Aerospace Vehicle Design And System Integration 3: Design Methods AENG30016

(AVDASI3: Design Methods)

Rotary Wing Design

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Rotorcraft Design Objectives

- Understand key design aspects in the context of the initial sizing process
- Use the MATLAB and MS Excel Tools to conduct initial sizing and calculate Mission Performance for a fixed rotorcraft configuration
- Carry out design studies varying key parameters.

Helicopter Design Requirements

- **General requirements**, e.g. payload, speed, range, altitude, cost, etc.
- **Key mission requirements**, e.g. transportation, firefighting , training, surveillance, military, …
- **Compliance with the applicable airworthiness standards** (CS27, CS29 …)
- **Inoperable Engine requirements** (urban area, traffic controlled area, …)



Rotorcraft Configurations

Helicopters

Autogyros

Compound Helicopters

When we think of a helicopter……

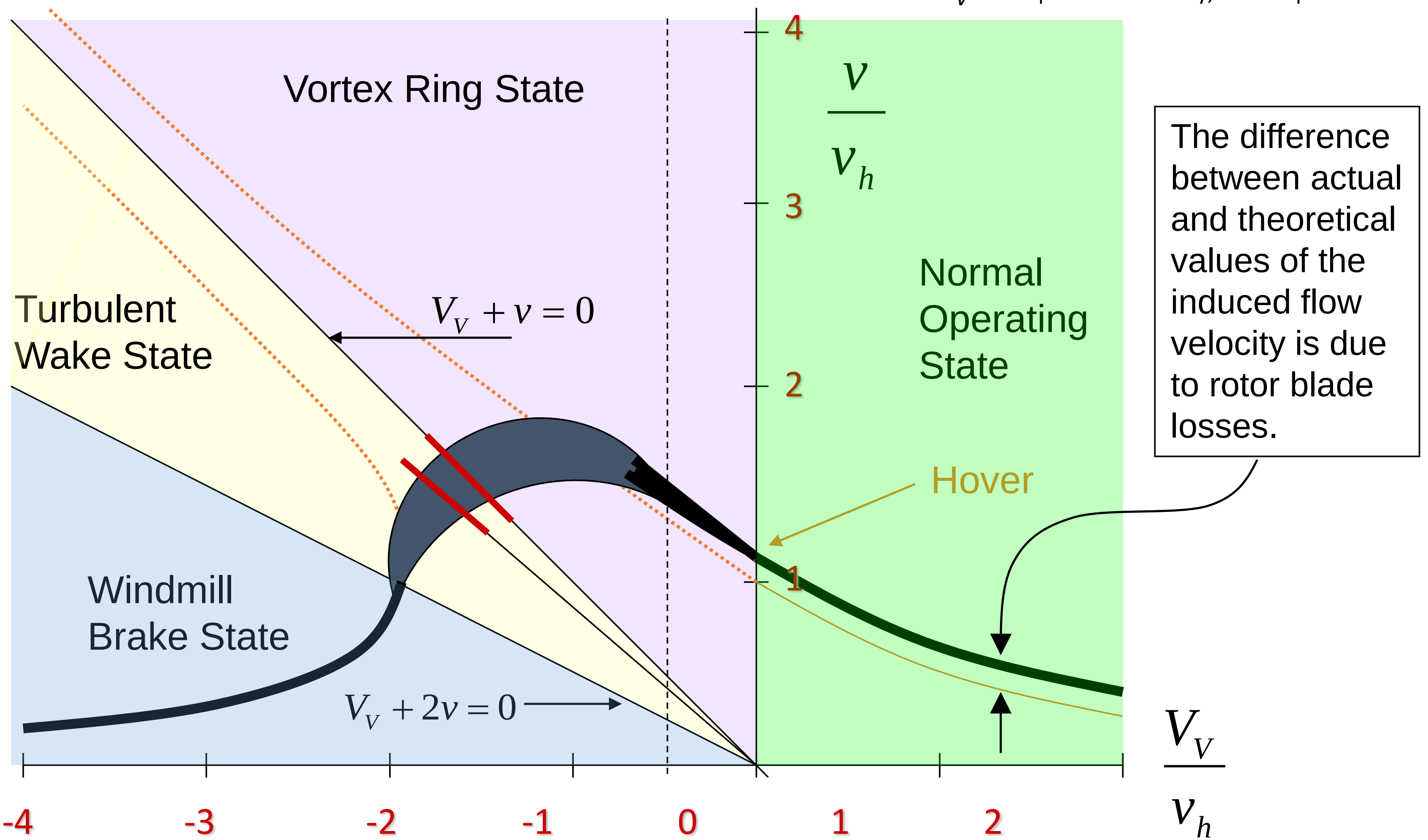
This is the kind of image that often comes to mind.
Hence the penny-farthing configuration is used in this course.

Recap

From second year Introduction to Helicopter Aerodynamics

The Universal Induced Velocity Diagram is axial flight

v: rotor induced velocity
***V**$_h$*: rotor induced velocity in Hover
***V**$_V$*: Helicopter axial velocity, climb is positive



$$\text{Rememberin g that } P = T(V+v), \text{ then at } (V+v)=0, T \neq 0, P = 0$$

T: rotor thrust ***P***: rotor induced power

HELICOPTER in AUTOROTATION

In general (and this very much depends upon rotor diameter and helicopter weight), helicopters settle down to an autorotational descent rates such that:

$$\frac{V}{v_h} \approx -1.7$$

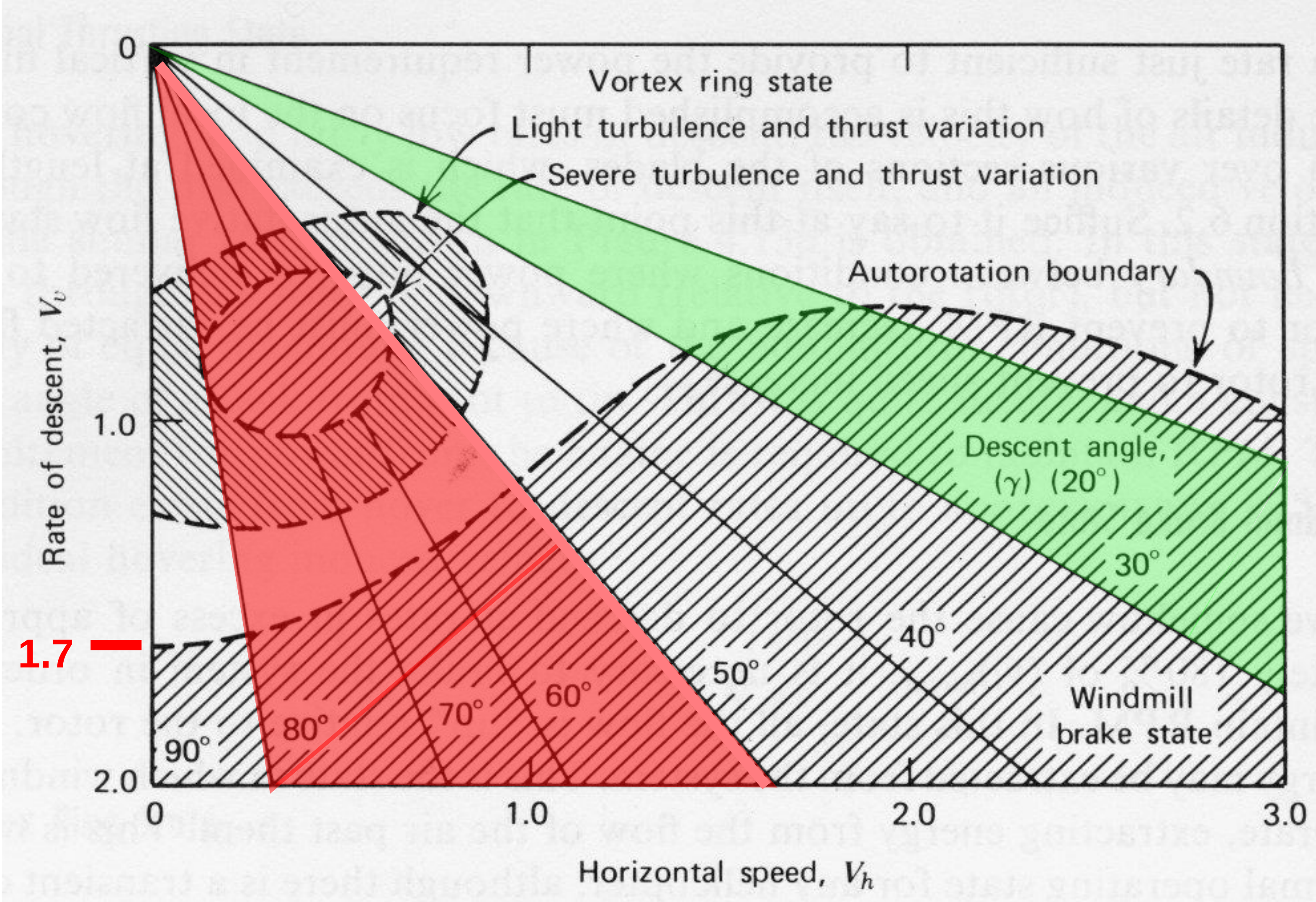
Westland Super Lynx

Mass = 5330kg

Rotor Diameter = 12.8 m

$$v_h = \sqrt{\frac{T}{2\rho A}} = \sqrt{\frac{52287}{315}} = 12.8 \text{ m/s} \text{ , vertical autorotation descent} \approx 22 \text{ m/s.}$$

