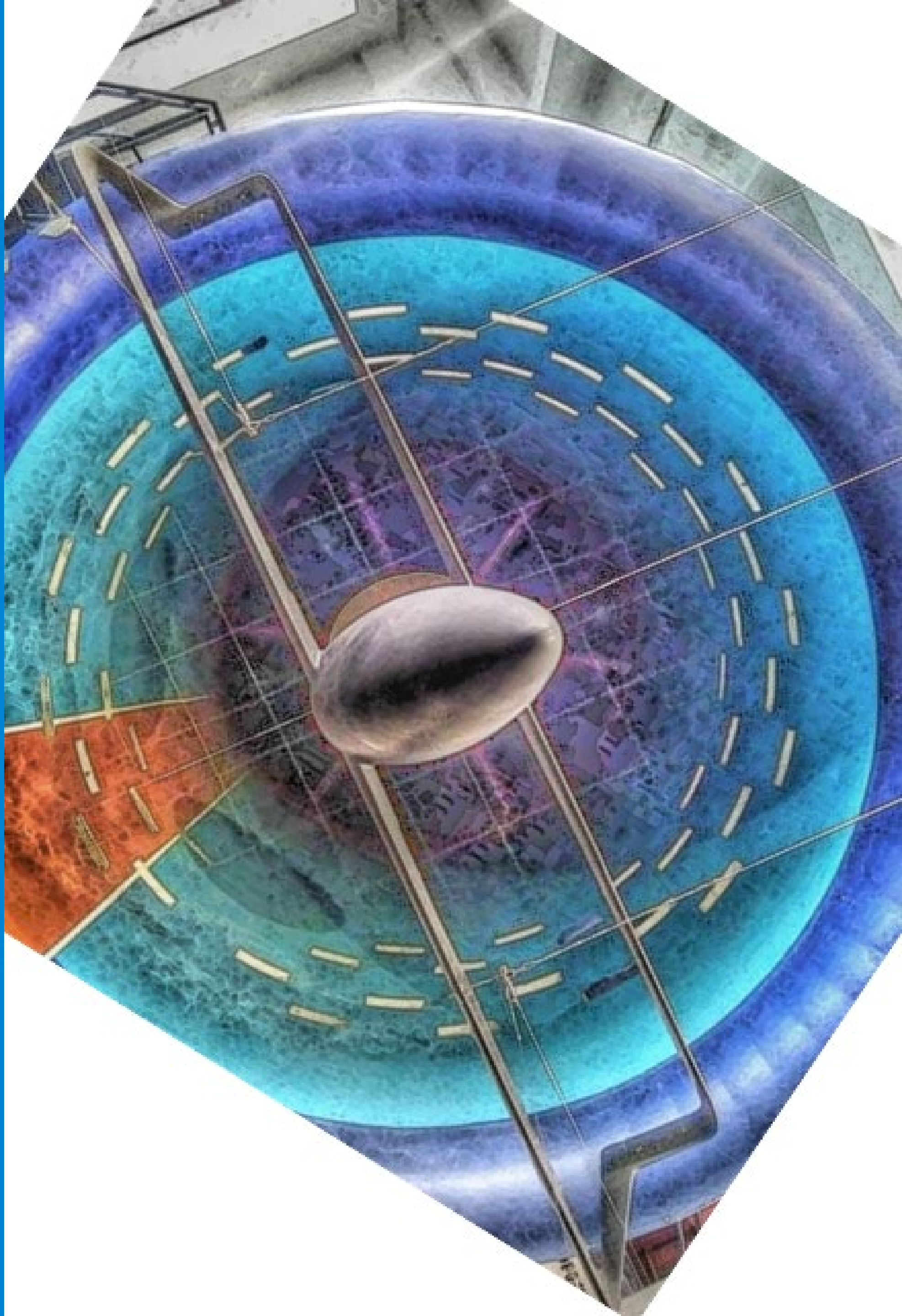
Propellers



Propeller-airframe interaction

Propeller configurations
Propeller geometry, efficiency
Propeller types
The effect of diameter and number of blades on propeller efficiency
Fans (ducted) propulsors versus free propellers
Propeller «P» effects
Asymmetric light twin
Propeller–wing aerodynamic interaction
Distributed propulsion concept

References:

1. Gudmundsson, Snorri. "General Aviation Aircraft Design: Applied Methods and Procedures." (2013)
2. Stinton, Darrol. "The Design of the Airplane." (1983).
3. Raymer, Daniel P. "Enhancing Aircraft Conceptual Design using Multidisciplinary Optimization." (2002).
4. Aref, Pooneh, Mehdi Ghoreyshi, Adam Jirásek, Matthew Satchell and Keith Bergeron. "Computational Study of Propeller–Wing Aerodynamic Interaction." Aerospace (2018).
5. Marcus, P. "Aerodynamic modelling and performance analysis of over-the-wing propellers: A combined numerical and experimental study." (2018).
6. Sinnige, Tomas; van Arnhem, Nando; Stokkermans, Tom C. A.; Eitelberg, Georg; Veldhuis, Leo L. M. (2018). Wingtip-Mounted Propellers: Aerodynamic Analysis of Interaction Effects and Comparison with Conventional Layout. Journal of Aircraft, 1–18. doi:10.2514/1.C034978
7. Sinnige, Tomas; van Arnhem, Nando; Stokkermans, Tom C. A.; Eitelberg, Georg; Veldhuis, Leo L. M. (2018). Wingtip-Mounted Propellers: Aerodynamic Analysis of Interaction Effects and Comparison with Conventional Layout. Journal of Aircraft, 1–18. doi:10.2514/1.C034978
8. Aircraft Performance and Design. J.D. Anderson. McGraw-Hill Publishing Company, Shoppenhangers Road, Maidenhead, Berks SL6 2QL, UK. 1999. 580pp
9. Moore, Kevin R. and Andrew Ning. "Distributed Electric Propulsion Effects on Traditional Aircraft Through Multidisciplinary Optimization." (2018).

Tractor or pusher configuration?

Tractor

Advantages:

- The heavy engine is at the front, which helps to move the center of gravity forward and therefore allows a smaller tail for stability consideration
- The propeller is working in an undisturbed free stream.
- There is a more effective flow of cooling air for the engine.

Disadvantages:

- The propeller slipstream disturbs the quality of the airflow over the fuselage and wing root.
- The increased velocity and flow turbulence over the fuselage due to the propeller slipstream increase the local skin friction of the fuselage.

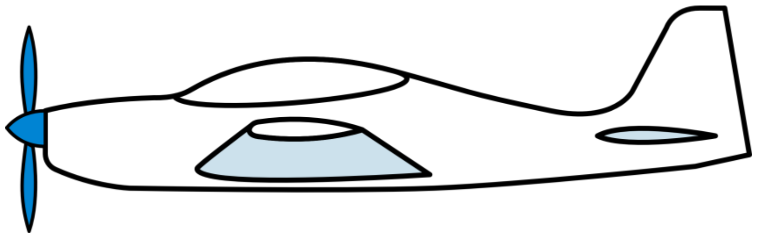
Pusher

Advantages:

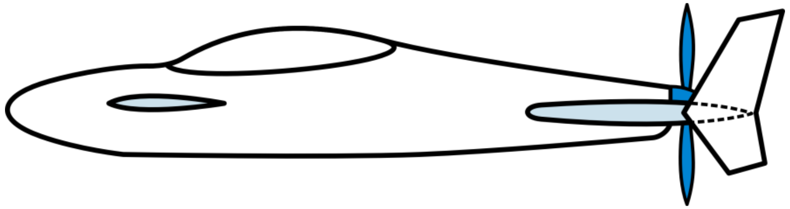
- Higher-quality (clean) airflow prevails over the wing and fuselage.
- The inflow to the rear propeller induces a favorable pressure gradient at the rear fuselage, allowing the fuselage to close at a steeper angle without flow separation. Engine noise in the cabin area is reduced.
- The pilot’s front field of view is improved.

