Aerodynamics 2 - Rotorcraft Aerodynamics

Translational Flight
(not so easy!)
Lecture 6

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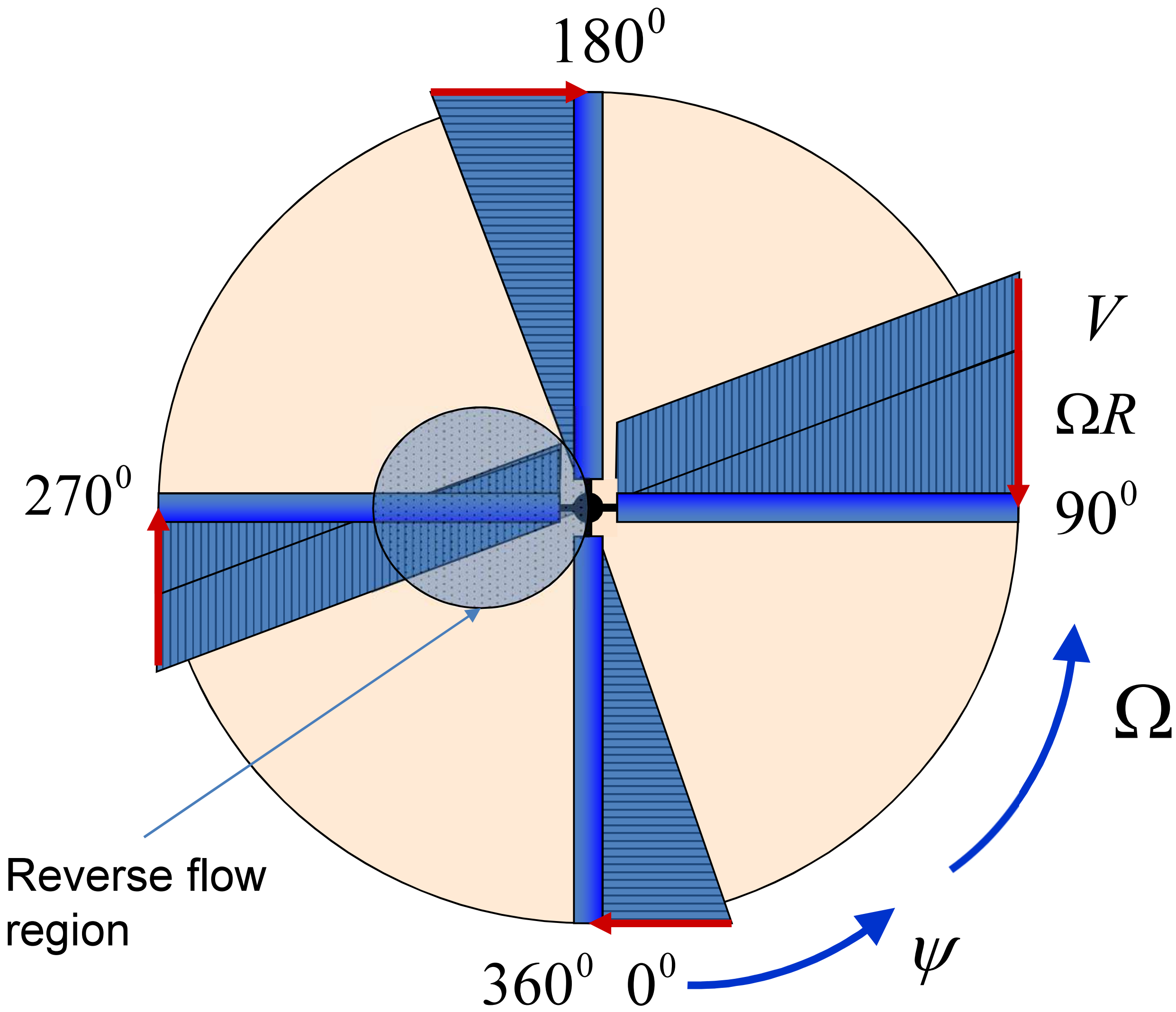
Translational Flight