HELICOPTER in AUTOROTATION



It is important to design for low autorotation rates

Rotor Efficiency in the Hover

$$\eta_r = FoM = Tv/P \qquad = \frac{T}{P}\sqrt{\frac{T}{2\rho A}}$$

T: rotor thrust
P: rotor induced power
v: rotor induced velocity
A: rotor disc area
ρ: air density

If, $\dfrac{T}{P} = \text{PL}$ (known as Power Loading) and $\dfrac{T}{A} = \text{DL}$ (known as Disk Loading)

then $$\text{PL} = 1.565\,FoM\,\frac{1}{\sqrt{\text{DL}}}$$ <u>This is Dimensional !</u>

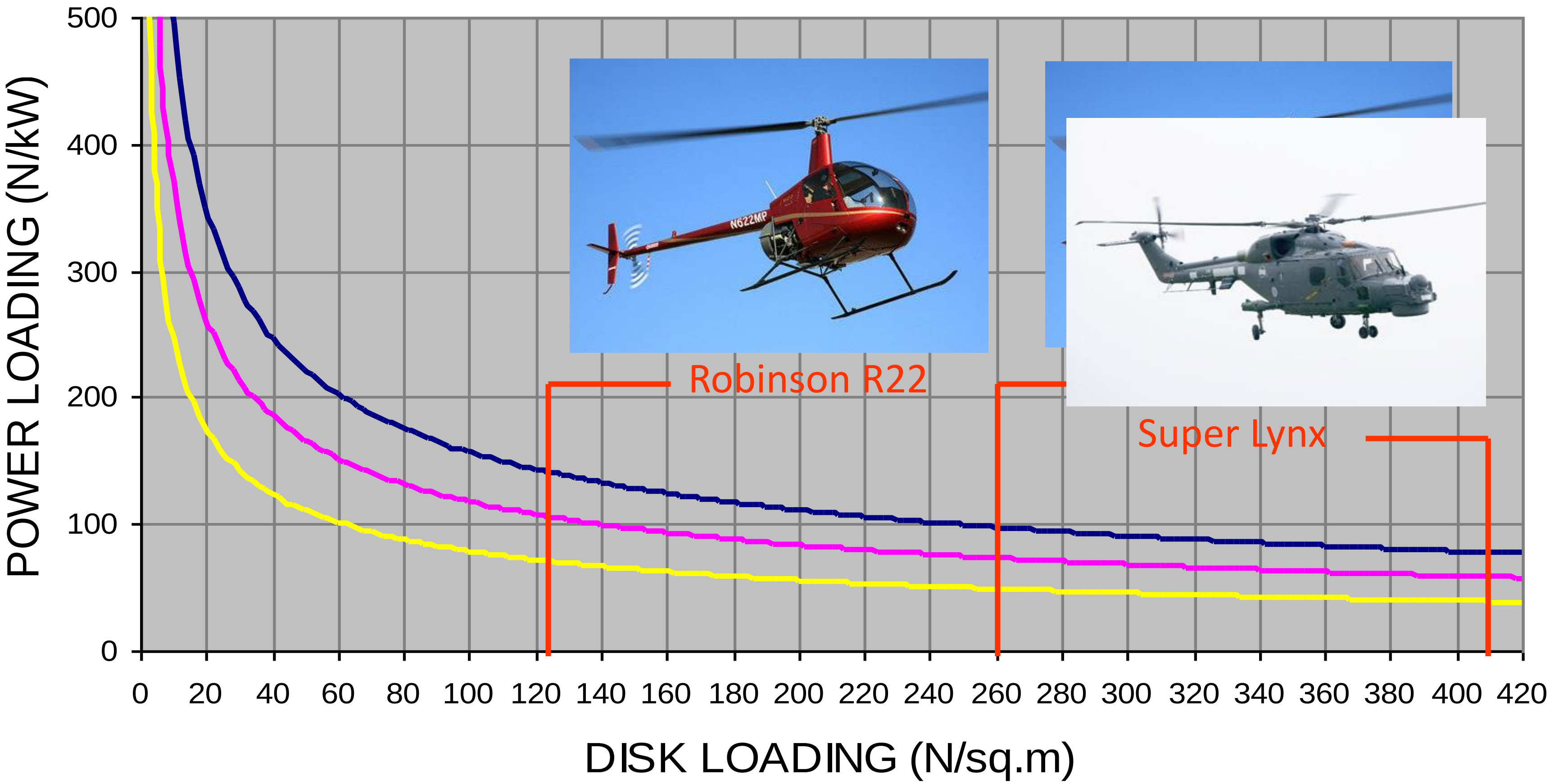
(based upon ρ=1.225 kg/m^3)

This relationship can be plotted and if the Figure of Merit is known, then for a given disk loading the power loading may be found from the graph.

Rotor Efficiency in the Hover

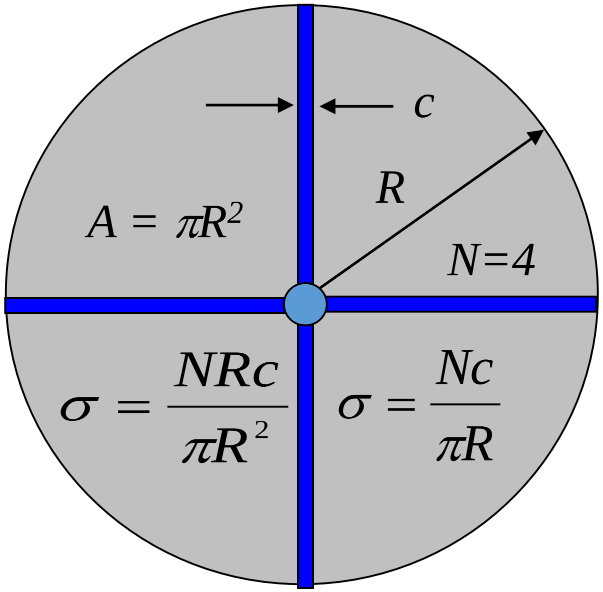
Man-powered
3500 N/kW

Rotor **POWER LOADING** vs **DISK LOADING** Curves



Rotor Performance Coefficients

$$\sigma = \frac{Nc}{\pi R}$$ (solidity, where N is number of blades)



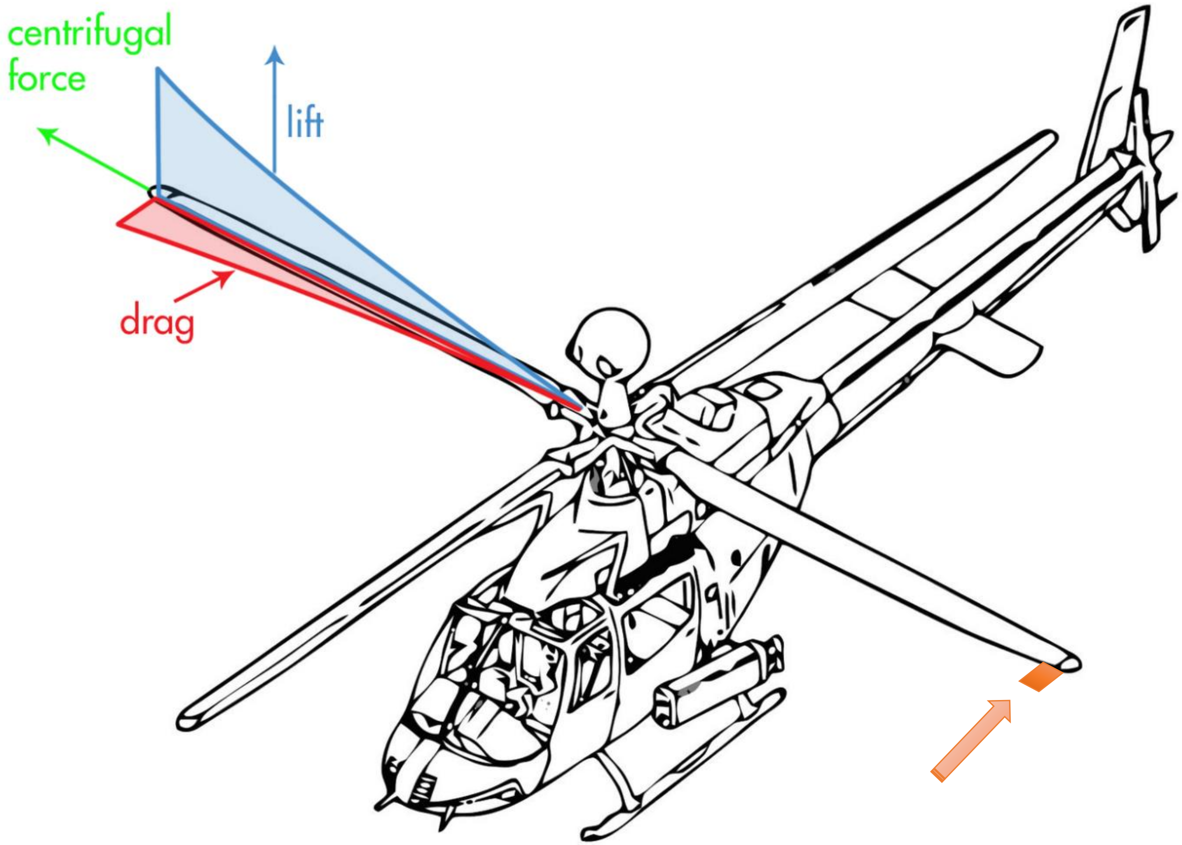
Thrust Coefficient $$C_T = \frac{T}{\rho A(\Omega R)^2}$$