Disadvantages:

- The heavy engine is at the back, which shifts the center of gravity rearward, hence reducing longitudinal stability.
- Propeller is more likely to be damaged by flying debris at landing.
- Engine cooling problems are severe.



A tractor configuration



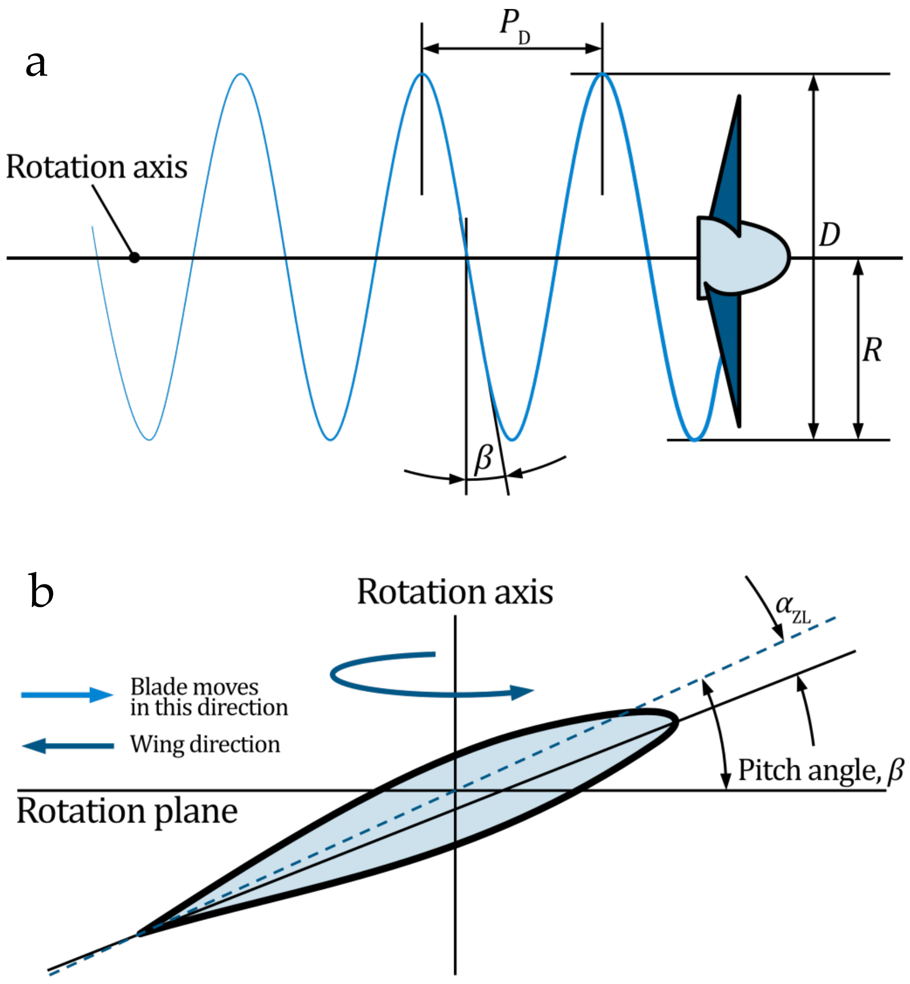
A pusher configuration

Propeller geometry

$$\tan\beta \ = \frac{P_D}{2\pi r_{ref}}$$

r_{ref} = reference radius, usually 75% of the propeller radius R

P_D = pitch distance of the propeller



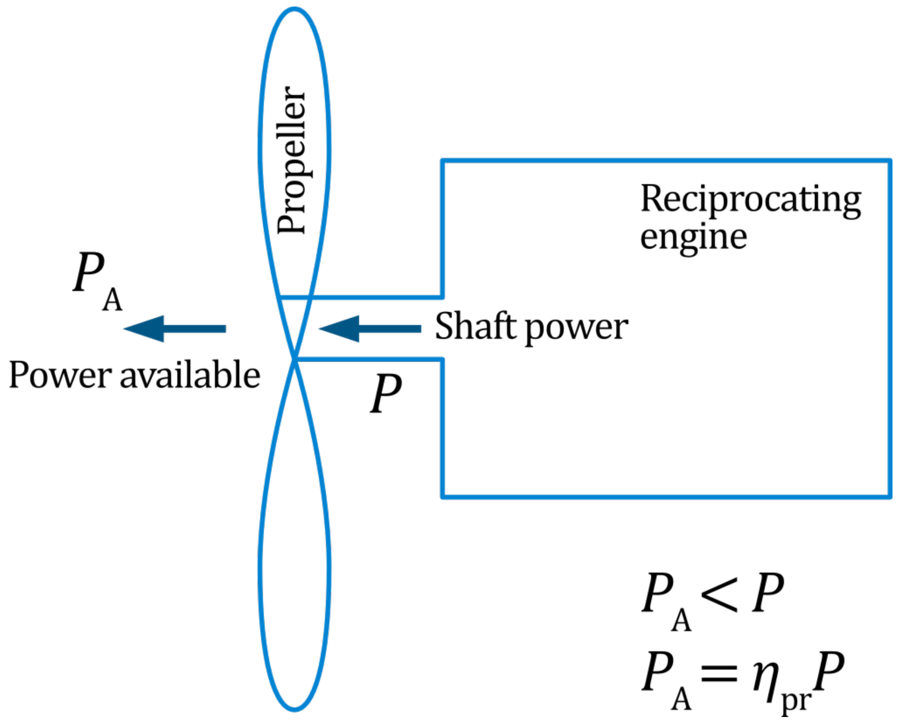
Schematics showing some propeller properties

Ref.: Gudmundsson, Snorri. "General Aviation Aircraft Design: Applied Methods and Procedures." (2013)

Propeller Efficiency

$$P_A = \eta_{pr} P \quad (1)$$

$$J = \frac{V_\infty}{ND} \qquad (2)$$



Schematic illustrating shaft power P and power available P_A from a propeller/reciprocating engine combination

Ref.: Stinton, Darrol. "The Design of the Airplane." (1983).

