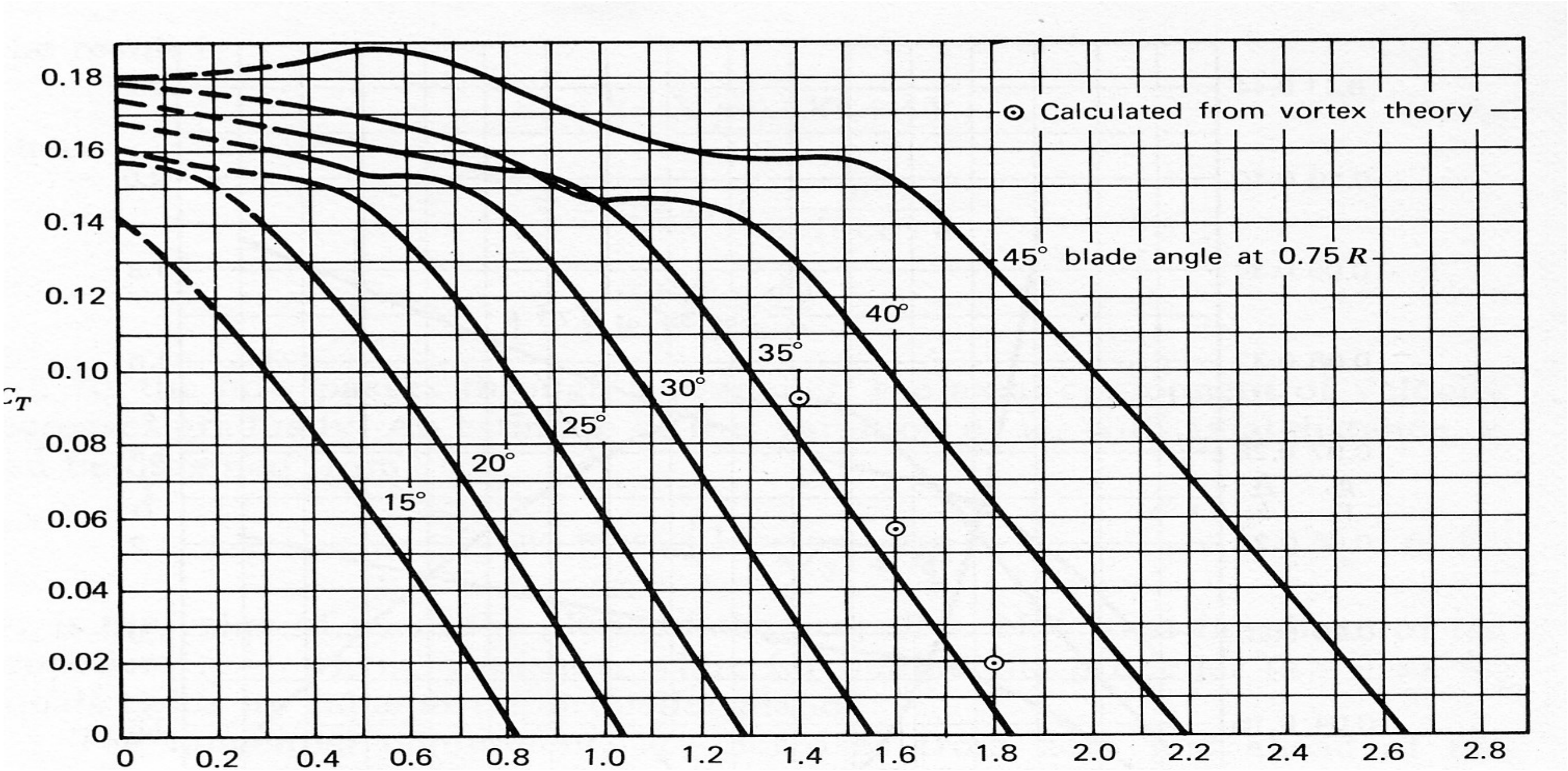


ϕ gets smaller

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

ABSORBING MORE POWER -

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:

- x Reduces ground clearance, increasing stone/chip damage
- x Increases blade tip speed, possibly incurring wave drag and compressibility noise
- x May require reduction gearbox to reduce tip speed, thus cost and weight penalty
- x Higher gyroscopic forces may affect handling

Increase propeller rotational speed

ABSORBING MORE POWER -

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:

- x Power is proportional to the cube of speed but thrust is proportional only to the square of speed
- x Increases blade tip speed, possibly incurring wave drag and compressibility noise
- x Increase engine and transmission noise
- x Higher gyroscopic forces may affect handling

Increase number of propeller blades.