Torque Coefficient $$C_Q = \frac{Q}{\rho A R(\Omega R)^2}$$

and Power Coefficient $$C_P = \frac{P}{\rho A(\Omega R)^3}$$

therefore $C_P = C_Q$

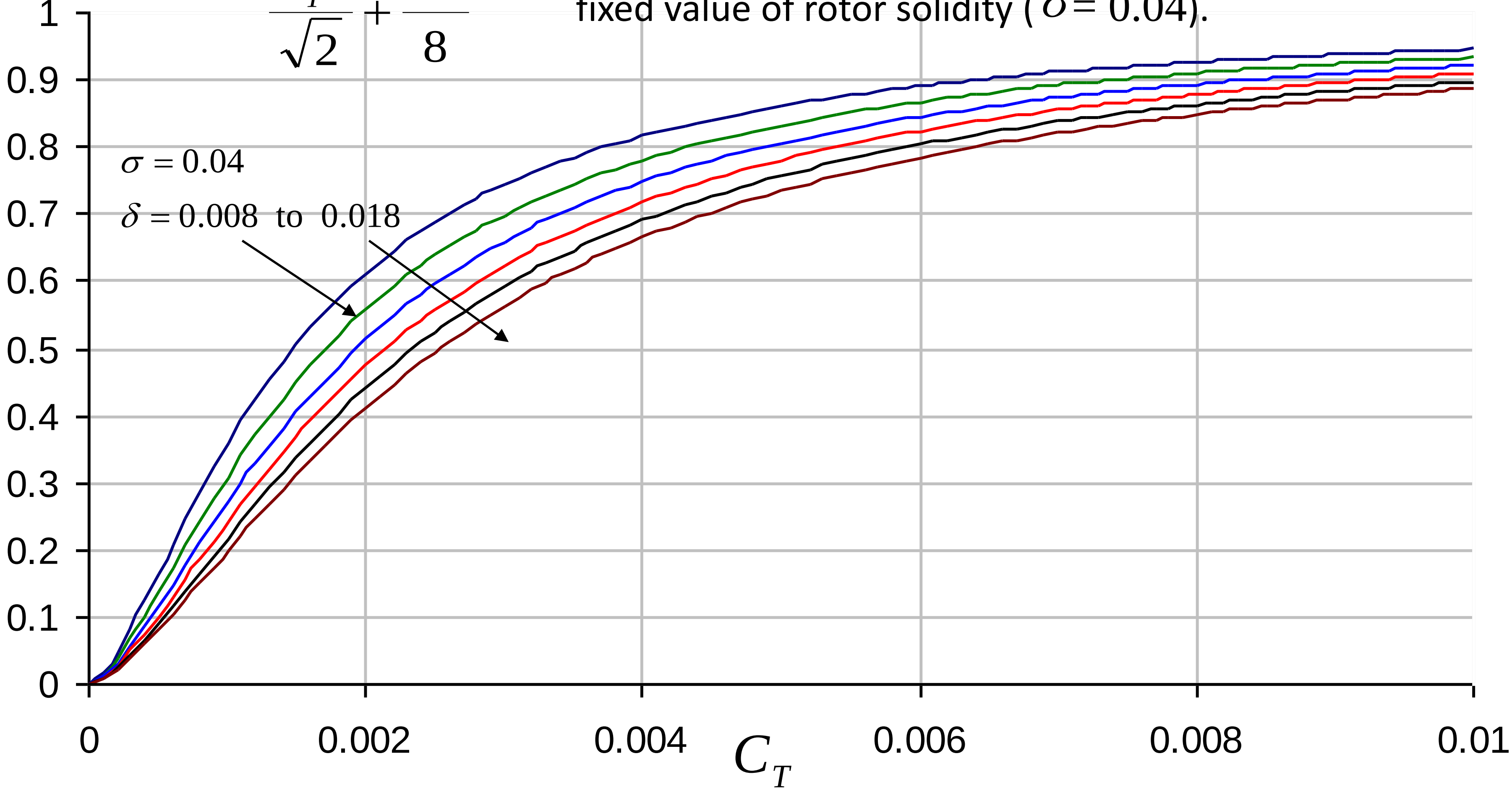
Forces Acting on the Blade



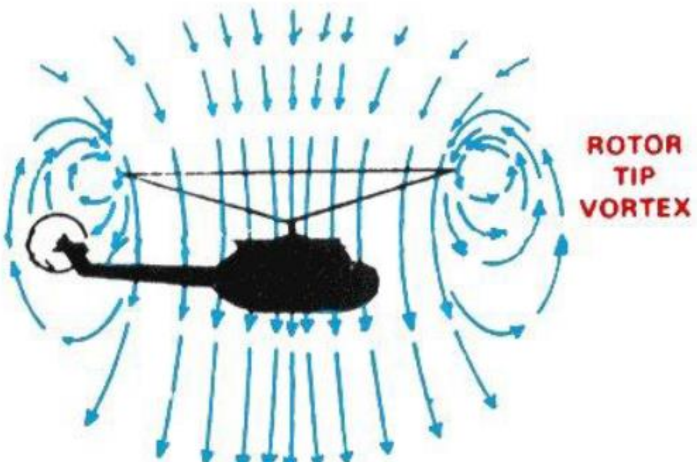
Maximising the Figure of Merit

$$M = 0.707 \frac{C_T^{\frac{3}{2}}}{\frac{C_T^{\frac{3}{2}}}{\sqrt{2}} + \frac{\sigma\delta}{8}}$$

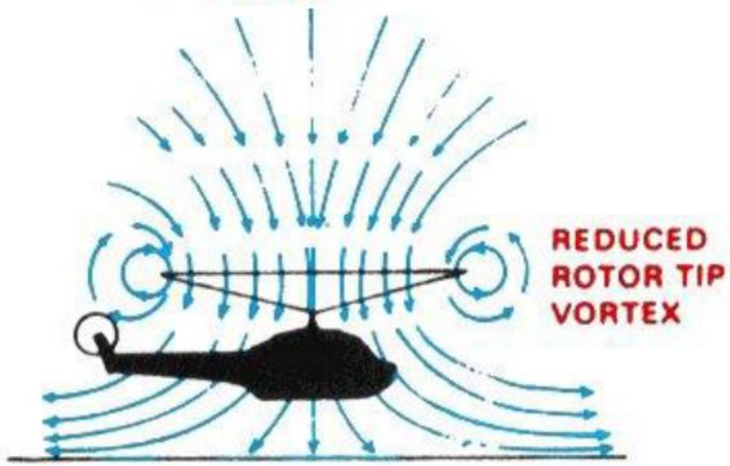
Figure of Merit against Coefficient of Thrust for a range of delta's (aerofoil profile drag coefficients) based on a fixed value of rotor solidity ($\sigma = 0.04$).