Propeller Efficiency

$$P_A = \eta_{pr} P \qquad (1)$$

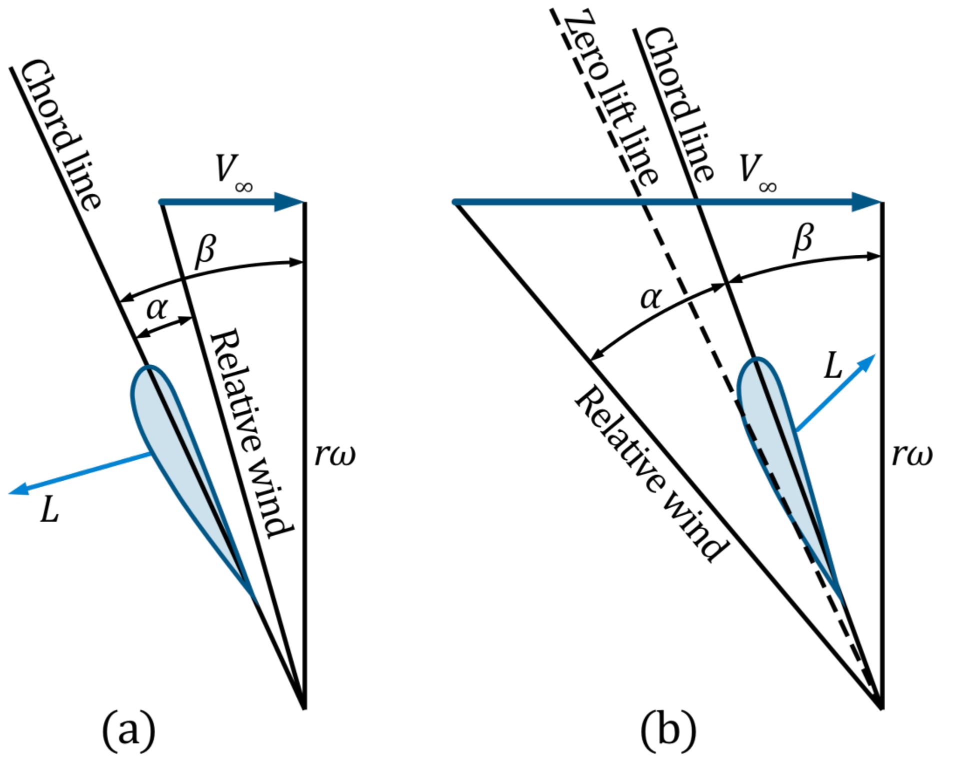
$$J = \frac{V_\infty}{ND} \qquad (2)$$

$r\omega$ = translational motion of the airfoil section due to the propeller rotation
r = the radial distance of the airfoil section from the propeller hub
ω = the angular velocity of the propeller
β = pitch angle, the angle between the airfoil chord line and the plane of rotation
α = the angle of attack, the angle between the chord line and the local relative wind

$$\frac{V_\infty}{r\omega} = \frac{V_\infty}{r(2\pi N)} \qquad (3)$$

$$\frac{V_\infty}{r\omega} = \frac{V_\infty}{D(\pi N)} = \frac{J}{\pi} \qquad (4)$$

Ref.: Stinton, Darrol. "The Design of the Airplane." (1983).

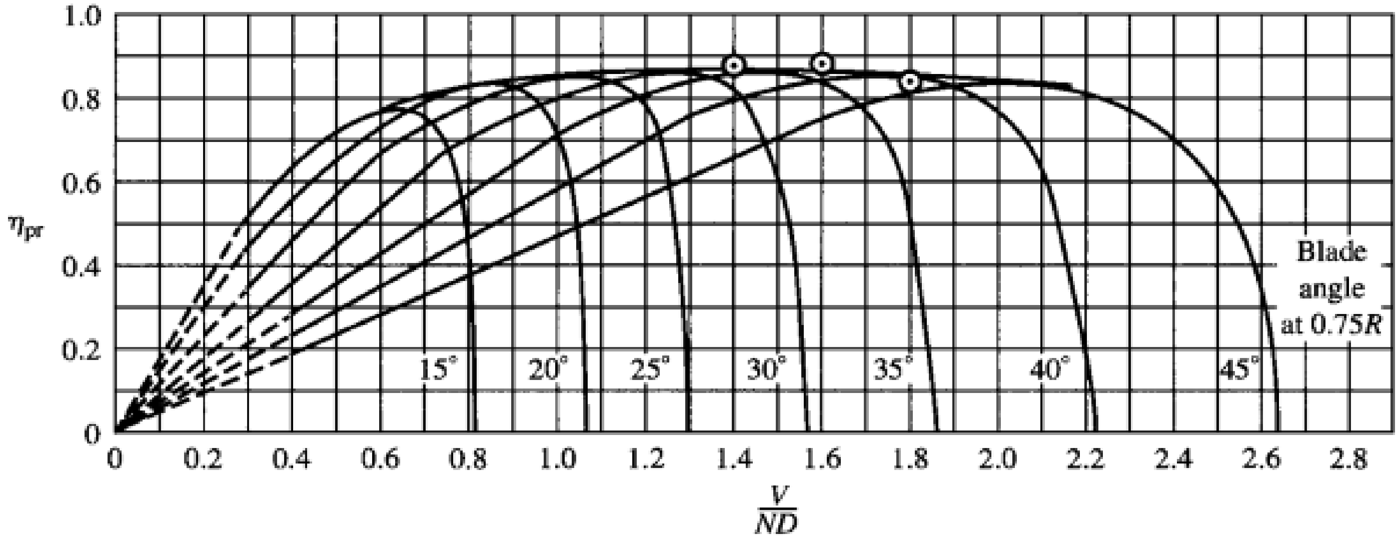


Velocity and relative wind diagrams for a section of a revolving propeller: (a) case for low V_∞ and (b) case for high V_∞

Propeller Efficiency

$$P_A = \eta_{pr} P \qquad (1)$$

$$J = \frac{V_\infty}{ND} \qquad (2)$$



Propeller efficiency as a function of advance ratio for various pitch angles. Three-bladed propeller with Clark Y sections

Ref.: Aircraft Performance and Design. J.D. Anderson. McGraw-Hill Publishing Company, Shoppenhangers Road, Maidenhead, Berks SL6 2QL, UK. 1999. 580pp

Propeller Efficiency

$$P_A = \eta_{pr} P \qquad (1)$$

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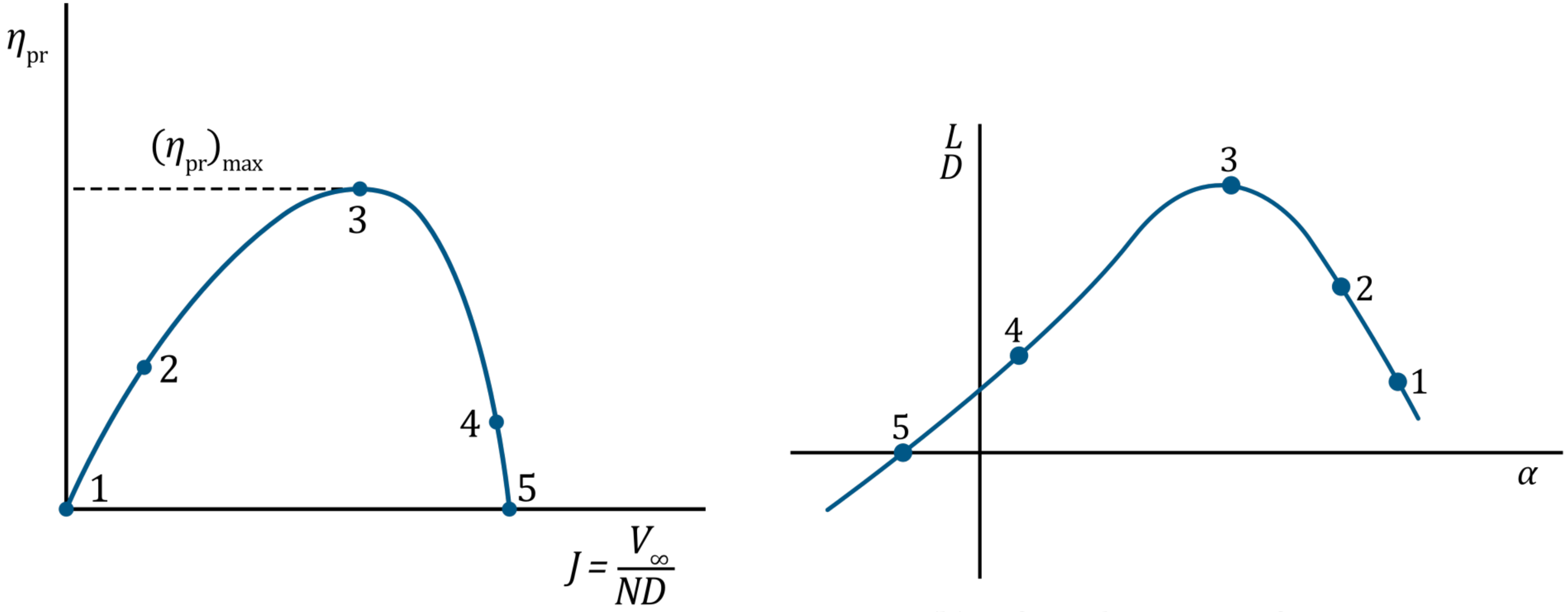