ABSORBING MORE POWER -

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:

- x Requires new hub assembly
- x Increases hub complexity, particularly for controllable or constant speed propellers
- x Expensive to modify and maintain

Increase propeller blade chord

ABSORBING MORE POWER -

Advantages:

- ✓ Increases rotor solidity and therefore thrust generating potential
- ✓ Easy retrofit if blades are detachable
- ✓ Increases Reynolds number

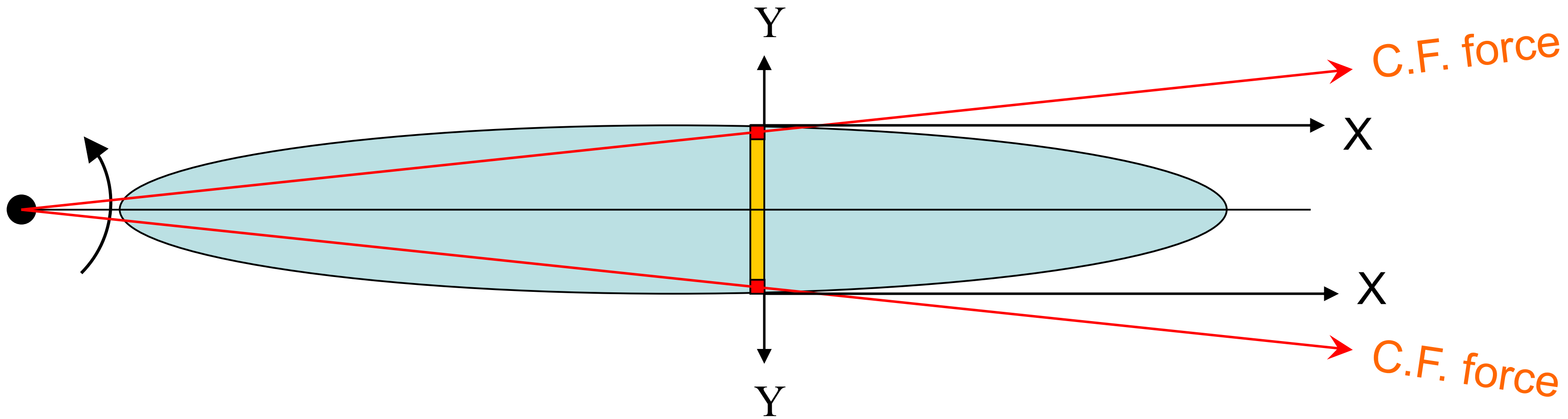
Disadvantages:

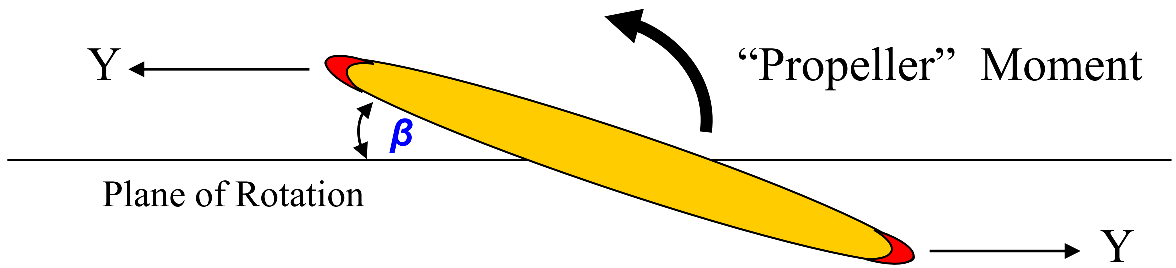
- x Increases the "Propeller Moment" and thus associated control loads
- x Reduces blade aspect ratio, increasing tip losses
- x May compromise aerofoil performance due to higher camber
- x Generally more expensive to manufacture

Propeller Moment

ABSORBING MORE POWER – The "Propeller Effect"

Consider an elemental strip of propeller blade to be made up of discrete masses.





Increase propeller blade pitch

ABSORBING MORE POWER -

Advantages:

✓ The easiest option, no modifications required

Disadvantages:

x Operating off the design point for the blade aerofoil

x General increase in vibration, due to localised stalling

Contra-Rotational Coaxial Propeller

ABSORBING MORE POWER – The “Contra-Rotational Coaxial Propeller”
One way of absorbing more power is to introduce another set of blades that rotate in the opposite direction. This has a number of advantages…..and disadvantages.

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.

