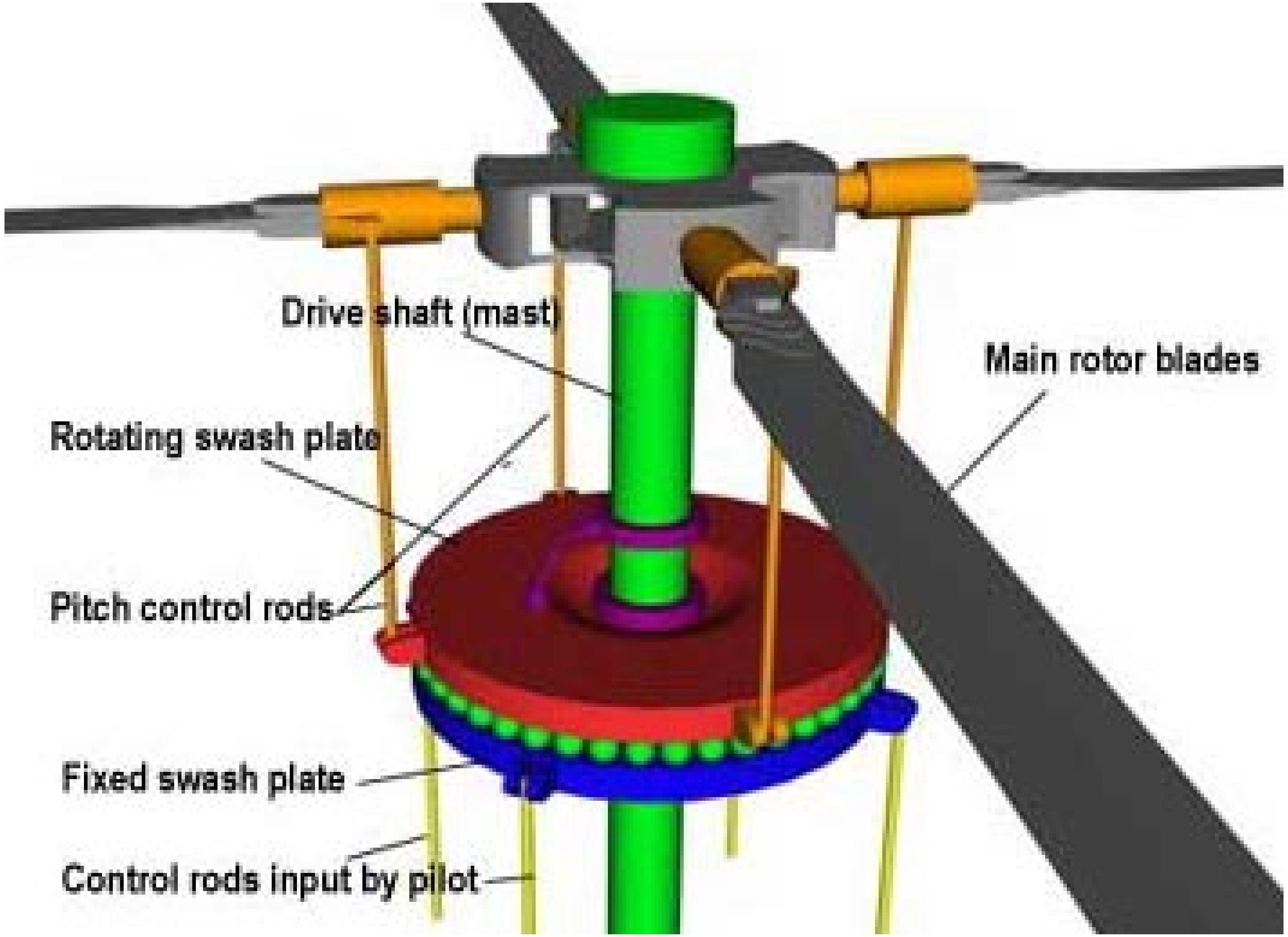
Forward Flight

Blade Flapping Dynamics and Response to Pilot Input


Drive shaft (mast)
Main rotor blades
Rotating swash plate
Pitch control rods
Fixed swash plate
Control rods input by pilot