(a) Propeller efficiency

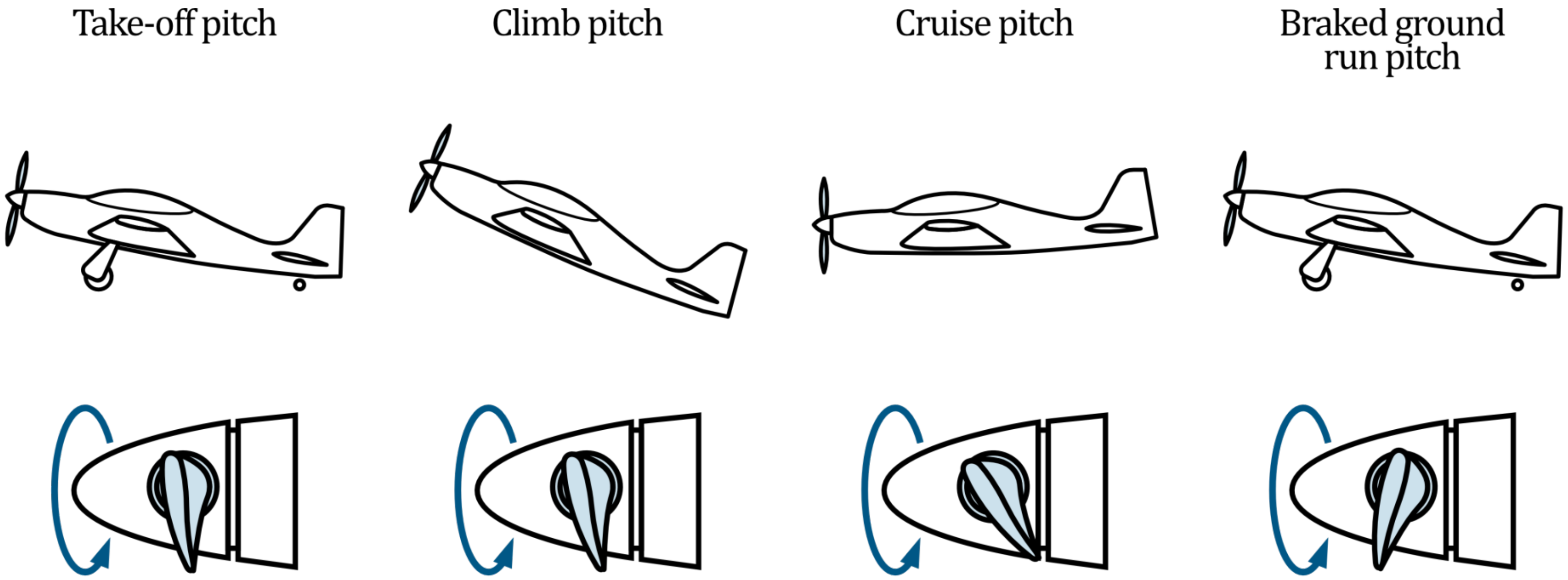
(b) Lift-to-drag ratio of a given propeller airfoil cross-section

Effect of section lift-to-drag ratio on propeller efficiency

Ref.: Aircraft Performance and Design. J.D. Anderson. McGraw-Hill Publishing Company, Shoppenhangers Road, Maidenhead, Berks SL6 2QL, UK. 1999. 580pp

