Blade tip shape

• The incident Mach Number is:

\[ M_n = \frac{\Omega R}{a} \left( r + \mu \sin \Psi \right) \cos \Lambda = M_{\text{tip}} \left( r + \mu \sin \Psi \right) \cos \Lambda \]

- \( a \) is the sonic velocity
- \( M_{\text{tip}} \) is the hover tip mach number

• The design point will be \( \psi = 90^\circ \) and \( M_n \) must not reach \( M_{dd} \).

\[ \Lambda = \cos^{-1} \left( \frac{M_{dd}}{M_{\text{tip}} \left( r + \mu \right)} \right) \]
Blade tip shape

![Graph showing blade tip shape with non-dimensional radial station and blade sweep angle required.](image)

- Non-dimensional radial station, $r$
- Blade sweep angle required, $\Lambda$ - deg.
- $M_{\text{tip}} = 0.64$, $M_{\text{dd}} = 0.82$
Blade tip shape
Airfoils Sections

![Graph showing the relationship between angle of attack and relative airspeed, with a separation boundary indicated.](image)
Airfoils Sections

Diagram showing the effect of angle of attack on lateral cyclic and forward speed, with annotations for forward speed VF and tip speed VT.
Airfoils Sections

![Diagram showing the relationship between angle of attack and relative airspeed with a mark indicating tip speed.](image-url)
Airfoils Sections

First generation airfoil sections

NACA 0012

NACA 23010

Second generation airfoil sections

"High-lift" airfoil sections

VR-12

OA-209

RC(4)-10

OA-212

OA-214

"High-speed" airfoil sections

Bell FX69-H-083

RC(5)-10

VR-15

OA-206
Airfoils Sections

• During each revolution the blade encounters a wide variety of operating conditions.
  – Transonic flow on the advancing region
    • Blade must be thin enough to maximize the $M_{dd}$.
  – High AOA on the retreating side
    • Minimum thickness and incorporate some camber to give a relatively high $C_{l_{max}}$.

• No single airfoil will meet all requirements. The balance is between:
  – High $M_{dd}$.
  – High $C_{l_{max}}$ at low $M$. 
Airfoils Sections

![Graph showing airfoil sections with different FM values and rotor induced power factor, k.](image)
Airfoils Sections

• Use a low drag airfoil:
  – Low $P_0 \rightarrow$ high $FM$

• Airfoil Drag has two components:
  – Pressure drag
    • Minimize using thin airfoils
  – Viscous drag
    • Minimize controlling the airfoil pressure distribution
    • Minimize by maximizing the chordwise extend of the laminar flow
Airfoils Sections

- These factors are limited by:
  - Low pitching moment
  - High lift coefficient
  - Insect accretion and blade erosion (TBL)
Airfoils Sections

• Influence of the airfoil thickness:
  – Using Abbot & von Doenhoff data on NACA symmetric airfoil series \(0.06<t/c<0.24\):
    \[ C_{d_0} \approx 0.007 + 0.025\left(\frac{t}{c}\right) \]
  – Assume that we have a thickness taper:
    • 12% at the root
    • 8% at the tip
    \[ dC_{d_0} \approx 0.007 + 0.025(0.12 - 0.04r) = 0.01 - 0.001r \]
Airfoils Sections

• The profile power is:

\[ C_{P_0} = \frac{1}{2} \sigma \int_{0}^{1} C_{d_0} r^3 dr = \frac{1}{2} \sigma \int_{0}^{1} (0.01 - 0.001r)r^3 dr = \frac{1}{8} \sigma (0.0092) \]

• A reduction of 8% when compared with the non thickness taper value of \( \frac{1}{8} \sigma (0.01) \)

• This results in:
  – Higher \( FM \) by 1 to 2%
  – Higher lifting capability by 0.5 to 1.5%
Conceptual Helicopter Design
BERP rotor

- British Experimental Rotor Program (BERP) rotor, was design to meet the conflicting requirements of the advancing and retreating blade conditions.
- The research paid off in 1986 when a Westland Lynx helicopter attained the absolute speed record for a conventional helicopter with a speed just over 400 km/h
Helicopters / Filipe Szolnoky Cunha

Conceptual Helicopter Design

BERP rotor

- High $C_{l_{max}}$ (1.55).
- High pitching moments
Helicopters / Filipe Szolnoky Cunha

Conceptual Helicopter Design

Slide 67

**BERP rotor**

- **Lower** $C_{l_{\text{max}}}$.
- **Offset of the high pitching moments** (RAE 9645)