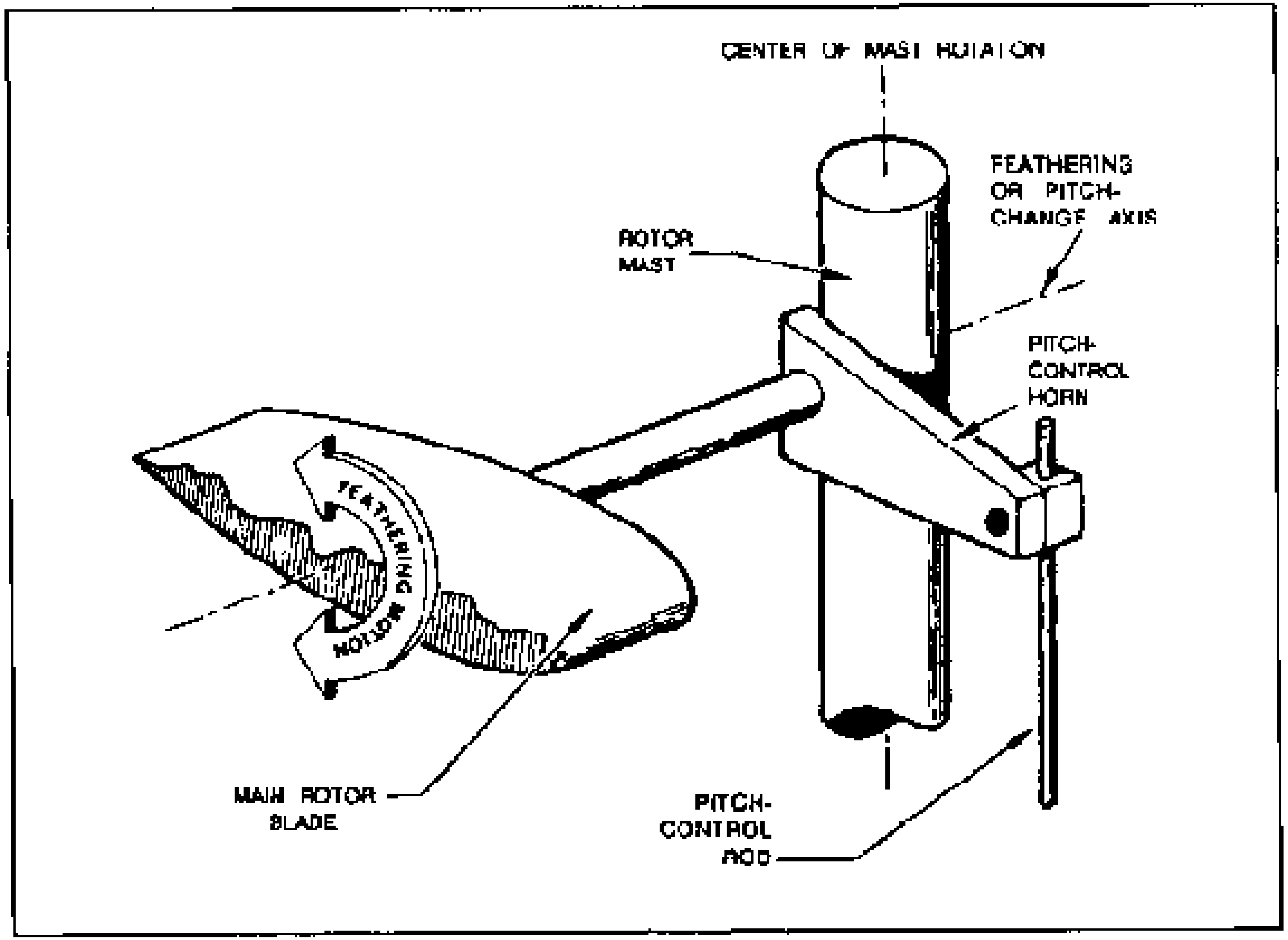


Figure 2-11. Feathering axis

Articulated Rotor

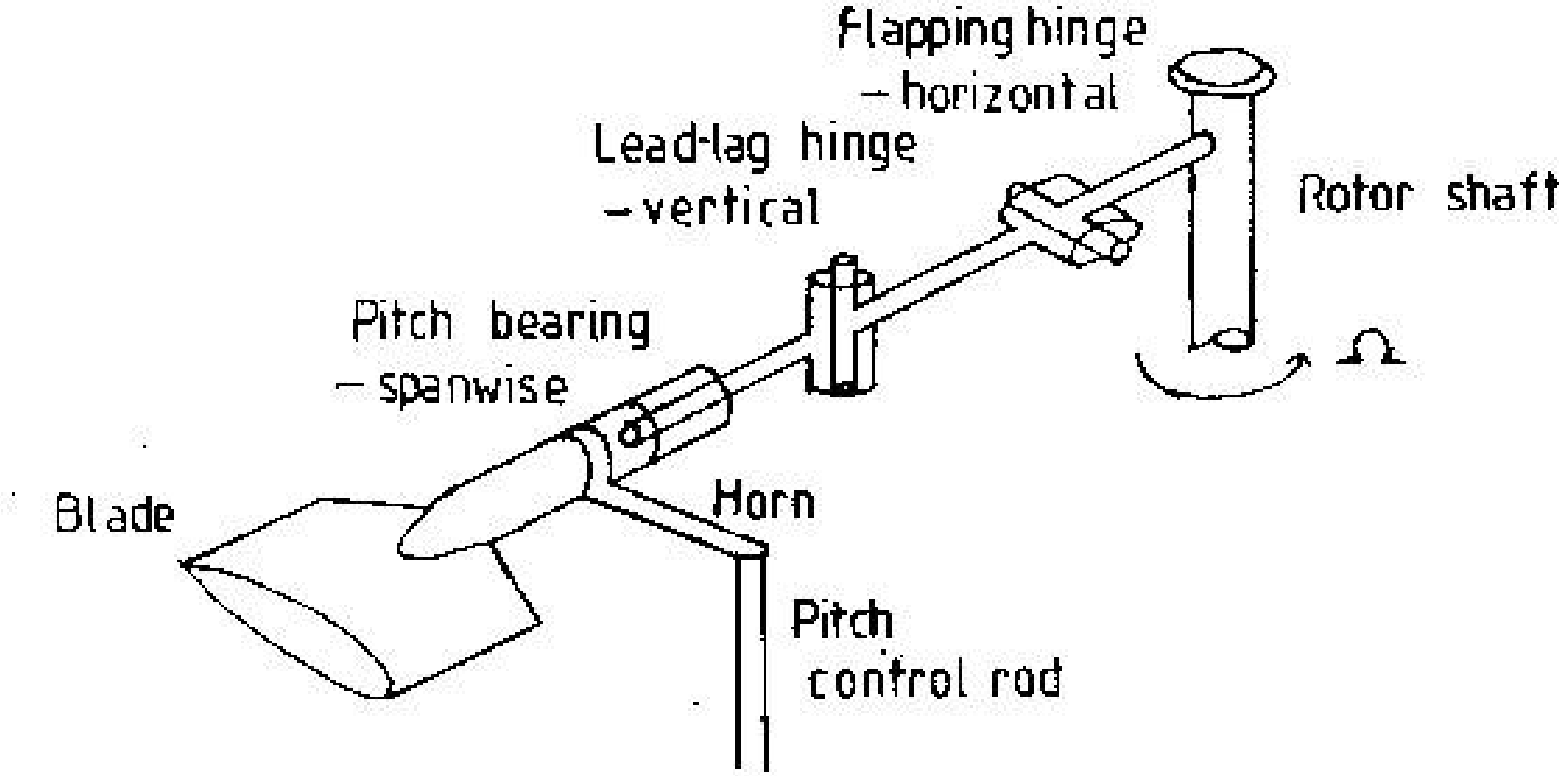
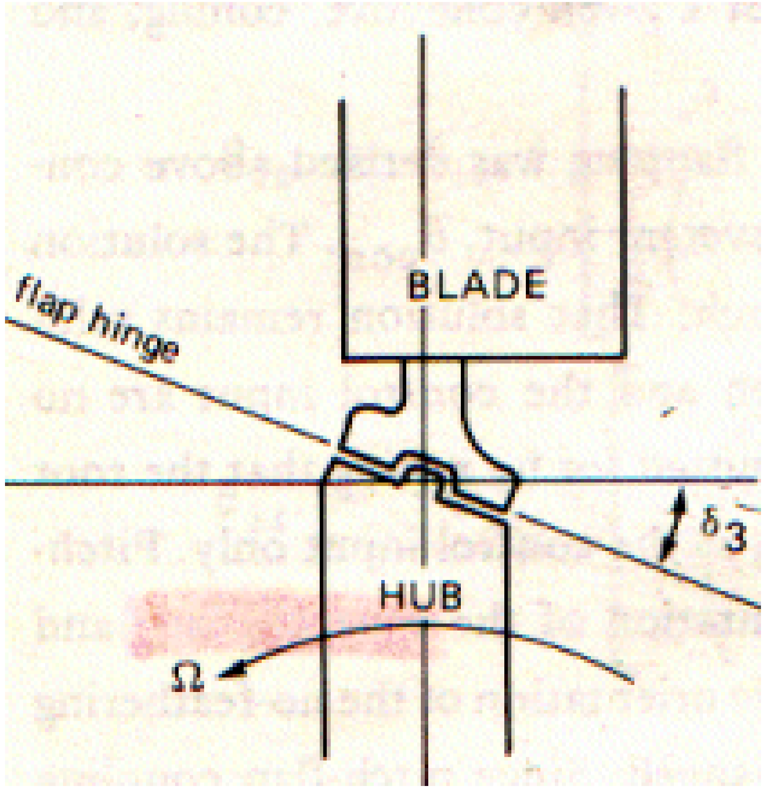
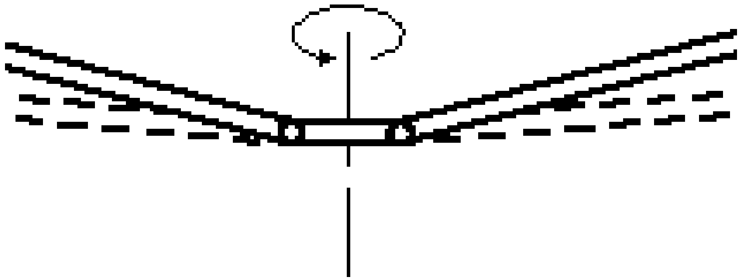