- **The Rotor in Edge-Wise Flow**
- Blade Flapping Motion
- Blade Flapping and Feathering Equivalence (1)

Helicopter in forward flight

The rotor hub

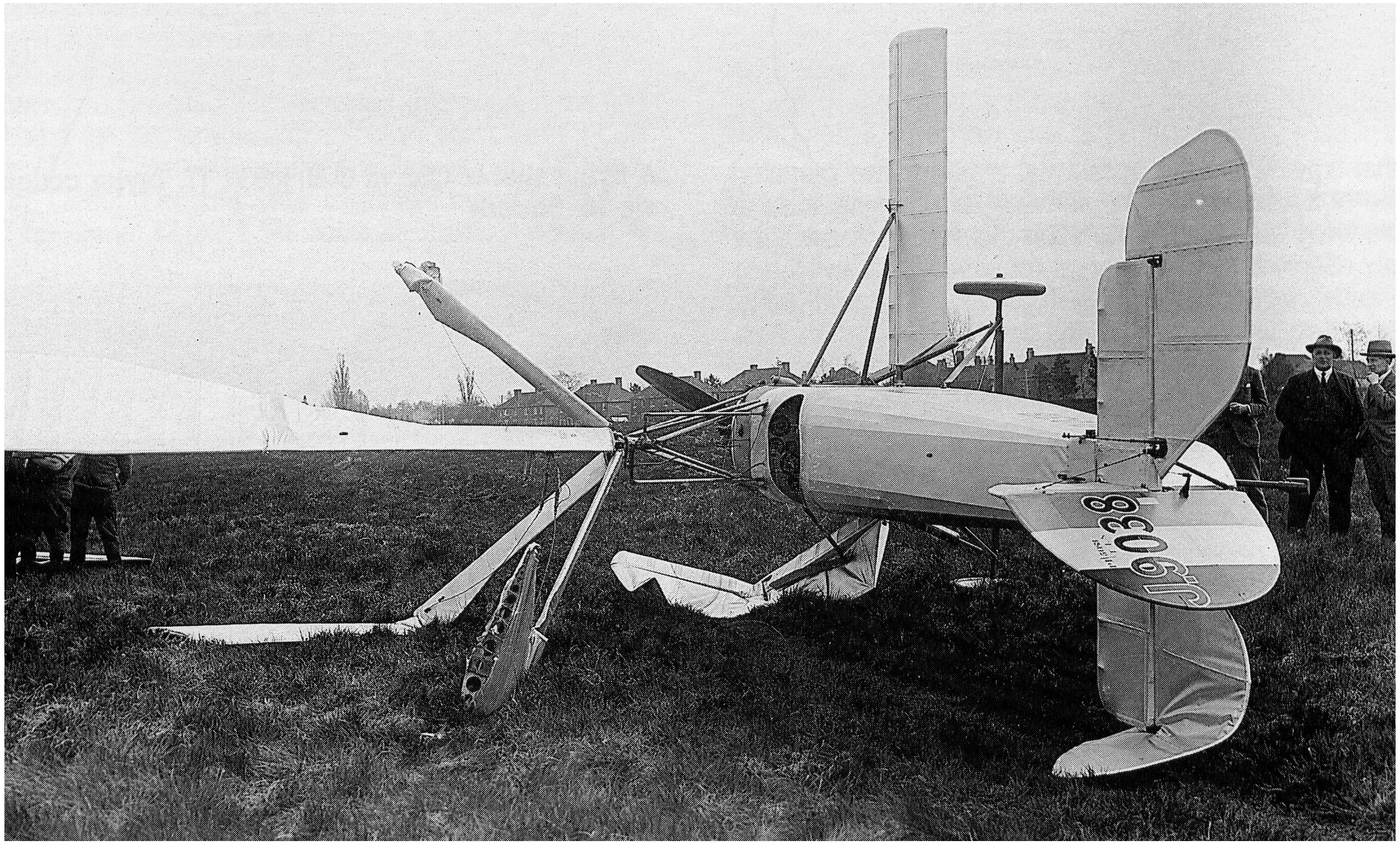
The Rotor in Edge-Wise Flow



In addition to the blade velocity due to rotation.

there is a common velocity acting on all elements due to edge-wise flight. This results in the asymmetry of lift.