Ground Effects

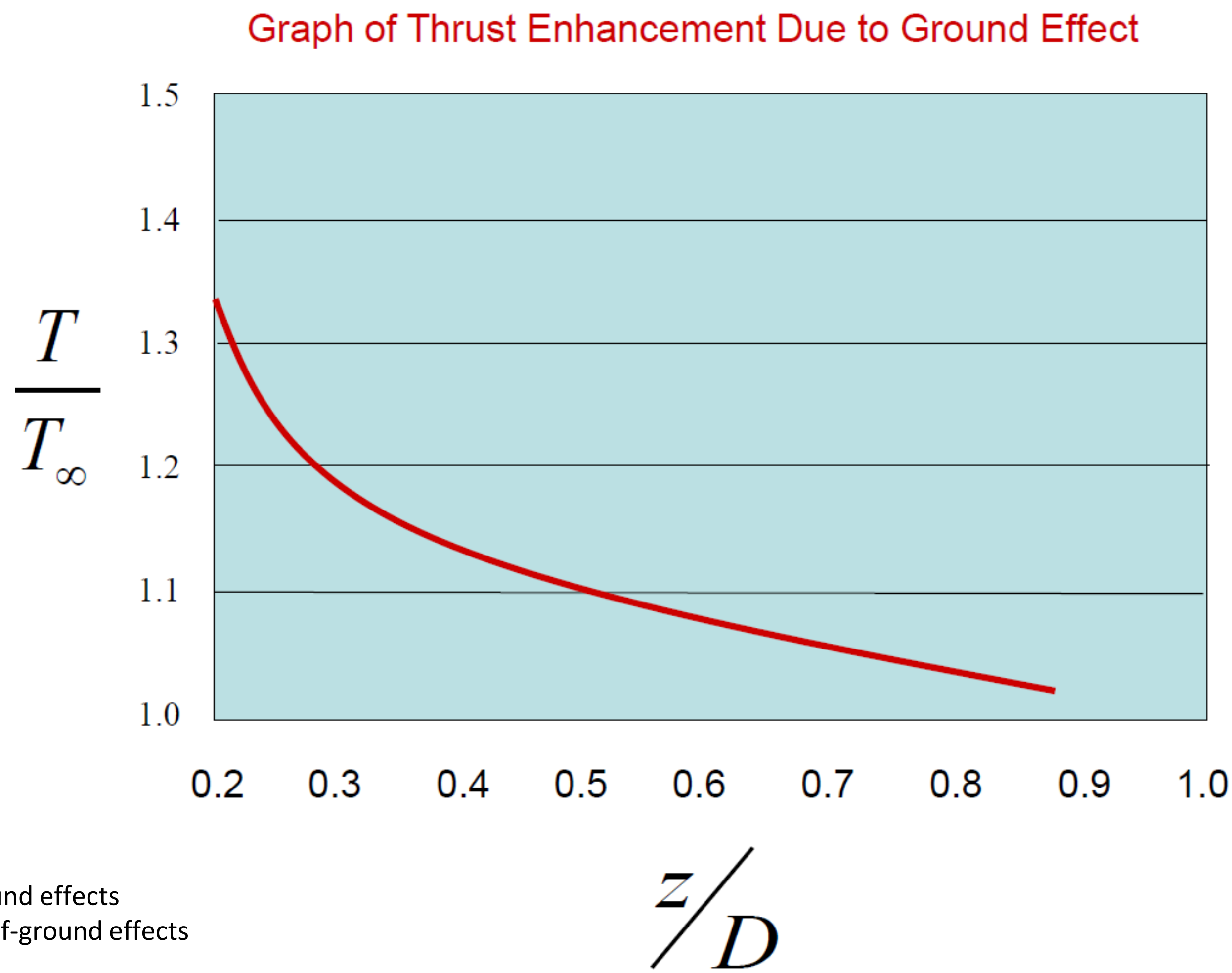


Schematic of a helicopter hovering as described in lectures to date. This is referred to as “operating Out-of-Ground Effect (OGE)”



Schematic of a helicopter hovering close to the ground and benefiting from the reduced induced power requirement. This is referred to as “operating In-Ground Effect (IGE)”