Fig. 4.5 **Principles of articulated rotor hinge system.**

Flap Hinge for Some Tail Rotors

http://www.unicopter.com/0941.html#delta3





http://huizen.dds.nl/
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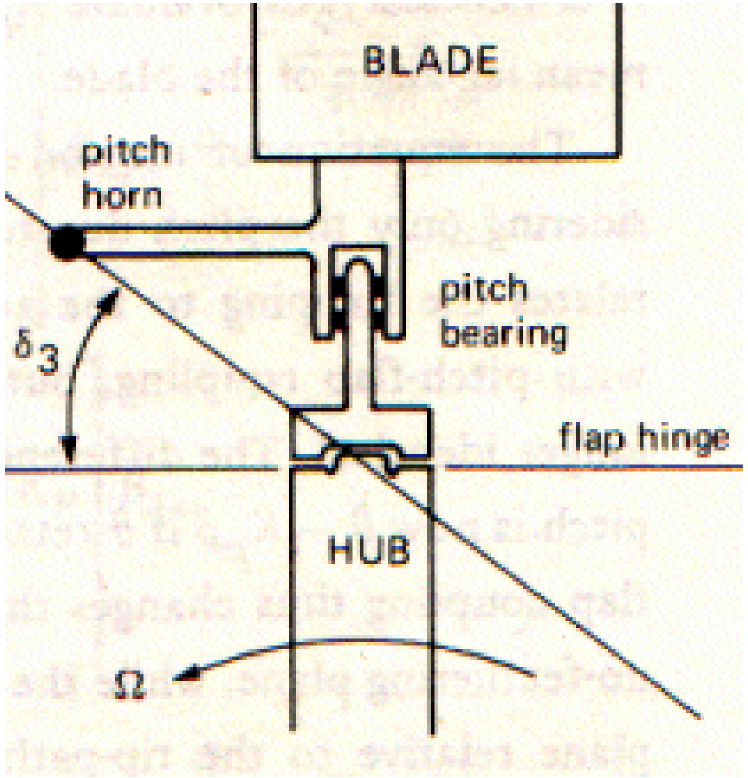
Pitch Horn