![Diagram of BERP rotor](image)
BERP rotor

- Low $t/c$ ratio (high $M_{dd}$)
- Cambered to give weak shock wave and low pitching moments
Mean centre of pressure located close to the elastic axis of the blade

\[ \frac{1}{4} \text{ chord offset forward} \]

Sweep maintaining the \( M_n \) approximately constant
BERP rotor

Low AoA

Tip vortex

High AoA

Notch vortex

Tip vortex
BERP rotor

[Diagram showing data points for Blade loading coefficient, $C_T/\sigma$ vs. Advance ratio, $\mu$, with annotations for Stall onset and World speed record.]
BERP rotor

Over The Edge
World Record

- Recently this record was broken by a compound helicopter

- The experimental Sikorsky X-2 reached the speed of 417 km/h

- The maximum theoretical speed of the X-2 is around 463 km/h
The Sikorsky X2 Technology demonstrator broke a quarter-century old speed record
Fuselage

- The fuselage is the largest airframe component and its aerodynamic characteristic have a significant impact on the performance of the helicopter.
- To be efficient the fuselage must be fully aerodynamically integrated with the main rotor, tail rotor and empennage.
- Isolated these component exhibit fairly well understood flow phenomena and aerodynamic characteristics.
Fuselage

- Earlier non-streamlined fuselages:

Sikorsky UH-34

Conceptual Helicopter Design
Fuselage

- More recent streamlined fuselages:

Sikorsky S76
Fuselage

- In reality there will be an interaction between all the components
Fuselage drag

- We have already seen the need to reduce the fuselage drag in order to increase the helicopter performance (increase speed and decrease fuel consumption).
- The drag of the helicopter fuselage can be one order of magnitude higher than a airplane with the same gross weight. Due to
  - Rotor shaft, Hub and blade attachments
  - After body drag
    - Large upsweep angles
Fuselage drag

- Current capabilities for design are based on synthesis on component drag using experimental data or by using a combination of experimental data and potential flow theory.
Fuselage drag

• To supplement numerical predictions of fuselage aerodynamics, semi-empirical drag predictions are used.

• These are based on experimental wind tunnel testing with some additional engineering judgement.

• An estimate of the fuselage parasitic equivalent wetted or flat area, $f$, can be determined from knowledge of the drag coefficient of the various components that make up the aircraft.
## Fuselage drag

Typical break down of parasitic drag components on a helicopter

<table>
<thead>
<tr>
<th>Component</th>
<th>$f/A$</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage</td>
<td>0.0021</td>
<td>30</td>
</tr>
<tr>
<td>Nacelles</td>
<td>0.0004</td>
<td>6</td>
</tr>
<tr>
<td>Rotor hub/shaft</td>
<td>0.0024</td>
<td>35</td>
</tr>
<tr>
<td>Tail rotor hub</td>
<td>0.0003</td>
<td>4</td>
</tr>
<tr>
<td>Main landing gear</td>
<td>0.0004</td>
<td>5</td>
</tr>
<tr>
<td>Tail landing gear</td>
<td>0.0003</td>
<td>4</td>
</tr>
<tr>
<td>Horizontal tail</td>
<td>0.0001</td>
<td>1</td>
</tr>
<tr>
<td>Vertical tail</td>
<td>0.0001</td>
<td>1</td>
</tr>
<tr>
<td>Rotor/fuselage interference</td>
<td>0.0004</td>
<td>7</td>
</tr>
<tr>
<td>Exhaust system</td>
<td>0.0002</td>
<td>3</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>0.0002</td>
<td>3</td>
</tr>
</tbody>
</table>
Fuselage drag

![Graph showing fuselage drag vs. helicopter gross weight](image)

- Utility helicopters
- S-58
- CH-46
- S-61
- SA 321
- CH-47
- CH-53A

- Clean helicopters
- BO-105
- S-52
- S-55
- UH-1
- S-67
- SA 341
- Lynx speed record

- Bell 222
- OH-6A

Graph equation: Equivalent flat plate area, $f - \text{ft}^2$ vs. Helicopter gross weight, $W - \text{lb}$, with $W^{1/2}$ relationship.
Fuselage Vertical drag

• It is normally assumed that the total thrust, $T$, is equal to the aircraft weight $W$.
• However there is a increment in power required because of the download or vertical drag, $D_v$.
• This is the result of the rotor slipstream velocity.
• Typically the download drag can be up to 5% of the aircraft weight.
• Because of the bluff-body nature of the flow around the fuselage estimates of $D_v$ can only be reliably obtain with wind tunnel testing.
Fuselage Vertical drag

- The total thrust will be:
  \[ T = W + \Delta T = W + D_v \]