The Rotor in Edge-Wise Flow



Cierva's early attempts at translational (edge wise flight) of a lifting rotor on full-size aircraft ended in disaster, yet his model Autogiro™ flew perfectly.

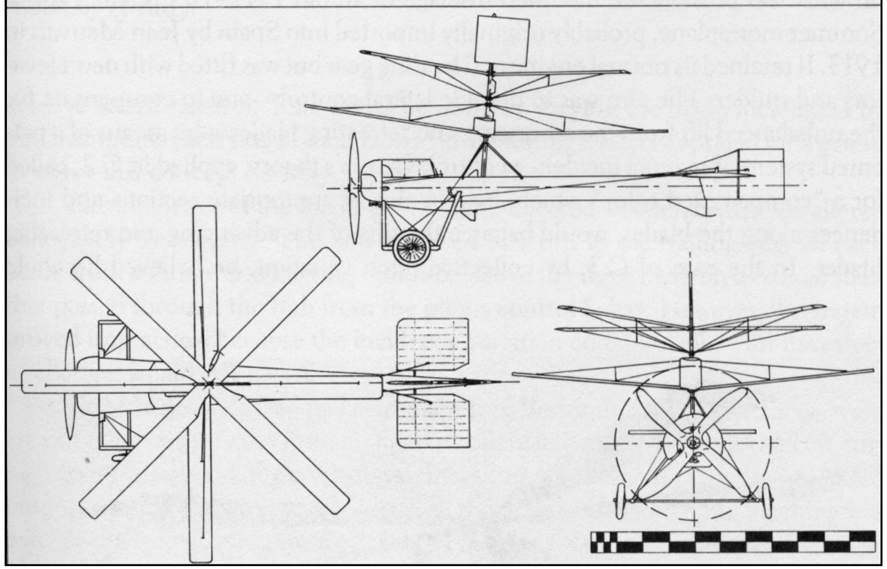
<u>The Rotor in Edge-Wise Flow</u>

This lateral rolling tendency was not unexpected. Indeed Cierva had anticipated this and had tried to counter the effect in his very first Autogiro, the C1.

Contra-rotating coaxial rotors didn't solve this problem. A problem that his single rotor autogyro model failed to exhibit.