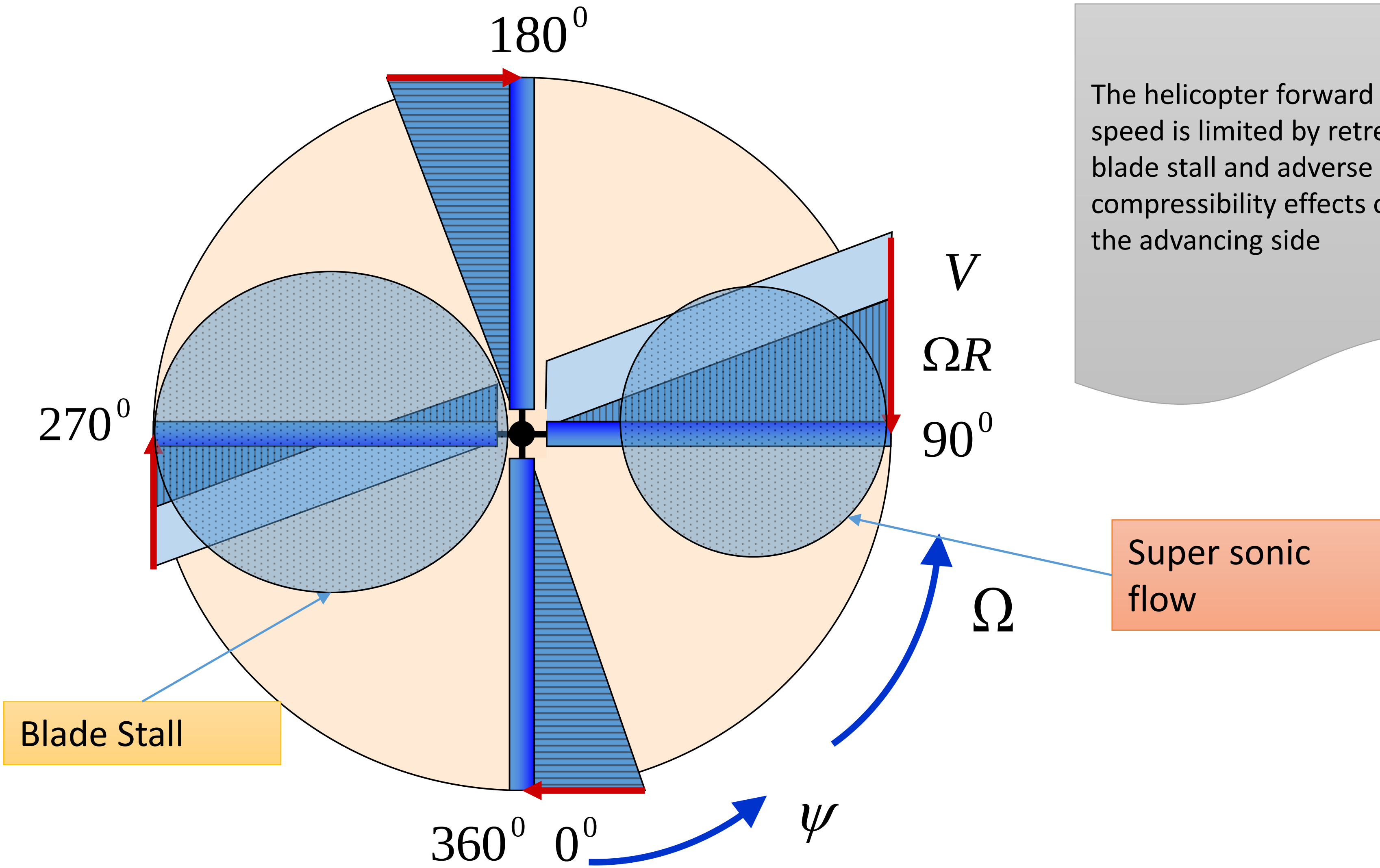
Ground Effects



T: rotor thrust in-ground effects
T_∞: rotor thrust out-of-ground effects

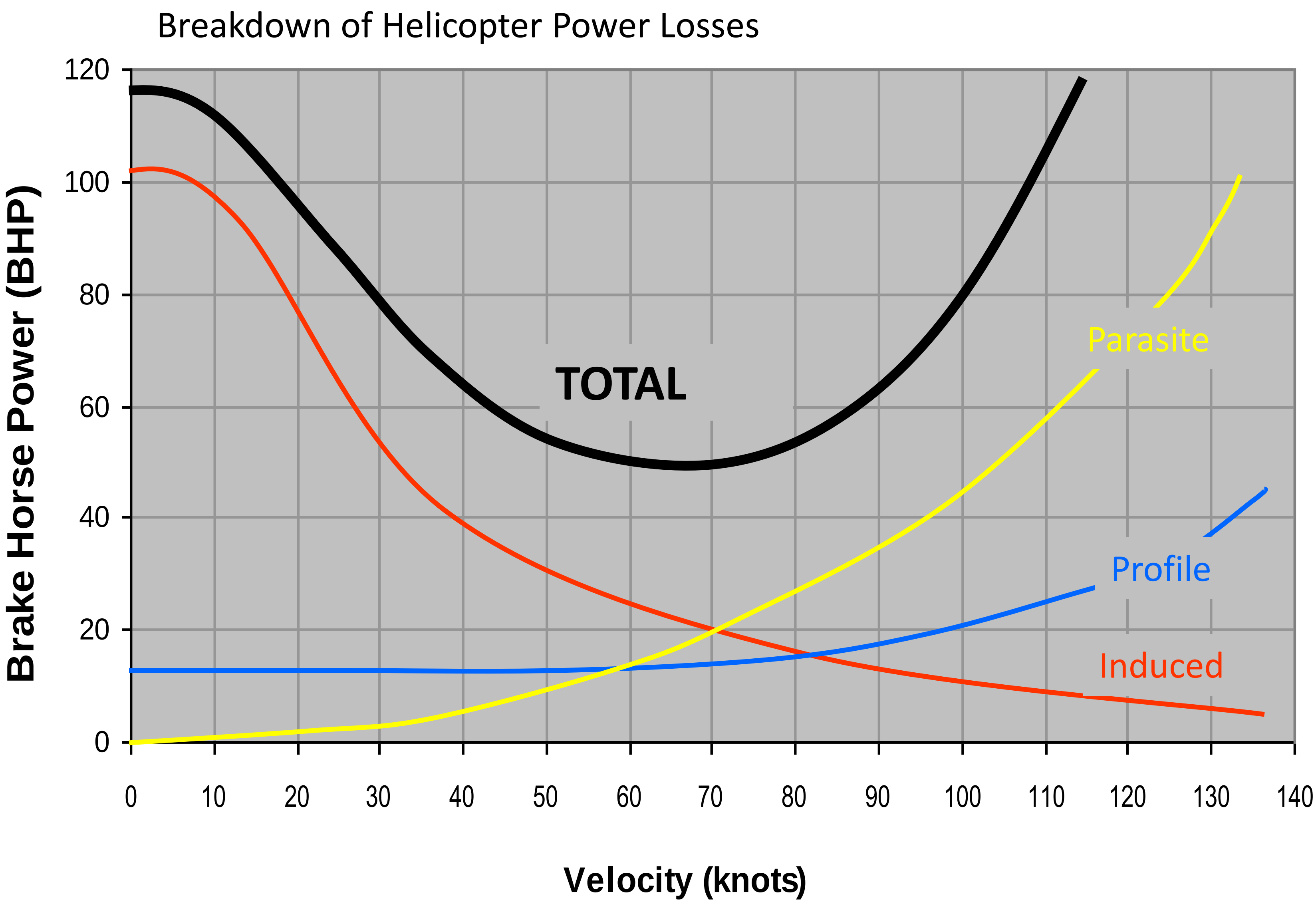
z: rotor distant from the ground
D: rotor disc diameter

The Rotor in Edge-Wise Flow



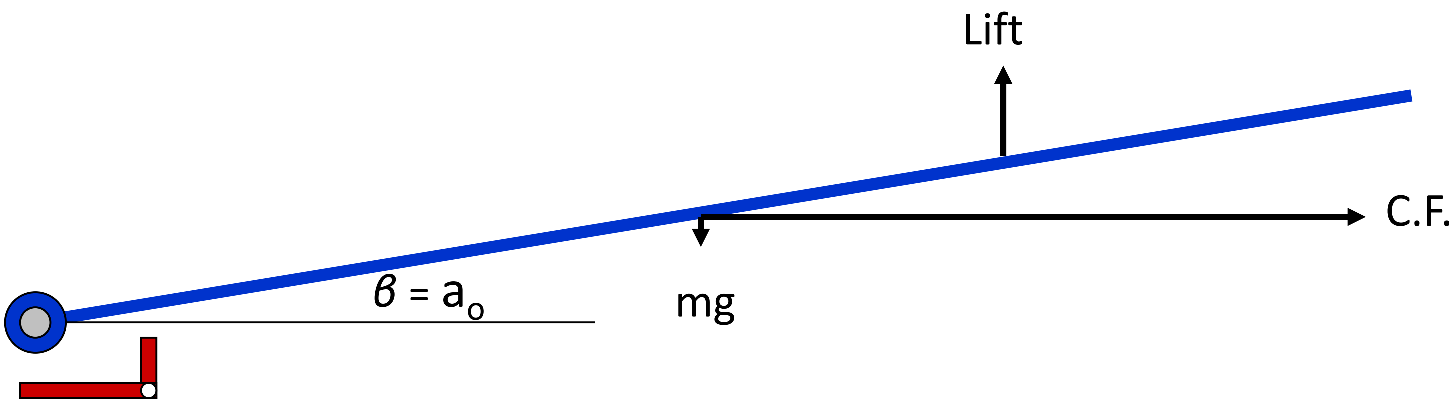
The helicopter forward speed is limited by retreating blade stall and adverse compressibility effects on the advancing side

Induced Velocity in Translational Flight



The Rotor in Edge-Wise Flow

Thus the rotor blade flapping hinge was invented, along with droop stops.



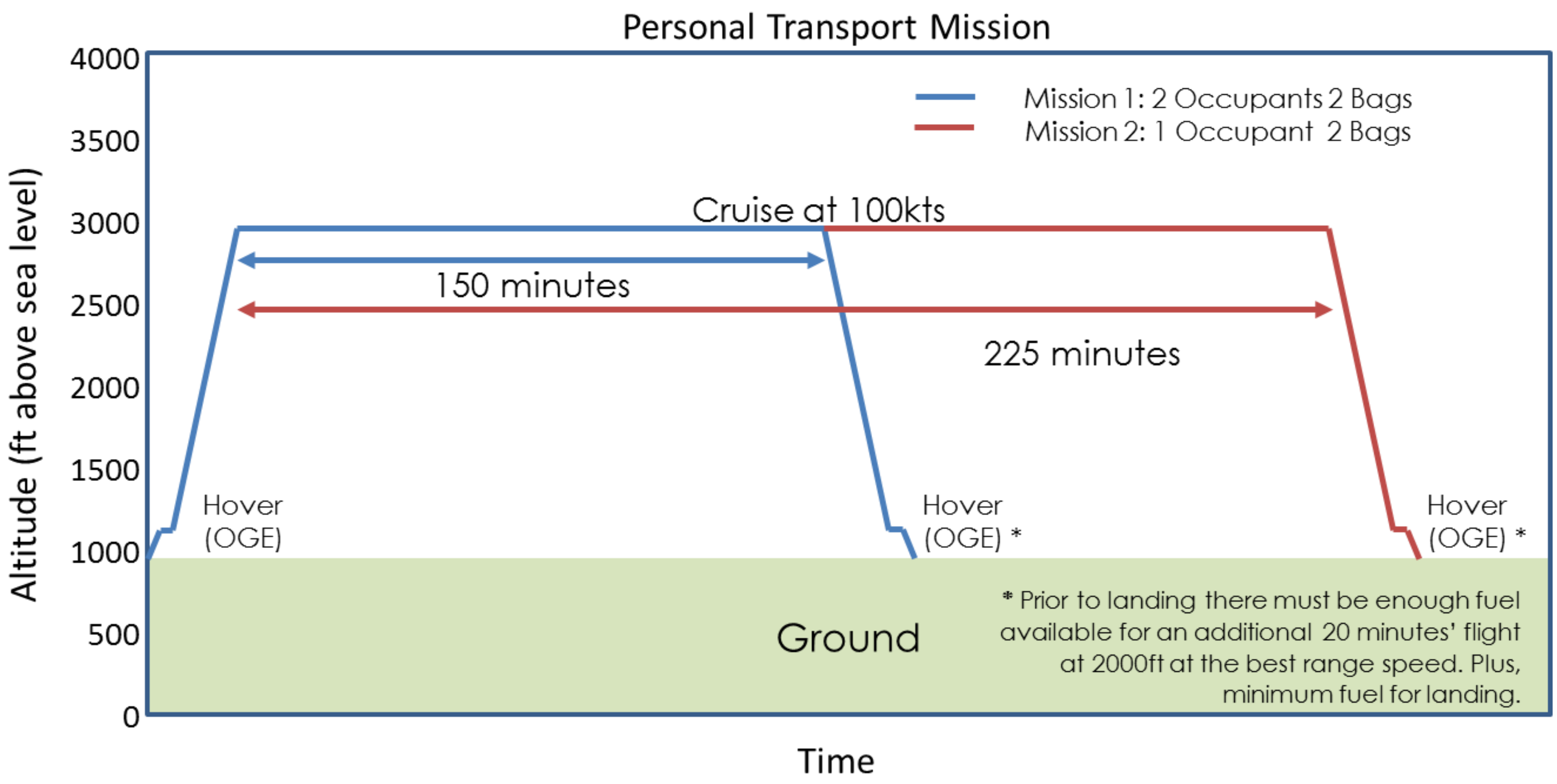
In a (no wind) hover, the Lift, Centrifugal Force and the blade weight result in a small amount of blade "coning" referred to as a_o.