http://www.unicopter.com/0941.html#delta3



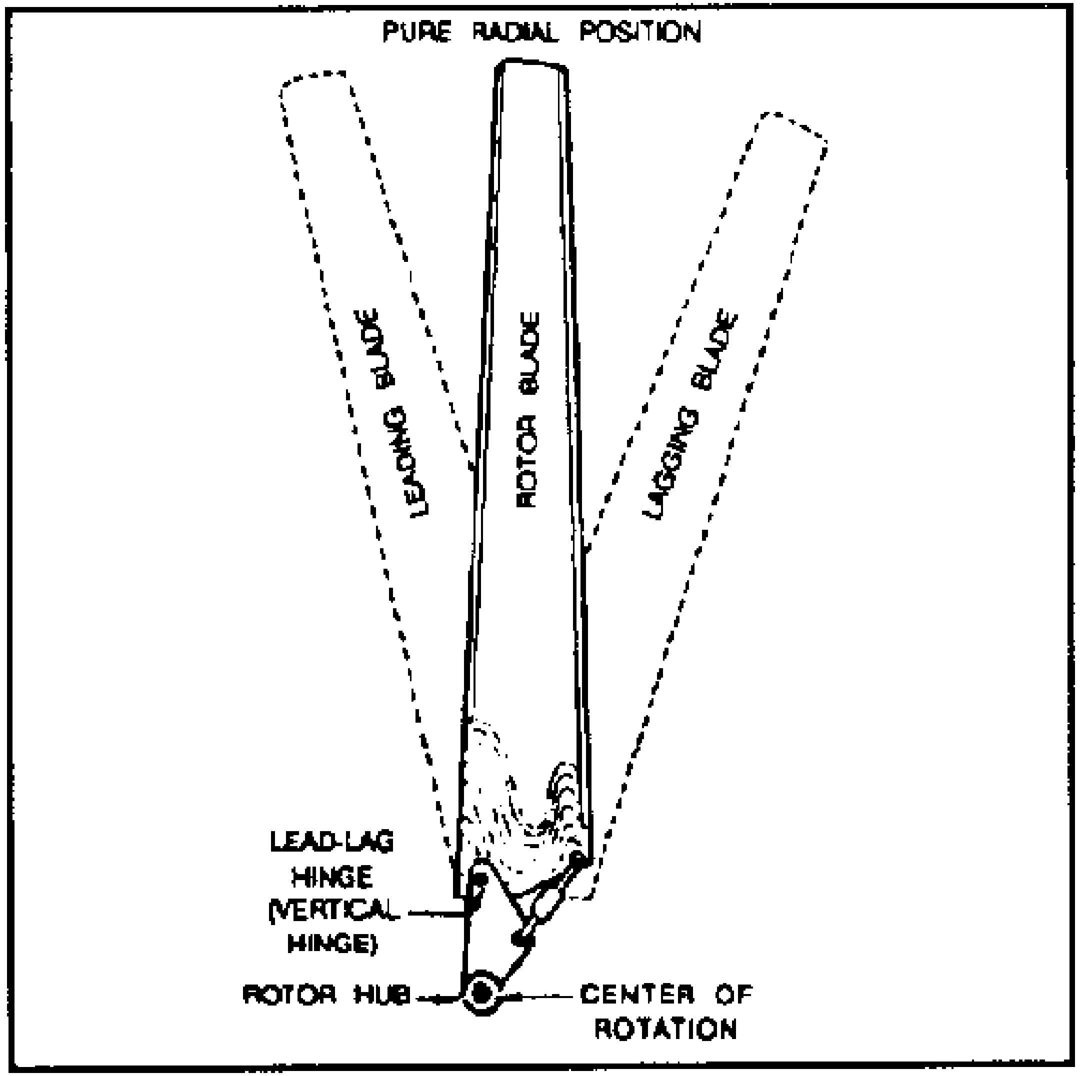
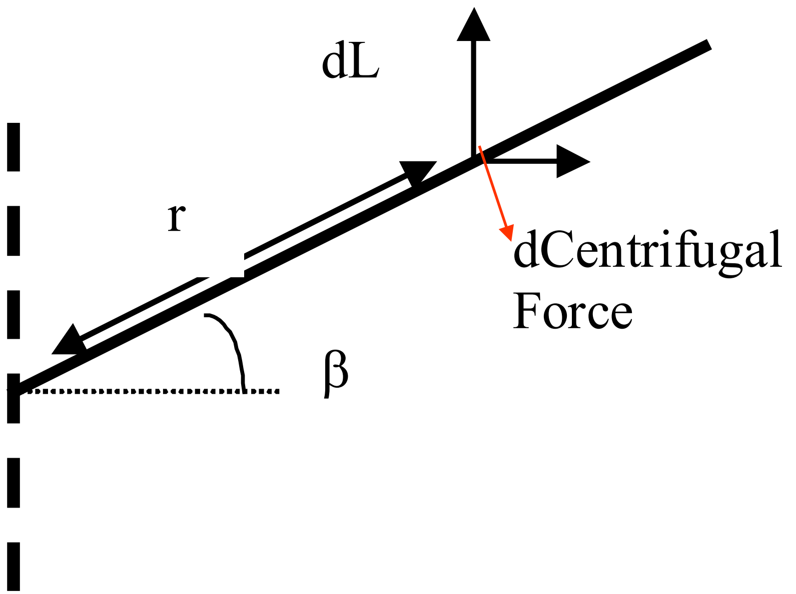


Figure 2-10. Lead and lag

Background

- As seen earlier, blades are usually hinged near the root, to alleviate high bending moments at the root.
- This allows the blades to flap up and down.
- Aerodynamic forces cause the blades to flap up.
- Centrifugal forces causes the blades to flap down.
- Inertial forces will arise, which oppose the direction of acceleration.
- In forward flight, an equilibrium position is achieved, where the net moments at the hinge due to these three types of forces (aerodynamic, centrifugal, inertial) cancel out and go to zero.

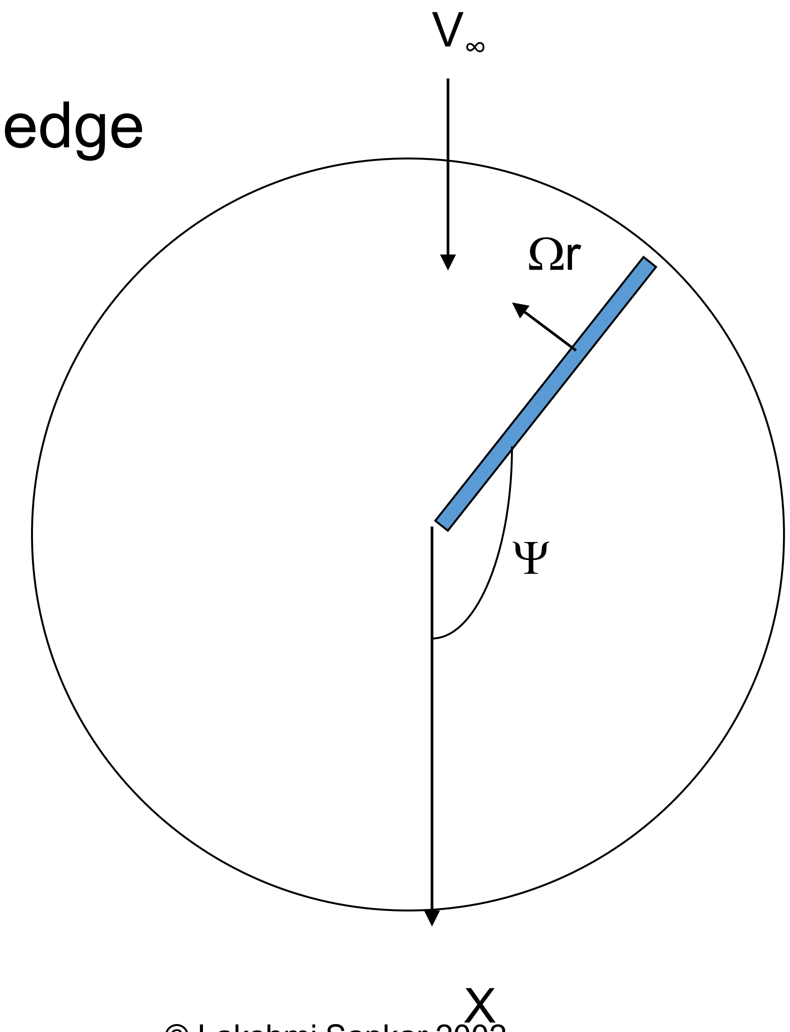
Schematic of Forces and Moments



We assume that the rotor is hinged at the root, for simplicity.
This assumption is adequate for most aerodynamic calculations.
Effects of hinge offset are discussed in many classical texts.