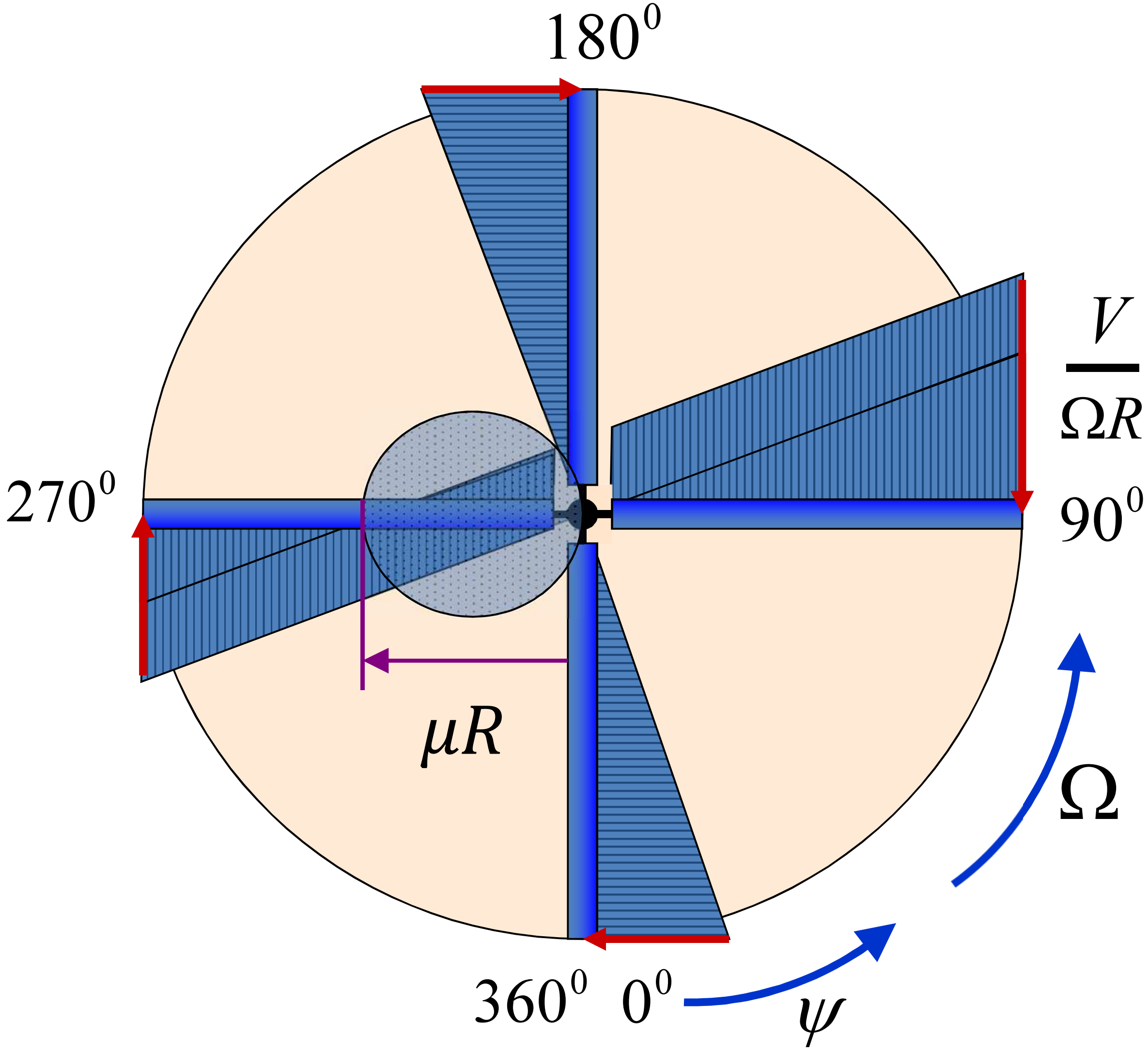
The reason was in fact quite simple. The model rotor blades were rigid enough not to require the bracing wires of the full scale aircraft. But they were not so rigid that they couldn't flap under load.

The Cierva C.1 was the first Autogiro design to be built. (Ministerio del Aire photograph, courtesy H-Ros.)



The Rotor in Edge-Wise Flow

The Asymmetry of Lift



In addition to the blade velocity due to rotation

there is a common velocity acting on all elements due to edge-wise flight.

$$\frac{V}{\Omega R} = \mu$$

Translational Flight

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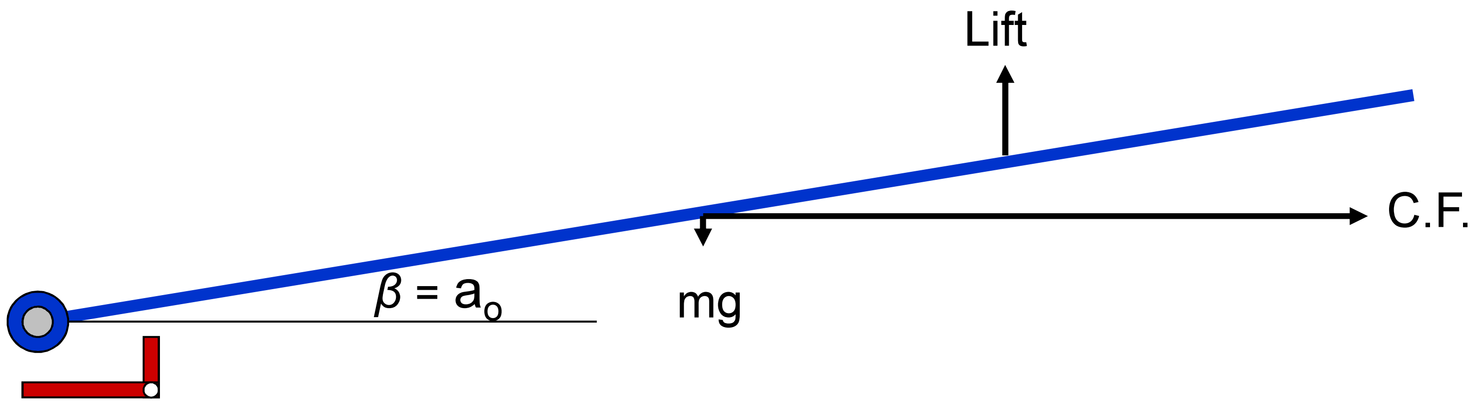
The Rotor in Edge-Wise Flow