In translational flight, the blade will flap about the flapping hinge and the general flapping motion can be expressed as:

$$\beta = a_0 - a_1 \cos\psi - b_1 \sin\psi - a_2 \cos 2\psi - b_2 \sin 2\psi - \ldots\ldots$$

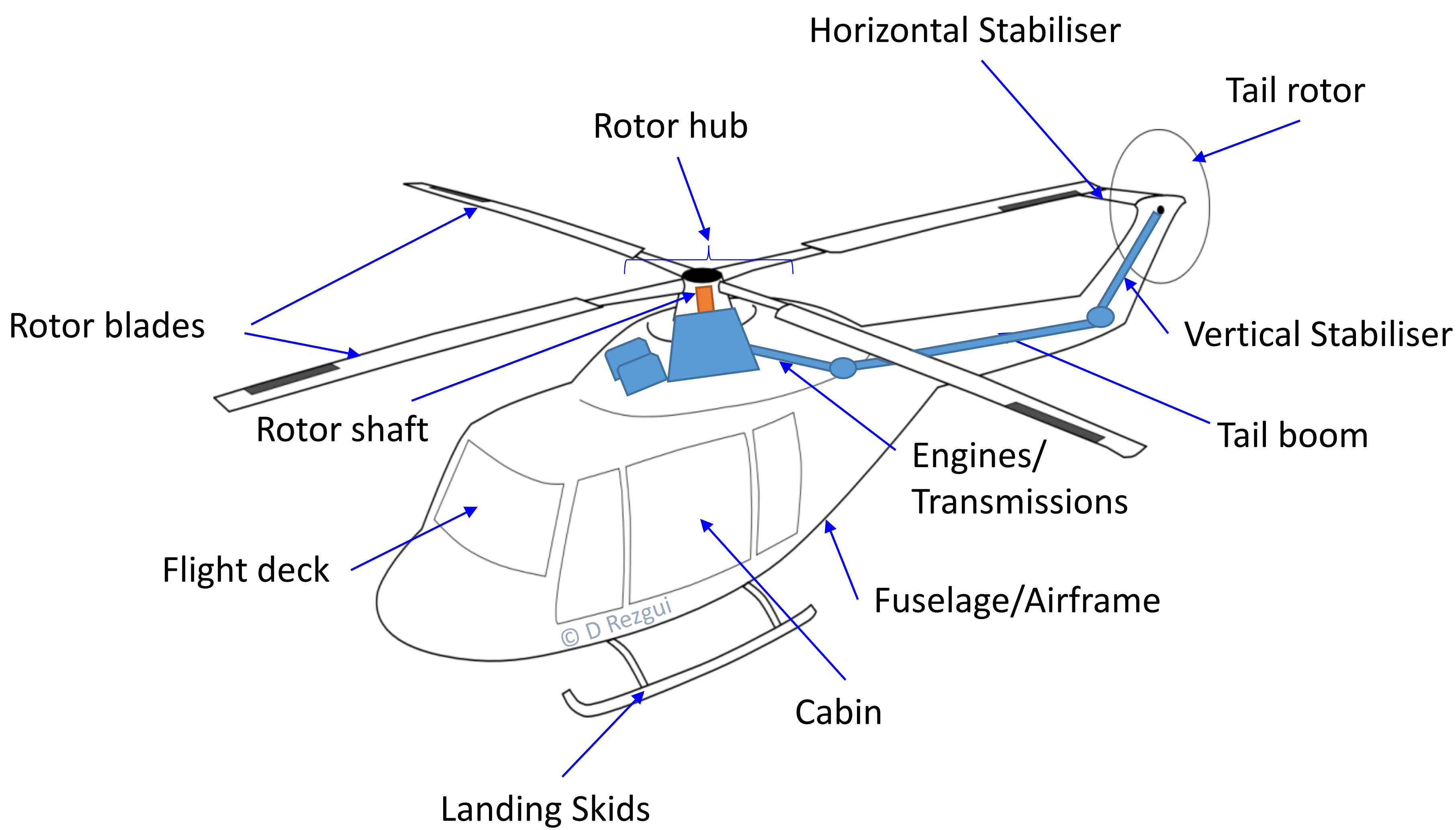
Helicopter Design

Typical Helicopter Mission

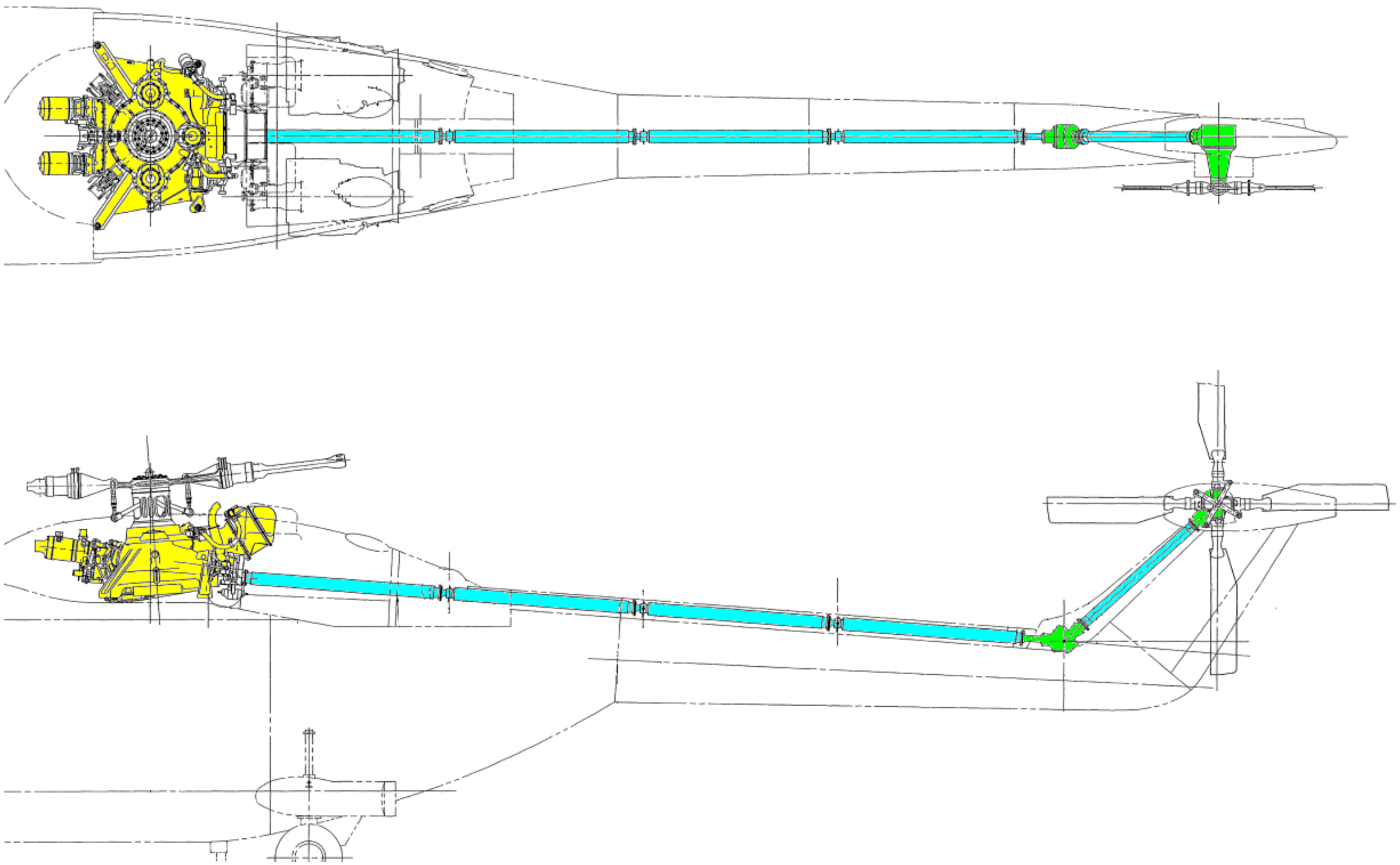


Main Helicopter Parts

(Penny Farthing Configuration)



A Typical Helicopter Drive Train



Initial Calculations

- **Carry out trade studies to understand how rotor geometry affects power consumption**
- **Identify sizing requirements**
  - Mission capabilities, hover, maximum airspeed, service ceiling
- **Estimate the required aircraft maximum gross mass**
  - MGM = empty mass + basic equipment + crew + role equipment + fuel + payload
  - At this stage assume a target empty mass fraction appropriate to the role
- **Calculate aircraft power required to meet performance requirements**
  - Rotor radius, tip speed, chord
  - Compare power requirements to power available (engine & transmission)
  - Mission fuel can be refined using typical engine specific fuel consumption values
- **This will be an iterative process to find an optimised solution**
  - Aircraft design is about compromise and you will need to balance hover versus cruise performance, size, mass, cost and functionality

Considerations

- **General**
  - Is the aircraft the correct size to do the task
- **Rotors**
  - Disc loading & blade loading
  - Growth potential
  - Noise
  - Maximum length with rotors turning
  - Flight envelope
- **Mission Performance**
  - Is the empty mass fraction achievable?
  - Is there sufficient space allowance for the required fuel volume?
  - Has all the necessary role equipment been accounted for?
  - Mission fuel = Trip Fuel + Reserve Fuel
- **Drive Train**
  - What engines are available and how many do I need?
  - Engine power lapses with altitude and temperature
  - Installation losses: typically 5-10%
  - What transmission limits do I need and can these be achieved within the allotted mass budget?