Velocity encountered by the Blade

Velocity normal to
The blade leading edge
is
$\Omega r + V_\infty \sin\Psi$



Moment at the Hinge due to Aerodynamic Forces

From blade element theory, the lift force dL =

$$\frac{1}{2}\rho c\left[\left(\Omega r + V_\infty \sin\psi\right)^2\right] C_l dr$$

Moment arm = r cosβ ~ r

Counterclockwise moment due to lift = $\frac{1}{2}\rho c\left(\Omega r + V_\infty \sin\psi\right)^2 r C_l dr$

Integrating over all such strips,

Total counterclockwise moment = $\int_{r=0}^{r=R} \frac{1}{2}\rho c\left(\Omega r + V_\infty \sin\psi\right)^2 r C_l dr$

Moment due to Centrifugal Forces

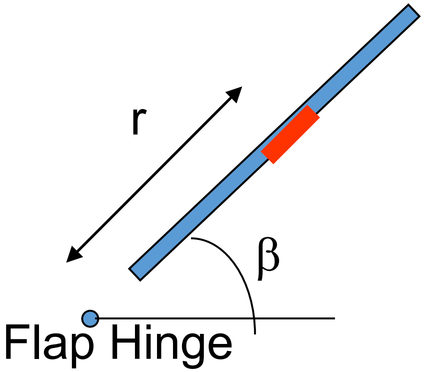
The centrifugal force acting on this strip = $\dfrac{(\Omega r)^2 \, dm}{r} = \Omega^2 r dm$

Where "dm" is the mass of this strip.
This force acts horizontally.
The moment arm = r sinβ ~ r β
Clockwise moment due to centrifugal forces = $\Omega^2 r^2 \beta dm$

Integrating over all such strips, total clockwise moment =

$$\int_{r=0}^{r=R} \Omega^2 r^2 \beta dm \equiv I \Omega^2 \beta$$

Moment at the hinge due to Inertial forces



Small segment of mass dm
With acceleration $r\ddot{\beta}$

β is positive if blade is flapping up

Associated moment at the hinge = $r\left(r\ddot{\beta}\right)dm$

Integrate over all such segments:
Resulting clockwise moment at the hinge= $I\ddot{\beta}$

At equilibrium..

$$I\ddot{\beta} + I\Omega^2 \beta = \int_{Root}^{Tip} \frac{1}{2} \rho c C_l \left(\Omega r + V_\infty \sin\psi \right)^2 r dr$$

Note that the left hand side of this ODE resembles a spring-mass system, with a natural frequency of Ω.

We will later see that the right hand side forcing term has first harmonic (terms containing Ωt), second, and higher Harmonic content.

The system is thus in resonance. Fortunately, there is Adequate aerodynamic damping.

How does the blade dynamics behave when there is a forcing function component on the right hand side of the form $A\sin\Omega t$, and a damping term on the left hand side of form $c\, d\beta/dt$?

To find out let us solve the equation:

$$I\ddot{\beta} + c\dot{\beta} + I\Omega^2\beta = A\sin\Omega t$$

To solve this equation, we will assume a solution of form:

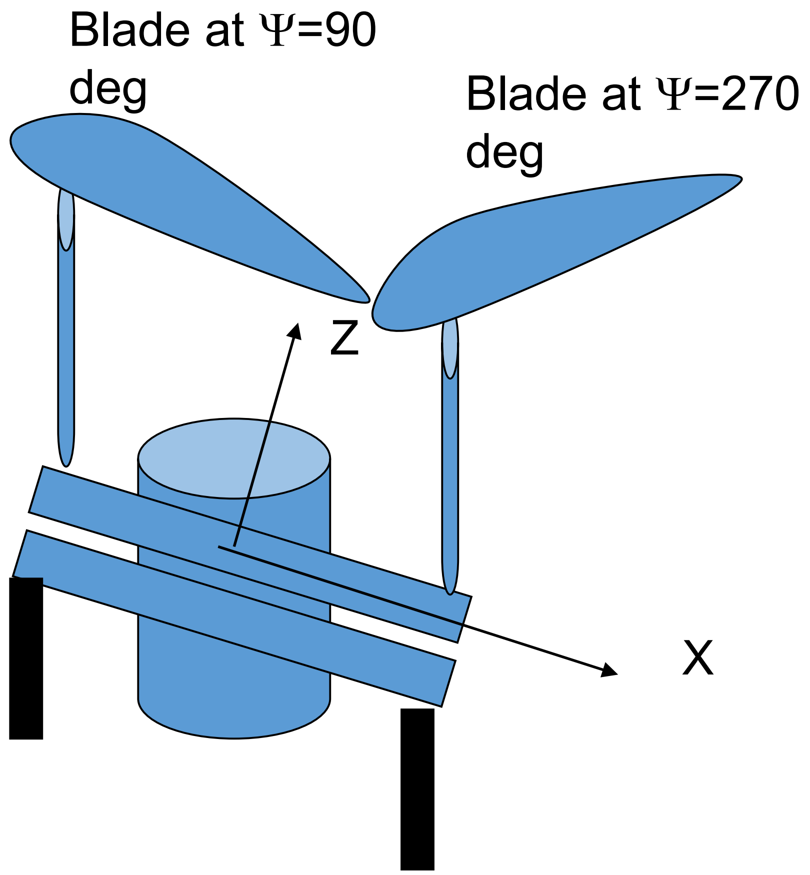
$$\beta = B\sin\Omega t + C\cos\Omega t$$

$$\beta = -\frac{A}{c\Omega}\cos\Omega t = \frac{A}{c\Omega}\sin\left(\Omega t - \pi/2\right)$$