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



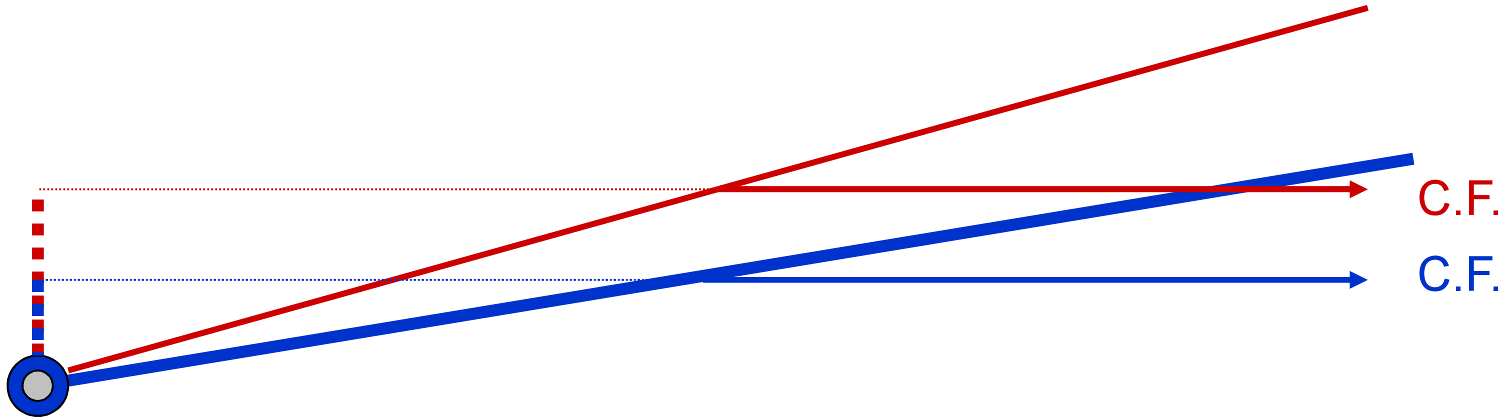
In a (no wind) hover, the Lift, Centrifugal Force and the blade weight result in a small amount of blade "coning" referred to as a_o.

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

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

Blade flapping motion

Blade Flapping Motion



If the blade flaps up, away from it's steady state, the increased C.F. moment arm will provide a restoring force, acting like a return spring.