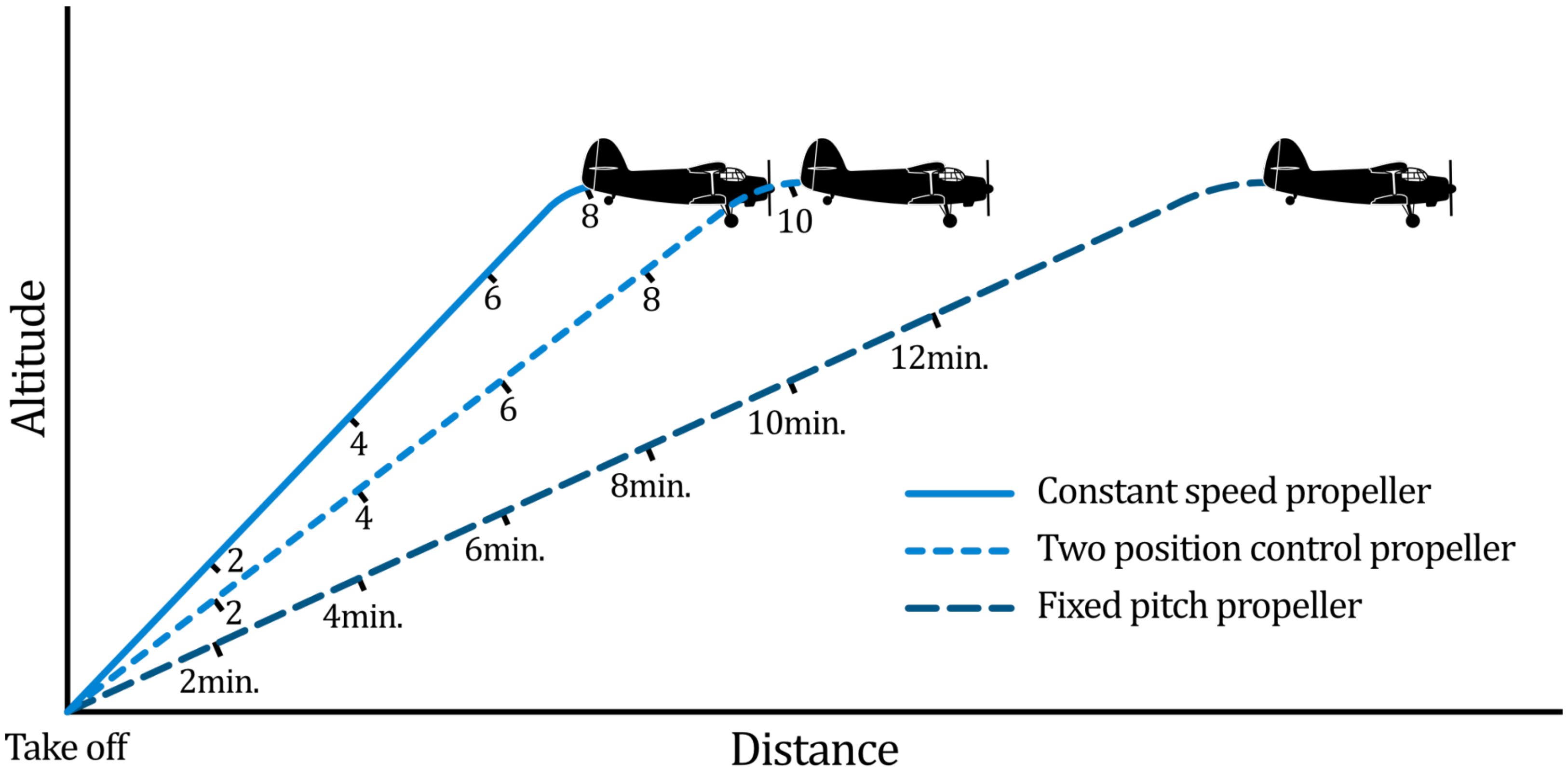
Propeller types

- Fixed-pitch propeller
- Ground-adjustable propeller
- Two-position propeller
- Controllable-pitch propeller
- Constant-speed propeller



The pitch angle adjusted throughout the flight mission

Propeller types



Comparison of airplane climb performance for three types of propellers, fixed-pitch, two-position, and constant speed taken from a textbook on practical aircraft aerodynamics by Carter, 1940

The effect of propeller diameter

$$D \uparrow \Longrightarrow \eta_{pr} \uparrow$$

The upper bound for the propeller diameter is set by a number of constraints, including:

- the required ground clearance must be ensured;
- the speed of sound must be avoided anywhere on the blades' surface.

The effect of the number of blades

The lower the number of blades, the better, as the preceding blade disturbs the airflow for the following blade.

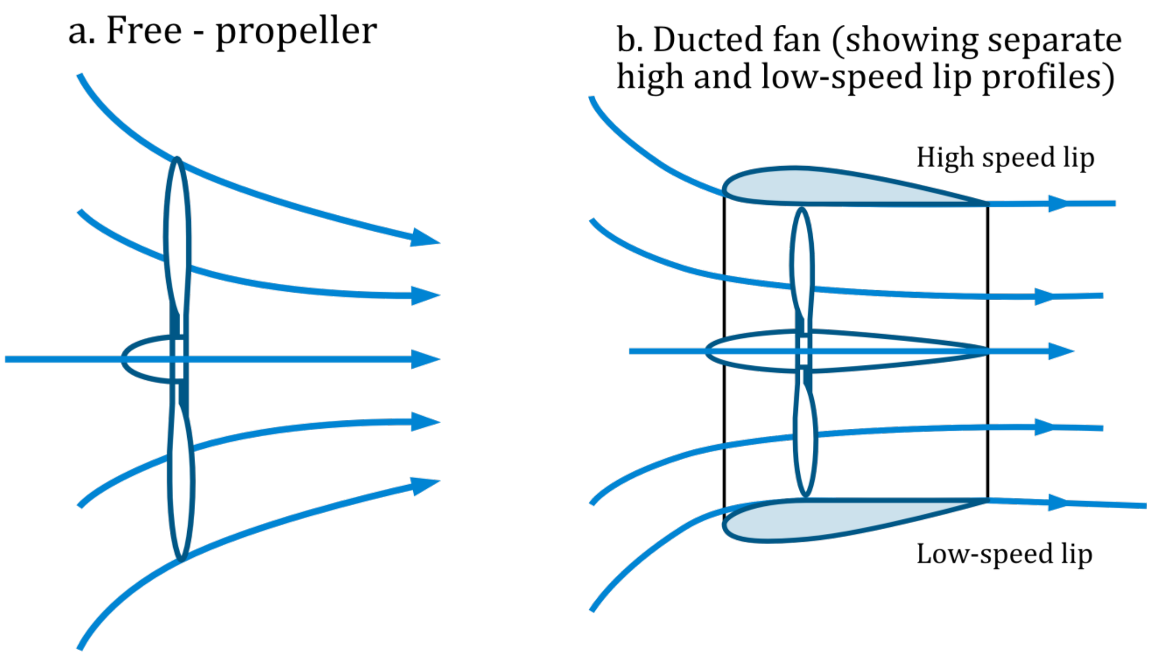
Fans (ducted) propulsors versus free propellers

For the same power and thrust, a free propeller:

- $\sqrt{2}$ times fan diameter;
- better at higher speeds;
- lighter (in general);
- needs longer undercarriage legs;
- less efficient at high rpm;

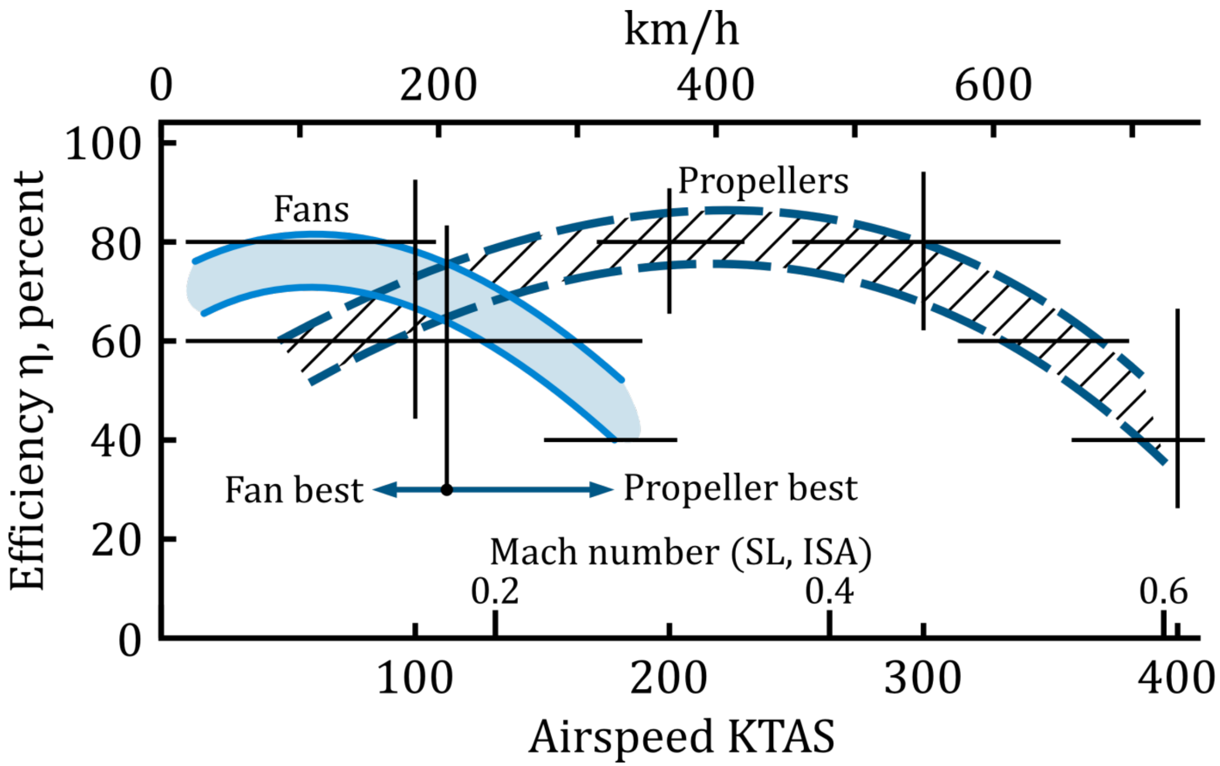
a ducted fan:

- 0.7 times propeller diameter;
- better at lower speeds;
- heavier than a propeller;
- suffers duct drag;
- permits shorter landing gear;
- needs large number of blades to avoid resonance;
- quieter than a propeller;
- centrebody can be up to 0.4 times fan diameter;
- close tolerances needed between fan tip and duct.