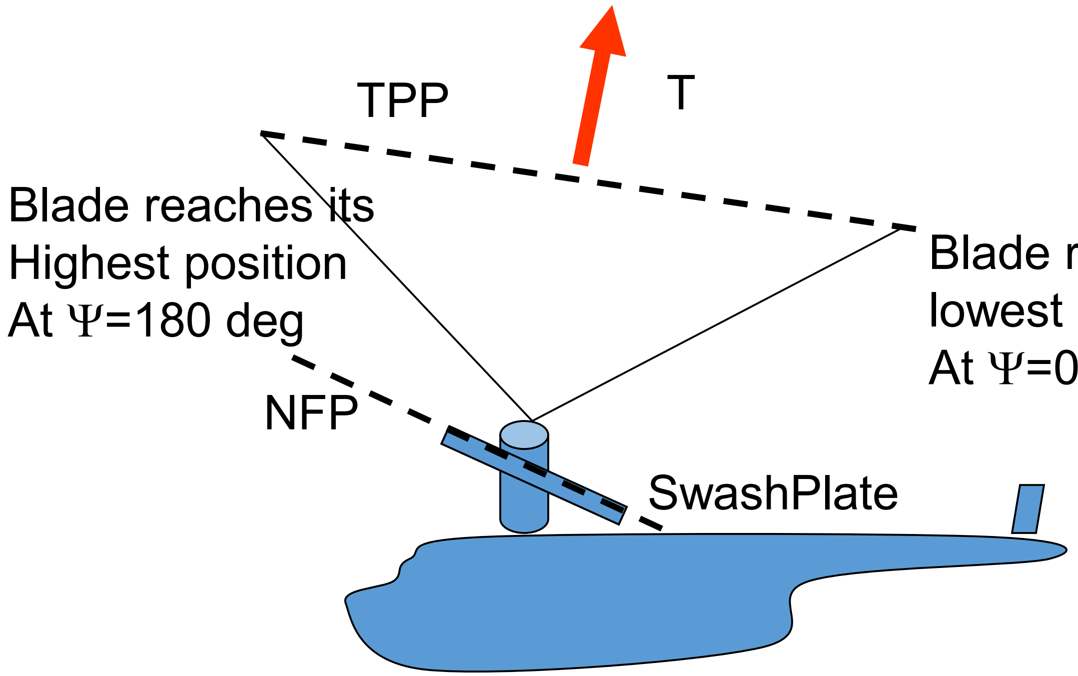
In other words, the blade response will be proportional to the amplitude A of the resonance force, but will lag the force by 90 degrees.

What happens when the pilot tilts the swash plate back?

- The blade, when it reaches 90 degrees azimuth, pitches up.
- Lift goes up instantly.
- The blade response occurs 90 degrees later (recall the phase lag).
- The front part of the rotor disk tilts up.
- The exact opposite happens with the blade at
- 270 degree azimuth.



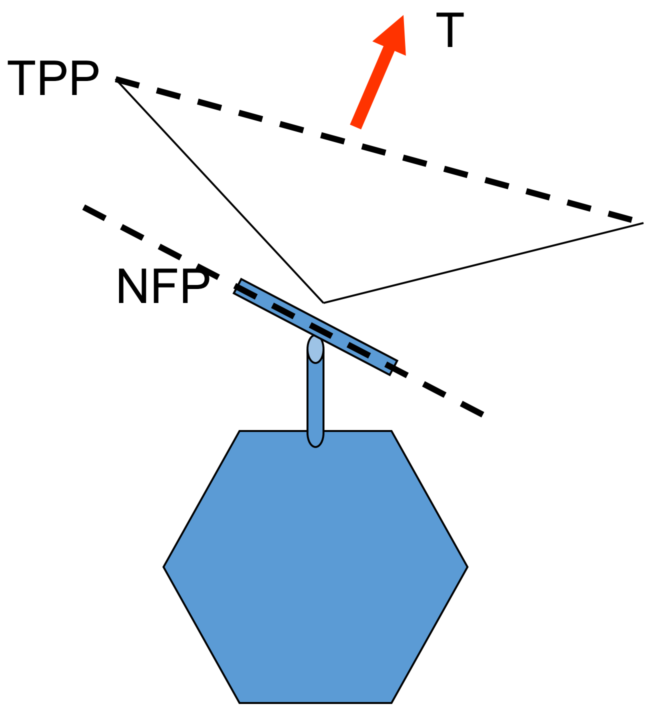
What happens when the pilot tilts the swash plate back?



The tip path plane tilts back. The thrust points backwards. The vehicle will tend to decelerate.

What happens when the pilot tilts the swash plate to his/her right?

- Blade at Ψ= 180 deg pitches up. Lift goes up.
- Blade responds by flapping up, and reaches its maximum response 90 degrees later, at Ψ= 270 deg.
- The opposite occurs with the blade at Ψ= 0 deg.
- TPP tilts towards the pilot’s right.
- The vehicle will sideslip.



Helicopter viewed from Aft of the pilot

Blade Flapping Motion

The blade flapping dynamics equation

$$I\ddot{\beta} + I\Omega^2\beta = \int_{Root}^{Tip} \frac{1}{2}\rho c C_l \left(\Omega r + V_\infty \sin\psi\right)^2 r dr$$