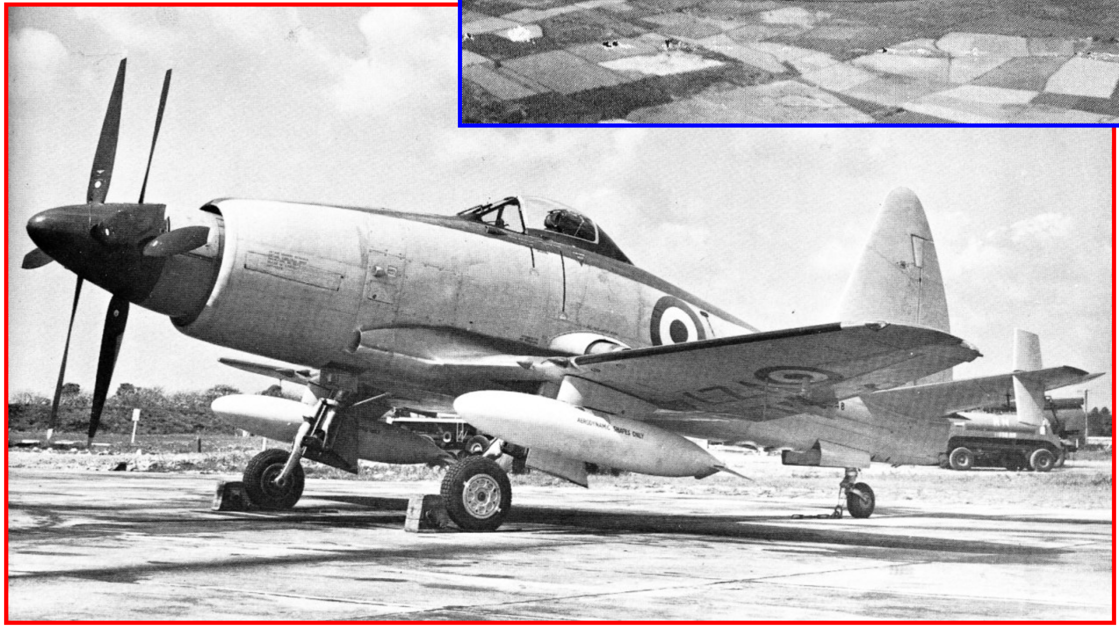
Disadvantages:

- x Expensive initial costs and maintenance.
- x High weight penalty.
- x Complex pitch change mechanism.

PROPELLER RE-DESIGN

ABSORBING MORE POWER – The "Contra-Rotational Coaxial Propeller"

Fairey Gannet

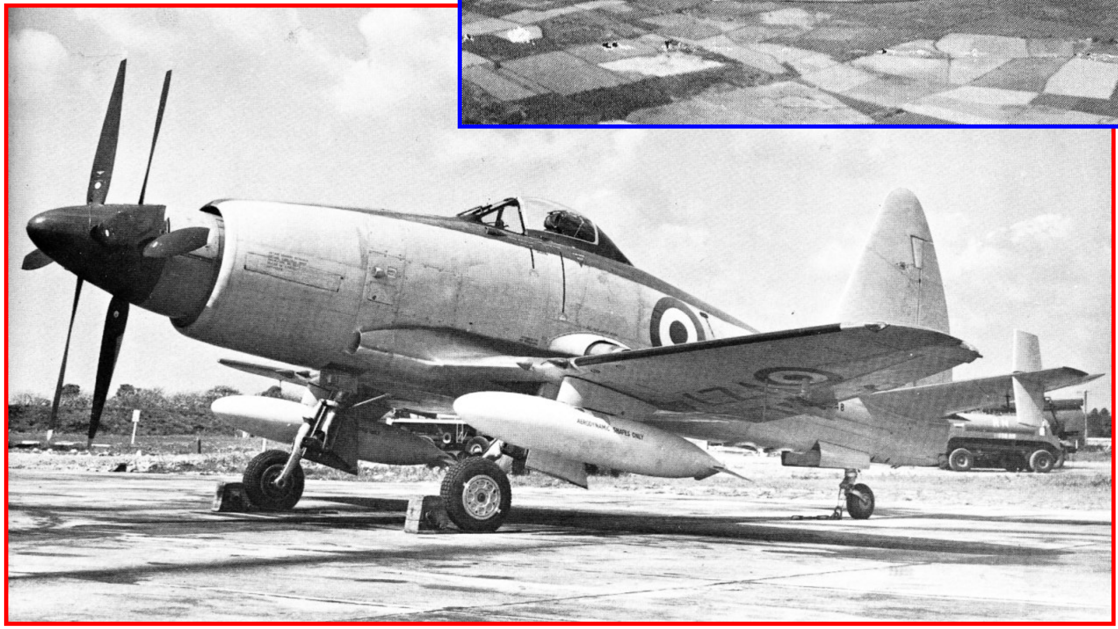


Westland Wyvern

TANDEM PROPELLERS

ABSORBING MORE POWER – The “Contra-Rotational Coaxial Propeller”

Fairey Gannet



Westland Wyvern

TANDEM PROPELLERS

ABSORBING MORE POWER – The “Contra-Rotational Coaxial Propeller System” and the – The “Counter-Rotational Propeller System”