Ref.: Stinton, Darrol. “The Design of the Airplane.” (1983).

Fans (ducted) propulsors versus free propellers

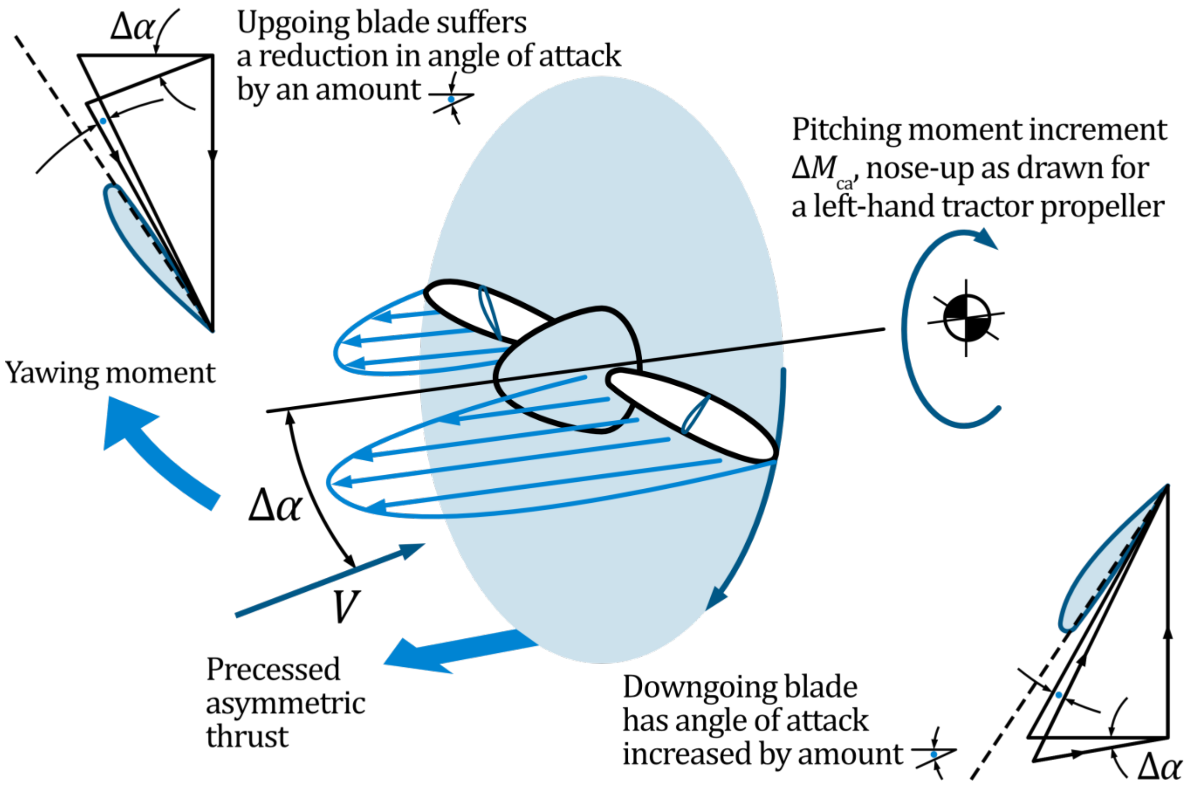


The efficiency of a free propeller versus a ducted fan

Ref.: Stinton, Darrol. “The Design of the Airplane.” (1983).

Propeller «P» effects

1. Asymmetric blade effect → a pitching or yawing moment

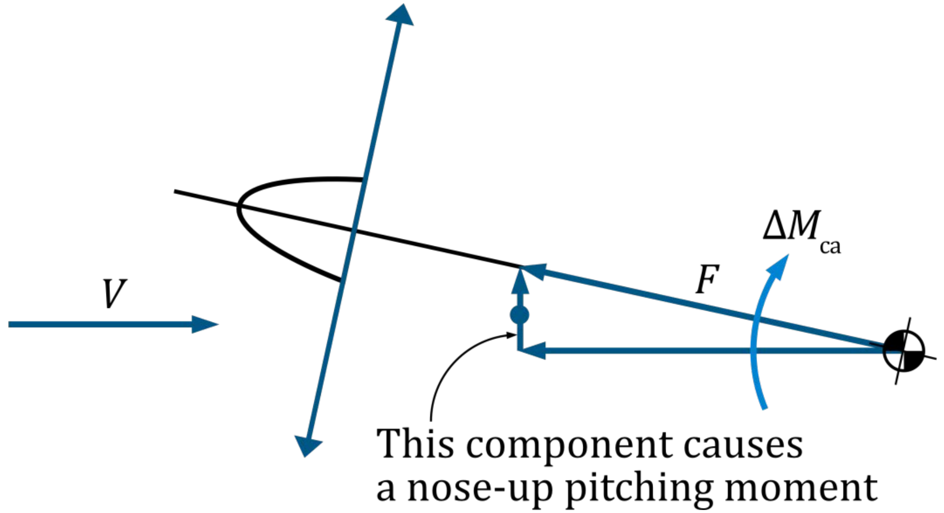


The lift distribution over the rotating propeller disc

Ref.: Gudmundsson, Snorri. "General Aviation Aircraft Design: Applied Methods and Procedures." (2013)