has the general solution of the form

$$\beta = \beta_0 + \beta_{1c}\cos\psi + \beta_{1s}\sin\psi +$$

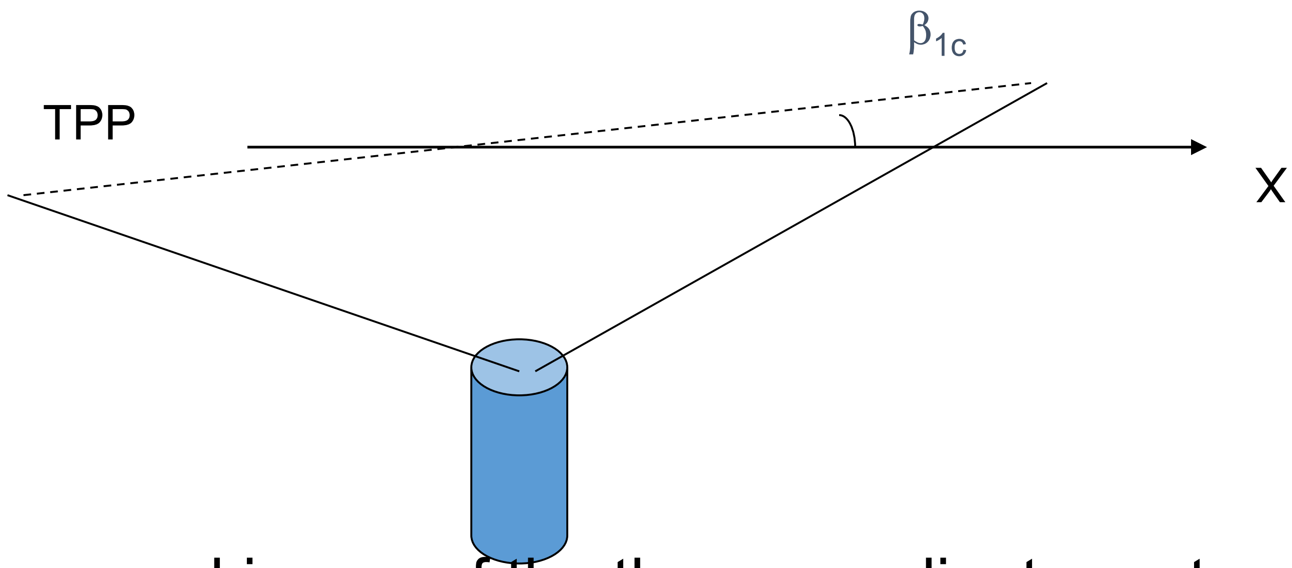
$$\beta_{2c}\cos 2\psi + \beta_{2s}\sin 2\psi + \bullet\bullet$$

higher harmonics

Coning Angle

$\Psi=\Omega t$

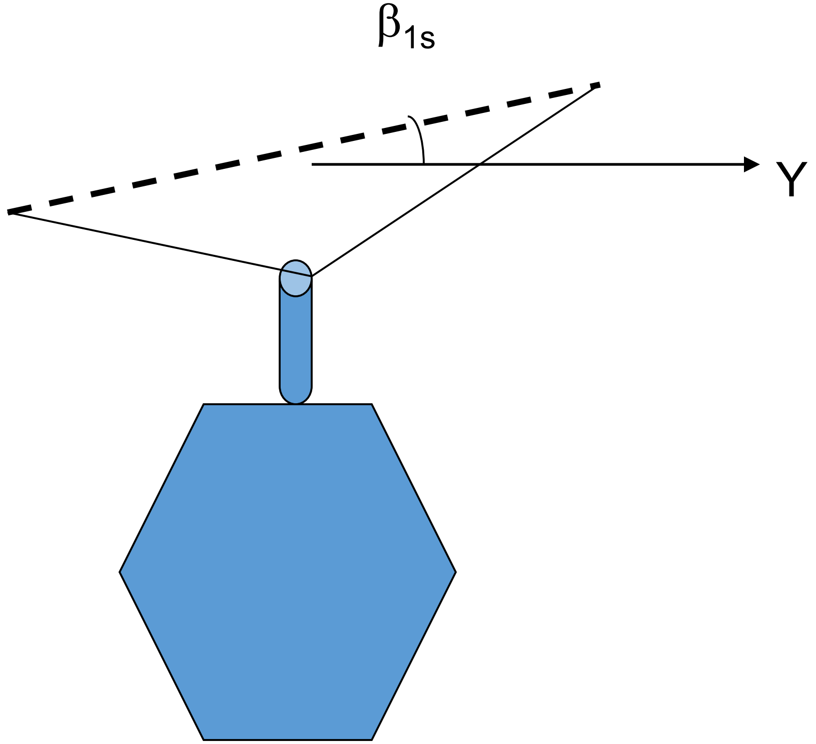
β_{1c} determines the fore-aft tilt of TPP



This angle is measured in one of the three coordinate systems (Shaft plane, TPP, or NFP) that we have chosen to work with. Some companies like to use TPP, others like NFP or shaft plane.

If TPP is our reference coordinate system, what will β_{1c} be? Ans: Zero.