Initial Sizing and Power Model Calculations

Initial Sizing:

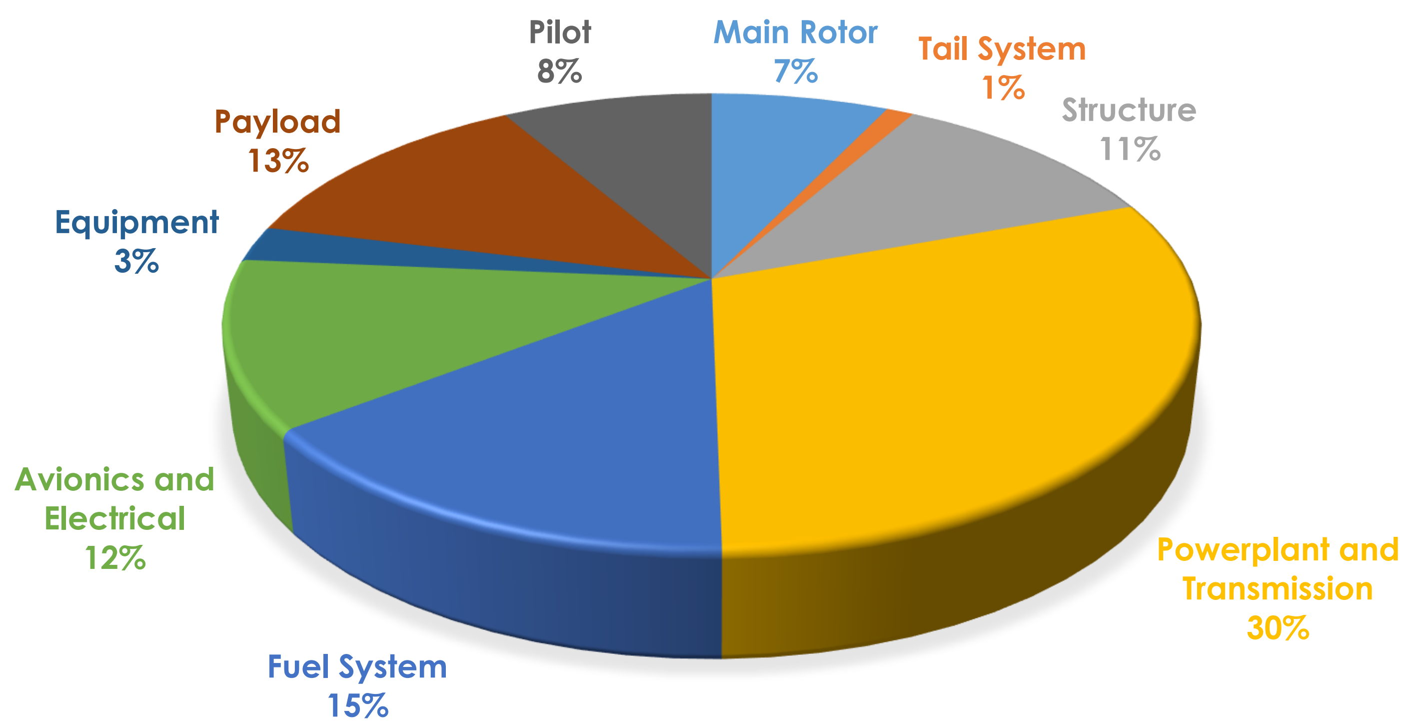
- Estimate/calculate weights (payload, fuel, All Up Weight…)
- Estimate/calculate rotor(s) parameters (disc area, blade area, diameter, rotor speed, chord, number of blades, technology …)
- Estimate/calculate airframe drag
- Estimate/calculate systems' power consumption (electric, hydraulic, pneumatic)
- Estimate engine and transmission losses

Power model:

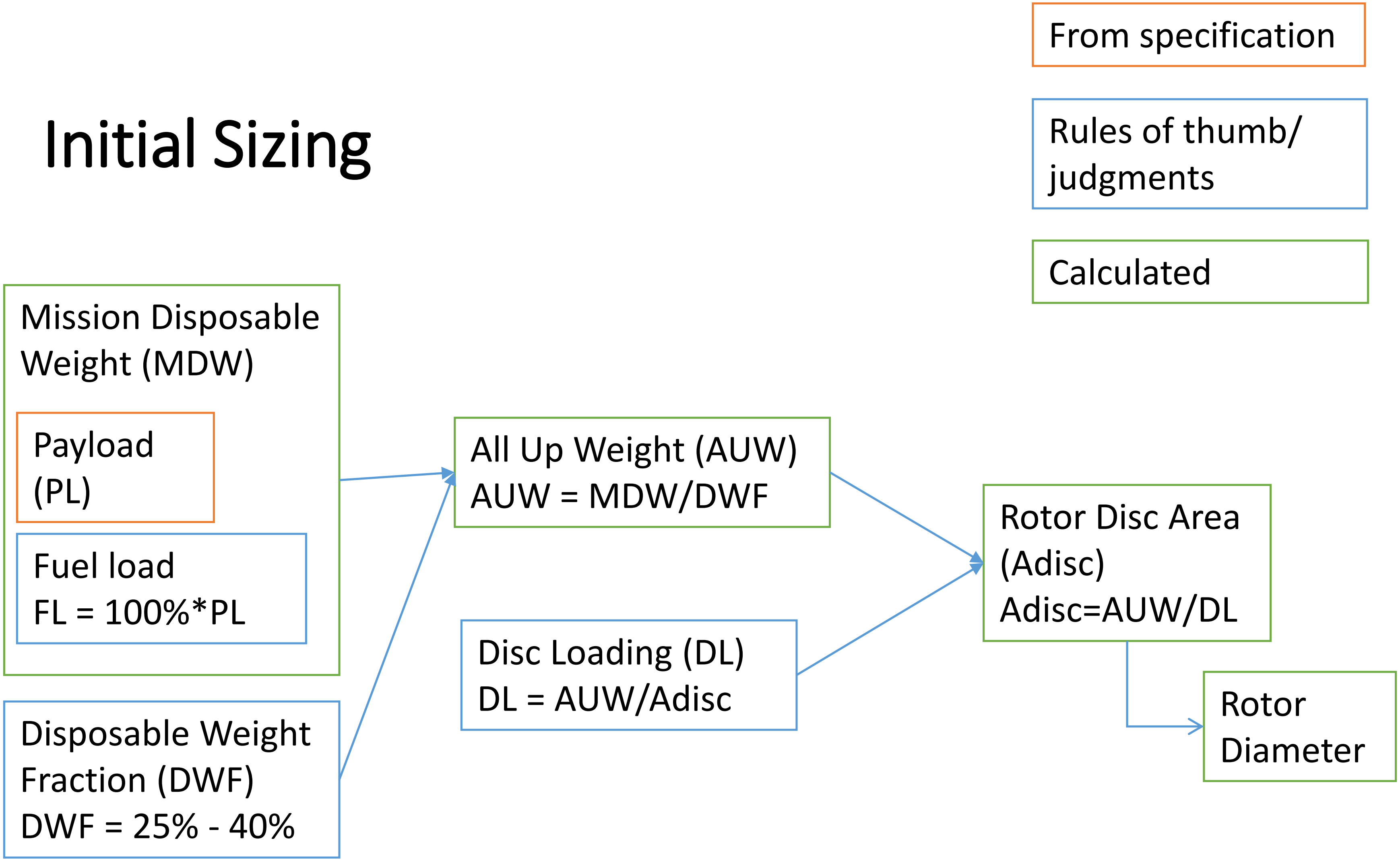
- Calculate required power (select propulsion solution)
- Calculate mission fuel weight
- Refine weight and size of various systems (engines, transmission, rotors, etc.)

Typical Weight Breakdown

APUS, AVDASI4 2016



Initial Sizing



Rotor Design Process

The design process is always iterative but there is a general order to the definition of rotor parameters and the various analyses required to select them: -

- Rotor Diameter
- Rotor Tip Speed
- Total rotor blade area
- Number of blades – and hence blade chord
- Blade Mass
- Blade Flap Stiffness
- Blade Mode Natural Frequencies
- Lag Damping

Rotor Sizing Overview

- Rotor diameter is primarily defined to optimise aircraft hover performance.
- Rotor tip speed is defined on the basis of providing the requisite rotor performance and providing acceptable noise levels and Mach No limit.
    - The chosen rotor speed will have a cross-discipline impact on transmission design
- The selection of blade aerodynamic technology will influence the required total blade area of the rotor.
- Blade area is to be defined on the basis of achieving a forward flight envelope to meet specification requirements. This defines the parameter which is the product of blade chord and blade number.
    - A parameter variation study of the effects of selecting different combinations of blade number and blade chord will be expected.