Propeller «P» effects

2. Pitching moment due to the propeller tilted up or down

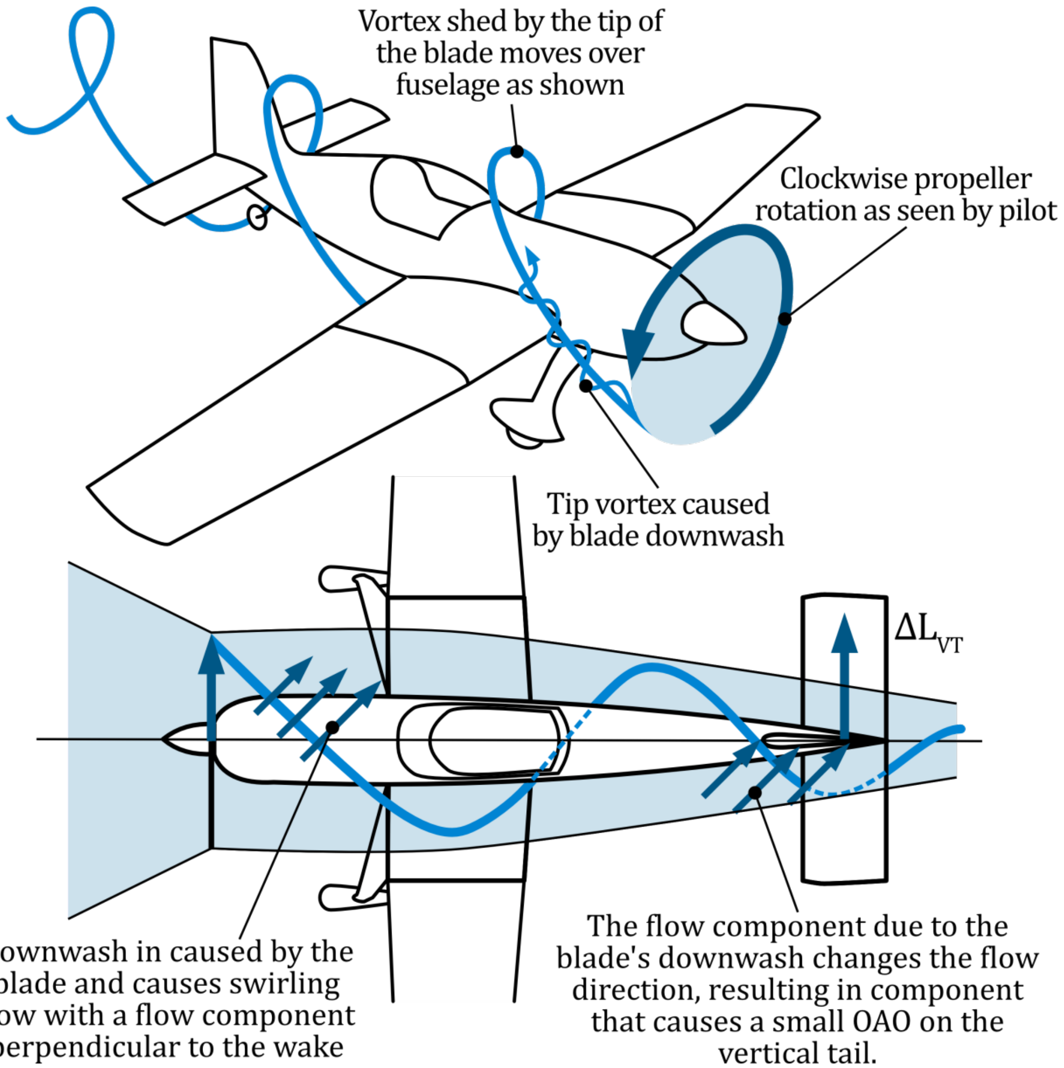


A propeller inclined to the flight path

Ref.: Stinton, Darrol. "The Design of the Airplane." (1983).

Propeller «P» effects

3. Propwash strikes the aircraft at an angle → especially powerful effect upon yaw



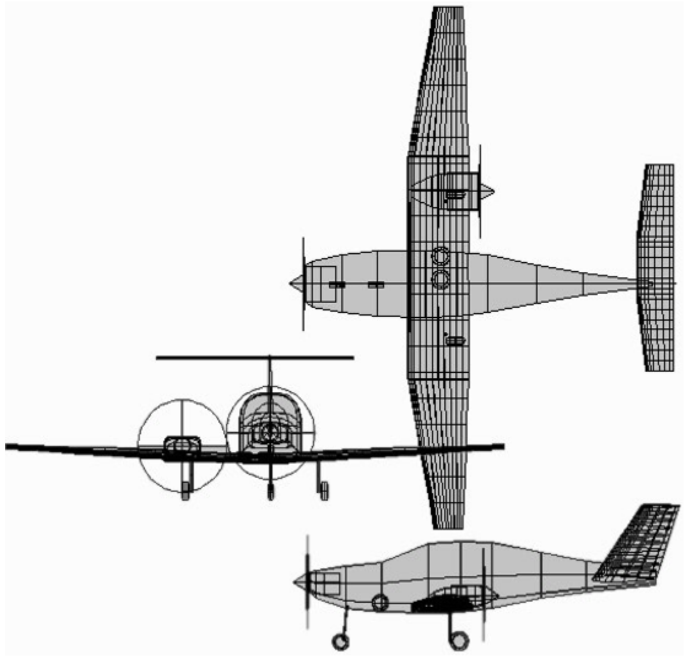
Ref.: Gudmundsson, Snorri. “General Aviation Aircraft Design: Applied Methods and Procedures.” (2013)

Propeller «P» effects

4. Angular Momentum and Gyroscopic Effects
→ a yawing moment

Supermarine Seafire 47

Asymmetric Light Twin



An Asymmetric Light Twin concept. *Ref.: Raymer, Daniel P. "Enhancing Aircraft Conceptual Design using Multidisciplinary Optimization." (2002)*

Propeller–wing aerodynamic interaction

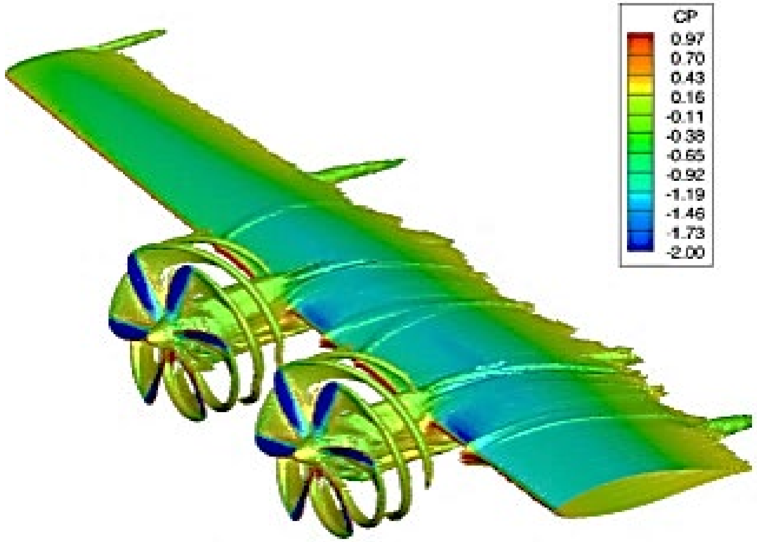
The effect of propeller slipstream on the wing:

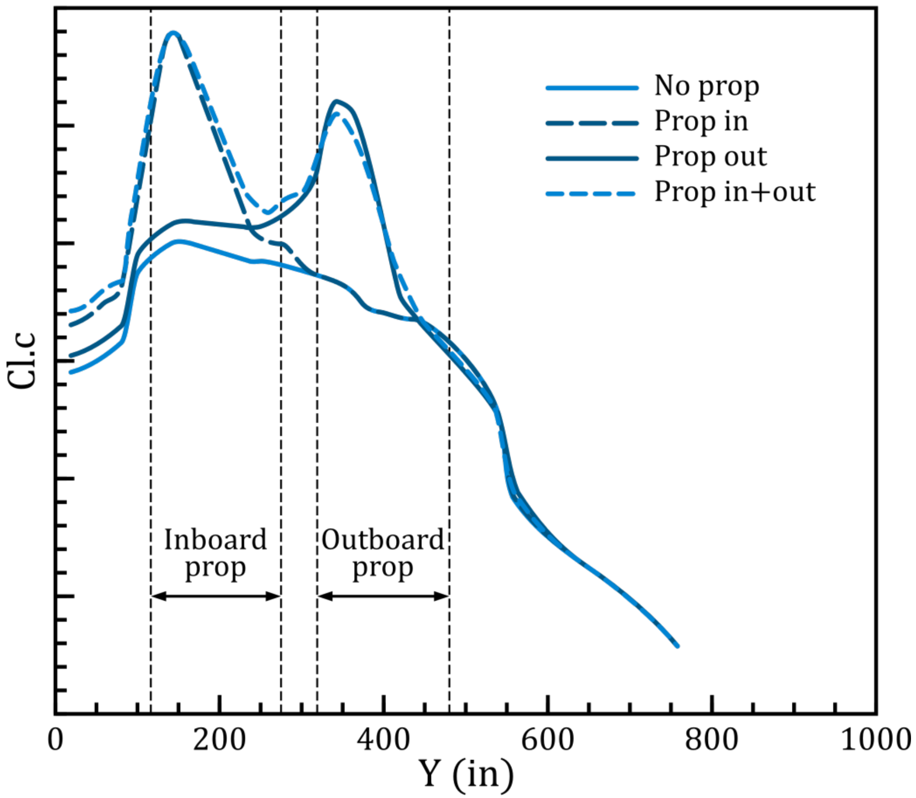
- the asymmetric blade effect causes the increase in lift behind the propeller to be different at the left and right sides of the propeller;
- the propeller increases air speed and alters the flow direction behind it;
- the change of flow direction leads to a variation of the wing local angle of attack;
- the propeller increases the pressure on the wing surface upstream of the propeller disk, while decreasing the pressure behind it;
- the propeller slipstream is expected to shift the wing transition line upstream.

The effect of wing wake on propeller:

- the wing induces axial velocities at the propeller disk, leading to a reduced disk loading;
- the wing wake tends to decrease propeller thrust, torque and efficiency.

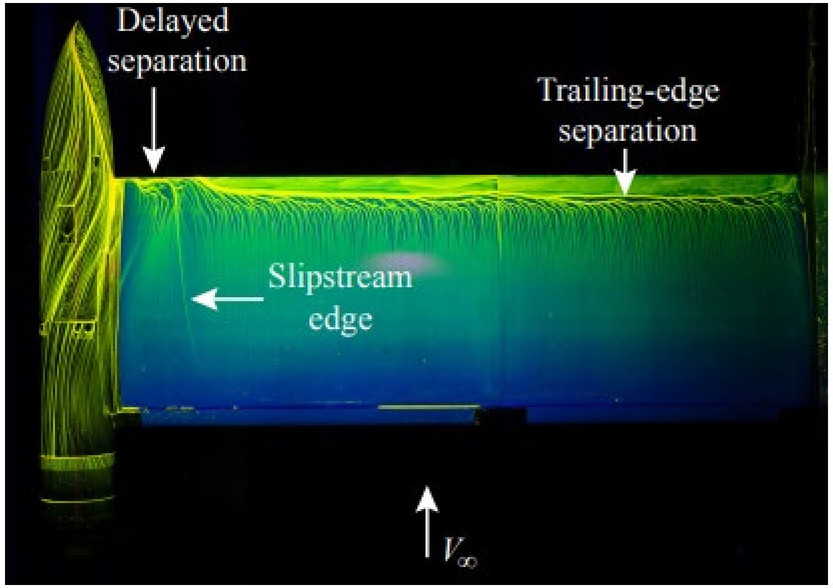
Propeller–wing aerodynamic interaction

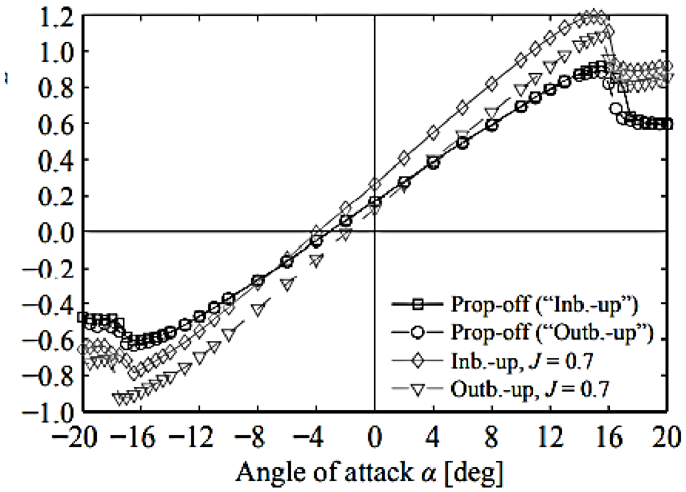




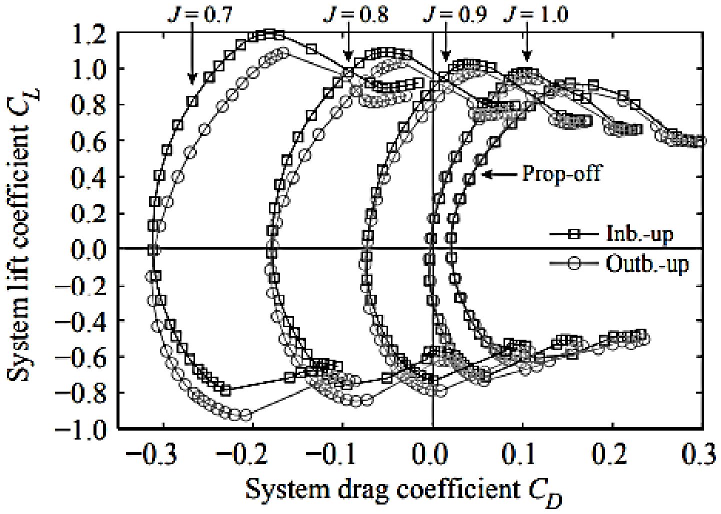
Propellers installed at inboard and outboard wing: vorticity iso-surface and wing spanwise lift distribution. Propellers have 20-deg blade angle and spin at 1024 rpm. *Ref.: Aref, Pooneh, Mehdi Ghoreyshi, Adam Jirásek, Matthew Satchell and Keith Bergeron. "Computational Study of Propeller–Wing Aerodynamic Interaction." Aerospace (2018).*

Propeller–wing aerodynamic interaction





Lift curves



Drag polars

Oil flow visualization. Prop on, J=0,7, C_T=0,123 C_L=0,5

Lift and drag polars including prop forces with inboard-up and outboard-up rotations. *Ref.: Sinnige, Tomas; van Arnhem, Nando; Stokkermans, Tom C. A.; Eitelberg, Georg; Veldhuis, Leo L. M. (2018). Wingtip-Mounted Propellers: Aerodynamic Analysis of Interaction Effects and Comparison with Conventional Layout. Journal of Aircraft, 1–18. doi:10.2514/1.C034978*

Distributed Propulsion Concept

Benefits:

- boundary-layer ingestion for improved propulsive efficiency and wake-filling benefits;
- the trailing vortex system of a lifting surface is mitigated;
- new capabilities in vehicle control.

The **power sources** for this system can be
any combination of *electrical power-producing devices* (that is, electric generator, fuel cell, et cetera)
and *energy storage devices* (that is, battery, capacitor, et cetera),
while the **propulsors** can be any combination of thrust producing devices such as electrically-driven propellers or fans.

NASA's X-57 Maxwell aircraft

Ref.: Moore, Kevin R. and Andrew Ning. "Distributed Electric Propulsion Effects on Traditional Aircraft Through Multidisciplinary Optimization." (2018).