- Where the fuselage vertical drag \( D_v \) is:
  \[ \Delta T = D_v = \frac{1}{2} \rho \bar{v}^2 S_{ref} C_{D_v} = \frac{1}{2} \rho \bar{v}^2 f_v \]

- The velocity \( \bar{v} \) is the average velocity in the rotor slipstream. In hover, and using the momentum theory, this velocity is twice the induced velocity
Fuselage Vertical drag

- In climb operations the induced velocity in the rotor is, for moderate climb velocities:

\[
\frac{v_i}{v_h} = 1 - \frac{V_c}{2v_h}
\]

- The velocity at the fully developed wake is

\[
\overline{v} = V_c + 2v_i
\]

- Substituting the last equation in the previous one we get:

\[
\overline{v} = 2v_h
\]

- The velocity \(\overline{v}\) is independent of the climb velocity
Fuselage Vertical drag

- The total thrust can be then written as:

\[ T = W + D_v = W + \frac{1}{2} \rho \bar{v}^2 f_v = W + 2 \rho v_h^2 f_v = \]

\[ = W + 2 \rho \left( \sqrt{\frac{T}{2 \rho A}} \right)^2 f_v = W + T \frac{f_v}{A} \]

- Therefore the total thrust is:

\[ T = W + T \frac{f_v}{A} \Rightarrow T = \frac{W}{1 - \frac{f_v}{A}} \]
Fuselage Vertical drag

- The vertical drag on the fuselage can be calculated by estimating the drag coefficient on individual two-dimensional fuselage cross-sections (strip approach)

![Diagram showing induced velocity and fuselage cross-sections with drag coefficients](image-url)
Fuselage Vertical drag

• The drag over a incremental length $dl$ will be:

$$dD_v = \frac{1}{2} \rho \bar{v}^2 C_{D_v} wdl$$

• The total drag will be:

$$D_v = \sum dD_v$$

• The helicopter cross-sectional drag coefficient average at 0.5 although the addition of sponsons or stub-wings can increase this value to 1.0
Vertical Drag Recovery

- When determining in ground effect hover capability, the vertical fuselage drag must be corrected to take into account for a favourable effect that occurs:

\[
\frac{D_{vIGE}}{D_{vOGE}} = k_g \approx 1 - 1.22e^{(-H_f/R)}
\]

- With \(H_f/R\) higher than 0.25
Fuselage Rotor interactions

- The fuselage will in turn influence the flow in the rotor disk.
- This influence will depend on the helicopter operation. It will be stronger for hover and lower advance velocities and weaker, due to the wake skew angle, at higher velocities.
Fuselage Rotor interactions

• In average the presence on the fuselage can be considered to have the same effect as a surface bellow the rotor.
Fuselage Rotor interactions

• Instantaneous effect will be different:

  – If the blade is perpendicular to the fuselage - small effect.

  – If the blade is on top of the fuselage – higher influence
Fuselage Rotor interactions

- Decreased rotor/body spacing
- Baseline rotor/body spacing
- Isolated Rotor

Hover, $C_T/\sigma = 0.08$

Blade section lift coefficient, $C_l$

5% (baseline) rotor/body spacing
3% (decreased) rotor/body spacing
Isolated rotor value

Blade azimuth, $\psi$ - deg.
Fuselage Rotor interactions

- The influence will also be different if:
  - The blade is over the cockpit (upwash)
  - The blade is over the tail boom (downwash)
Conceptual Helicopter Design
Empennage design

• Empennage of a helicopter consist:
  – Vertical stabilizer (Fin)
  – Horizontal stabilizer (Tail Plane)
  – Related fuselage structure

• The purpose is to create a aerodynamic force that enhances the helicopter stability about a particular axis.
Horizontal Stabilizer

• The fuselage/rotor combination has an adverse stability.

• Purpose of the horizontal stabilizer:
  – Enhance the pitch stability.
  – Better handling qualities

• The selection of the size and position is difficult.
  – The interaction with the main rotor wake can change dramatically the aerodynamic forces on the horizontal stabilizer
Horizontal Stabilizer

• The main rotor wake position will vary depending on the Helicopter trajectory.

• The interaction can change the AOA and therefore the magnitude of the aerodynamic forces will be sensitive to the flight conditions.

• If the empennage is totally submersed in the rotor wake then it will also experience a higher total pressure.
 Horizontal Stabilizer

- All these effects will change the forces on the empennage change therefore the pitching/yaw moment acting of the helicopter.

- If these changes occur suddenly or unpredictably undesirable handling qualities may occur.