Rotor Diameter

With an initial estimate of rotor area, rotor diameter is based on achieving the specified hover performance.

Blade radius can also be constrained by other limitations e.g. fuselage length, transportation stowage requirements (aircraft and ship), restricted landing zones.

- A feasible range of disc loadings will be specified

Relatively small rotor diameters will result in high Disc Loadings, wake velocities and hover powers.

Relatively large rotor diameters will require increased fuselage length (for adequate rotor separation) and hence higher aircraft weight.

Rotor Tip Speed

Rotor Tip Speed must be sufficiently high to provide the requisite rotor performance

Rotor Tip Speed must be constrained to provide acceptable noise levels to meet certification requirements

- Rotor noise is a function of the sixth power of tip speed!

Relatively low rotor speeds will: -

- Increase rotor torque levels and will therefore penalise transmission design.
- Require increased blade area (hence weight) to meet performance requirements.

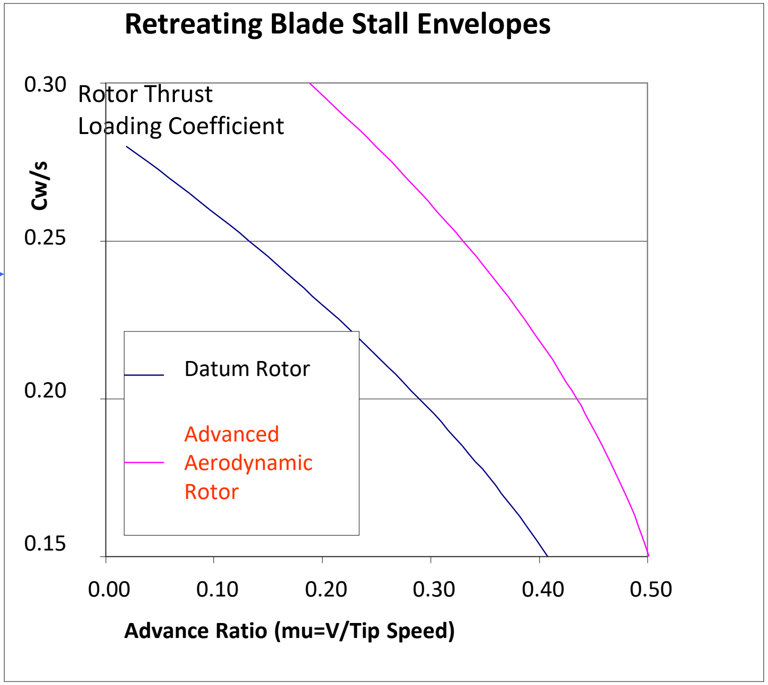
Relatively high rotor speeds will: -

- Generate unacceptable noise levels.
- Result in unacceptably high Mach Numbers (>0.97) at high speed conditions on the advancing blade tip.

Rotor Blade Area

The total blade area (NcR) is defined on the basis of achieving the required thrust and forward speed envelope.

- The blade loading C_W/s is defined as:
  - $C_W/s = \dfrac{T}{0.5\,\rho\,N\,c\,R\,(\Omega R)^2}$
- A range of blade aerodynamic technologies are available.



- A low level aerodynamic technology will result in increased blade area, drag and weight.
- Beware that an advanced aerodynamic technology may lead to inadequate blade area and hence rotational inertia for auto-rotation purposes.

Note that, for a given advance ratio limit, low tip speeds will also reduce maximum speed capability, as well as increase blade area

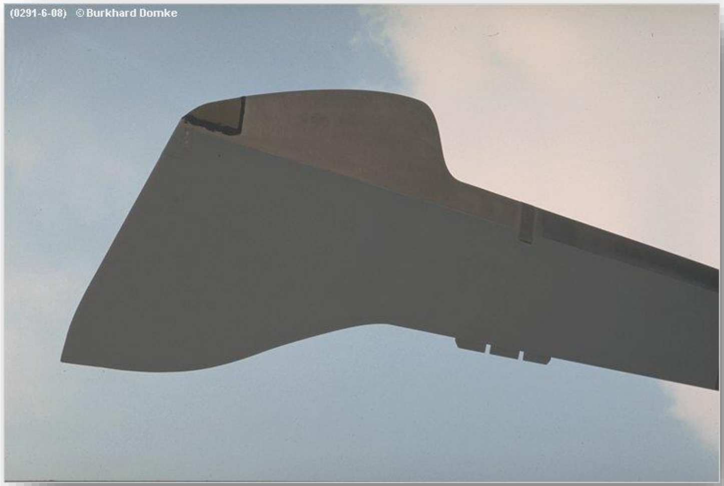
Rotor blade technology

High speed is limited by:

Advancing blade compressibility (wave drag)

Retreating blade stall (and reverse flow regions)

BERP rotor blade tip



Blue Edge Tip

Blade Number vs Blade Chord

Knowing the blade area the remaining blade sizing choice is to select the blade chord and the number of blades.

If the blade chord is too low the blade aspect (R/c) will be high

High aspect ratio blades can lead to low blade torsional stiffness with a tendency towards rotor instabilities and handling problems.

- For this reason an Aspect Ratio limit is imposed (<21).

A large blade chord will lead to higher profile power levels, higher blade mass and increased hub mass to withstand higher centrifugal load.

- A rotor weight limit will be prescribed.

Blade Number vs Blade Chord

A large blade chord will mean a low number of blades.

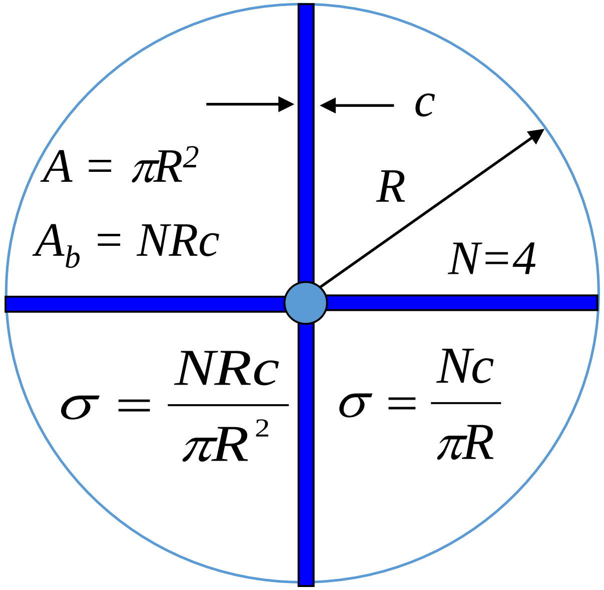
- Good for reduced part count and cost, but…..

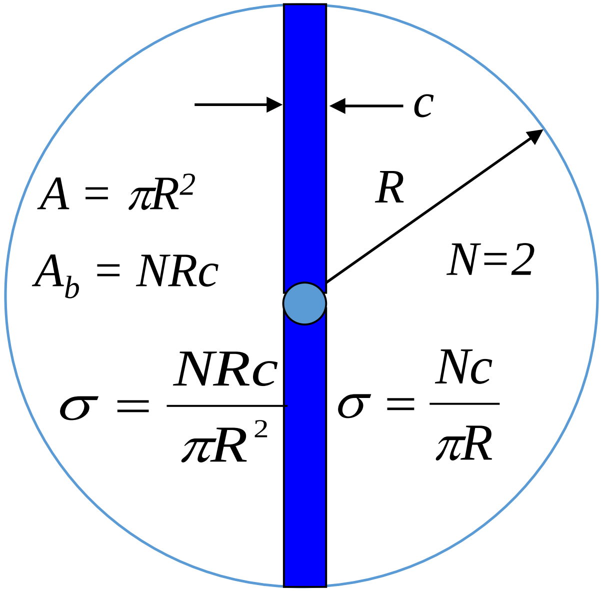
Vibration, which is a critical issue for a helicopter, increases with a lower number of blades.

Conversely, too many blades will result in a lower chord and a potentially unacceptable high blade aspect ratio.

A balanced decision should be based upon a rotor parametric variational analyses of: vibration, rotor mass, aspect ratio and rotational inertia for auto-rotational capability.

Once the rotor dimensions have been fixed the structural design of the rotor can be defined.





Getting Started with RW Performance Tool

- Download tools and guides from Blackboard
- Go through guide for initial sizing and MATLAB tool
- Attempt using the Performance Helicopter spreadsheet (developed by AgustaWestland (Leonardo)).
- Attend the lab for the RW Performance design exercise