β_{1s} determines the lateral tilt of TPP



Helicopter viewed from the back of the pilot

Pilot Input

$$\theta_{75\%R} = \theta_0 + \theta_{1c}\cos\psi + \theta_{1s}\sin\psi$$

Collective

Lateral control

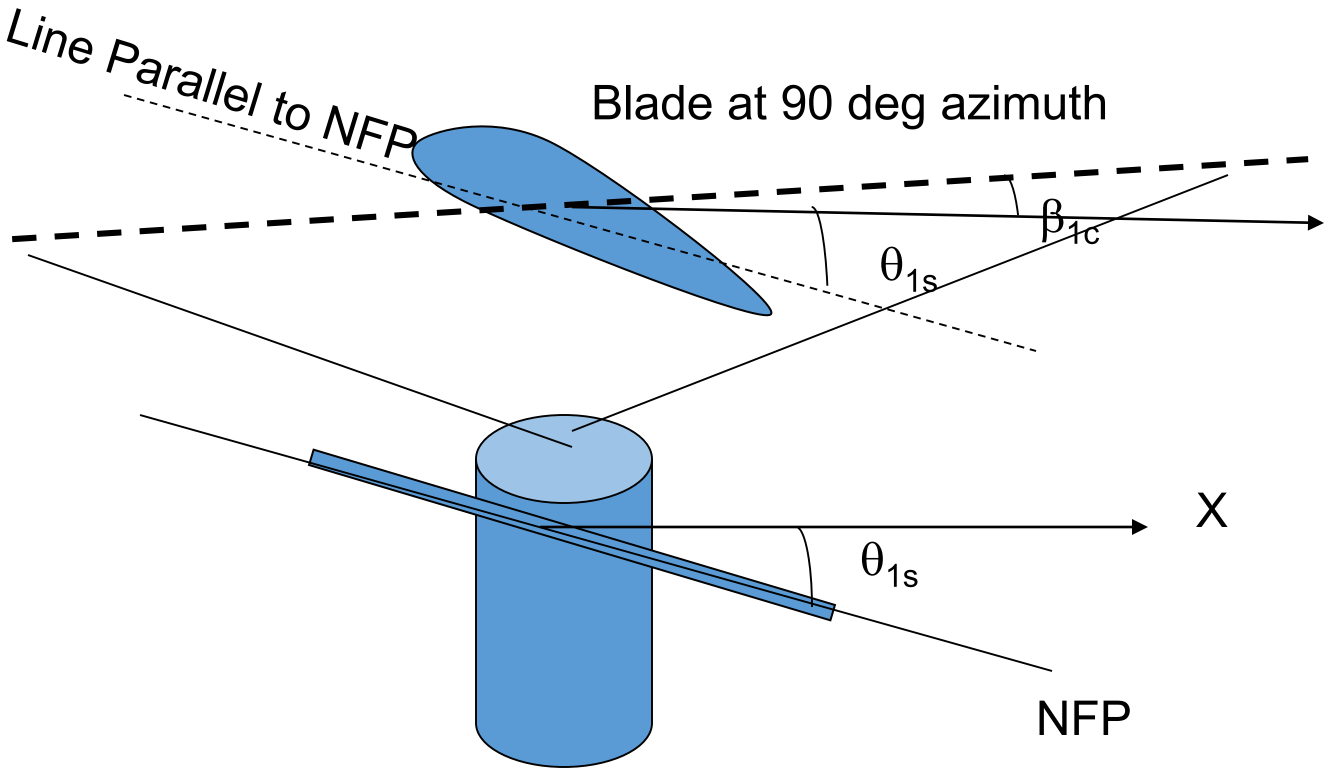
Longitudinal control

The pitch is always, by convention
Specified at 75%R.
The pitch at all the other radial locations may be found
If we know the linear twist distribution.

The pilot applies a collective pitch by vertically raising the swash plate up or down. All the blades collectively, and equally pitch up or down.

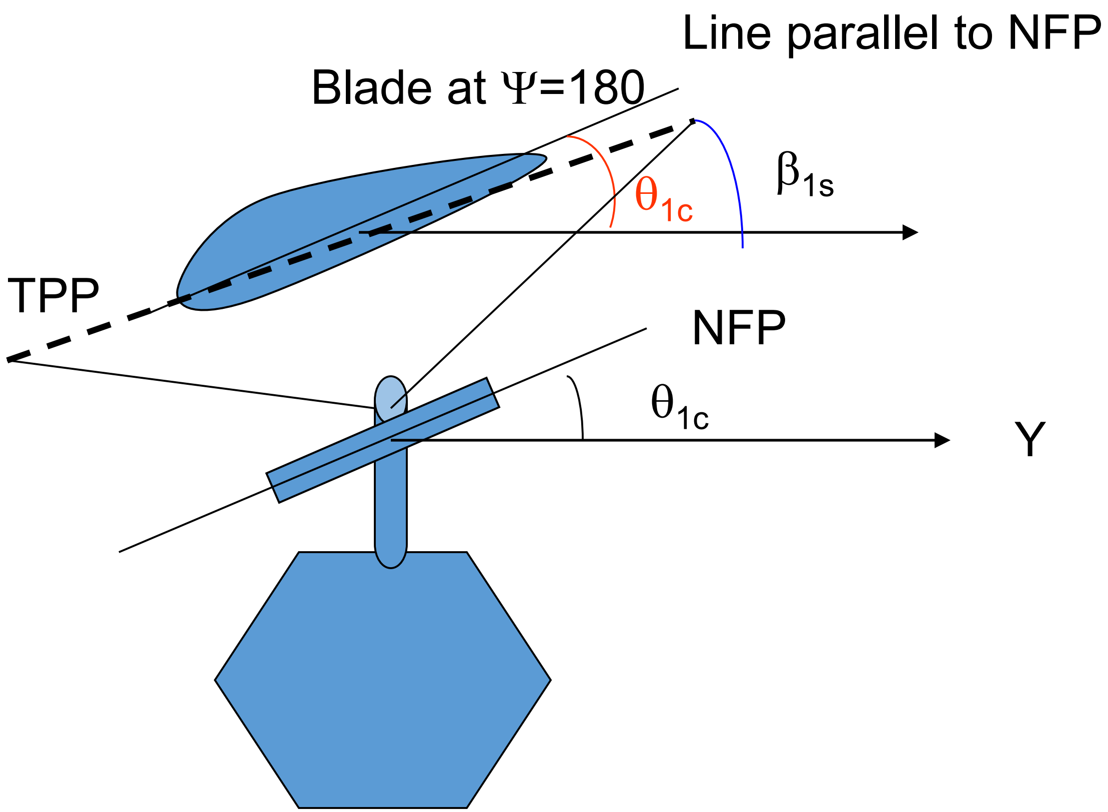
The pilot applies longitudinal control (i.e. tilts the TPP fore and aft) by
Tilting the swash plate fore or aft as discussed earlier.
Lateral control means tilt the swash plate (and the TPP) laterally.

Longitudinal control



Note that $\theta_{1s} + \beta_{1c}$ is independent of the coordinate system in which these angles are measured.

Lateral Control



Note that θ_{1c}-β_{1s} is independent of the coordinate system in which θ_{1c} And β_{1s} were measured.

As a result..

$$\beta_{1c} + \theta_{1s} = \beta_{1c}\Big|_{NFP} = \theta_{1s}\Big|_{TPP}$$

$$\beta_{1s} - \theta_{1c} = \beta_{1s}\Big|_{NFP} = -\theta_{1c}\Big|_{TPP}$$

In the future..

- We will always see $\beta_{1c}+\theta_{1s}$ appear in pair.
- We will always see $\beta_{1s}-\theta_{1c}$ appear in pair.
- As far as the blade sections are concerned, to them it does not matter if the aerodynamic loads on them are caused by one degree of pitch that the pilot inputs in the form of θ_{1c} or θ_{1s}, or by one degree of flapping (β_{1c} or β_{1s}).
- One degree of pitch= One degree of flap.