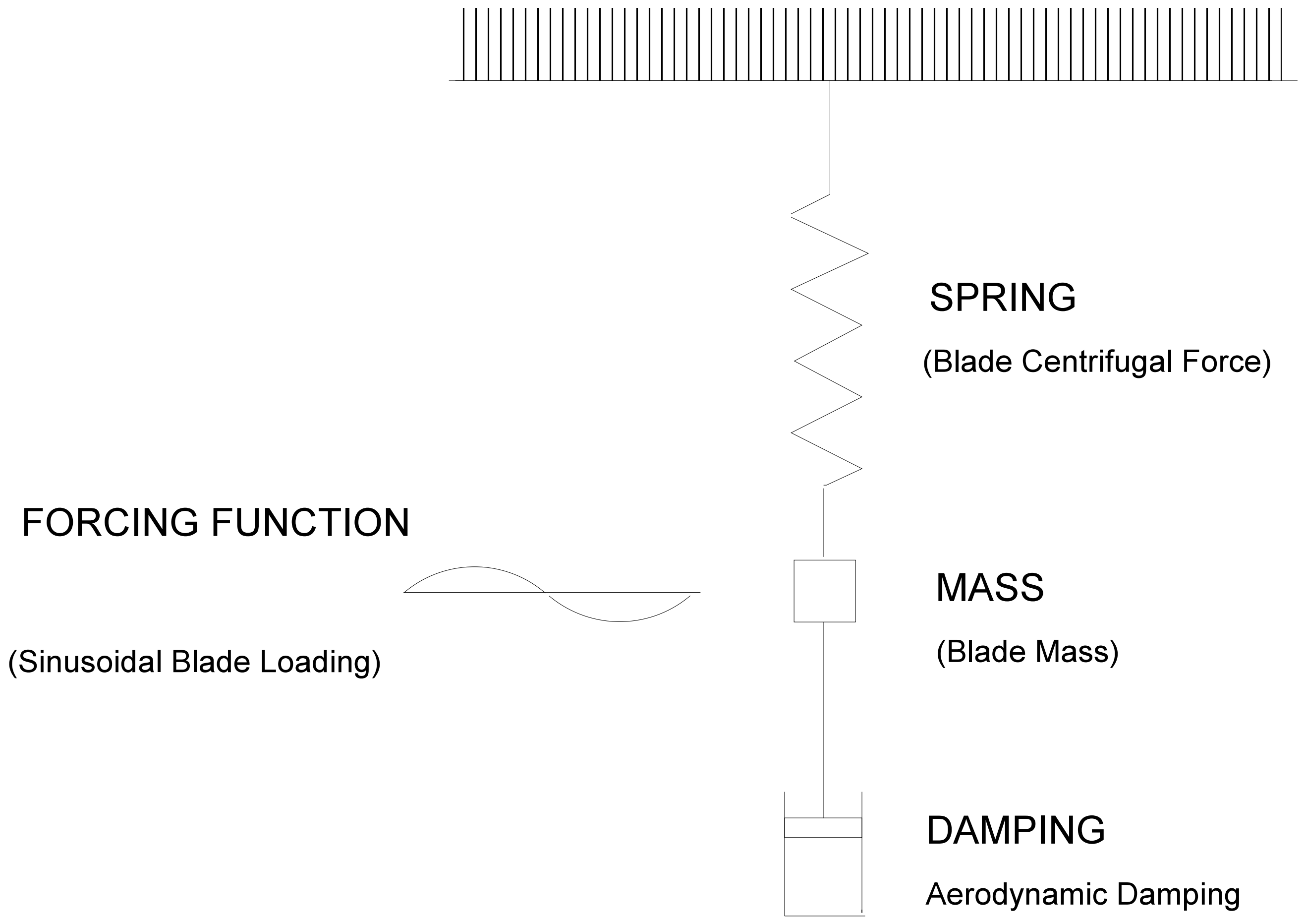
The blade dynamics provide a restoring spring force.

As the blade flaps up, the angle of incidence is reduced and so therefore is the lift which tends to oppose the upward flapping motion.

As the blade flaps down, the angle of incidence is increased and so therefore is the lift which tends to oppose the downward flapping motion.

The blade aerodynamics provide motion damping.

Blade Dynamics



Blade Dynamics

Using the general equation for rotational oscillations, the natural frequency is given by:

$$\omega_n = \sqrt{\frac{K}{I}}$$

where $K =$ spring constant $\boldsymbol{Nm / rad}$

$I =$ moment of inertia $\boldsymbol{kgm^2}$

The <u>spring constant</u> of the rotor blade is the restoring force provided by the centrifugal force.

The centrifugal force is $(C.F.) = mr\Omega^2$, (for a blade element at radius r)

which results in a moment about the flapping hinge, $(C.F.)r\sin\beta$

which for small angle approximations can be expressed as $(C.F.)r\beta$

Summating for all blade elements, $(C.F.)$ moment =

$$\int_0^R \Omega^2 r^2 \beta m dr = m\Omega^2\beta\frac{R^3}{3} = M\Omega^2\beta\frac{R^2}{3} = K\beta$$

The flapping moment of inertia of the rotor blade is $I = \frac{MR^2}{3}$

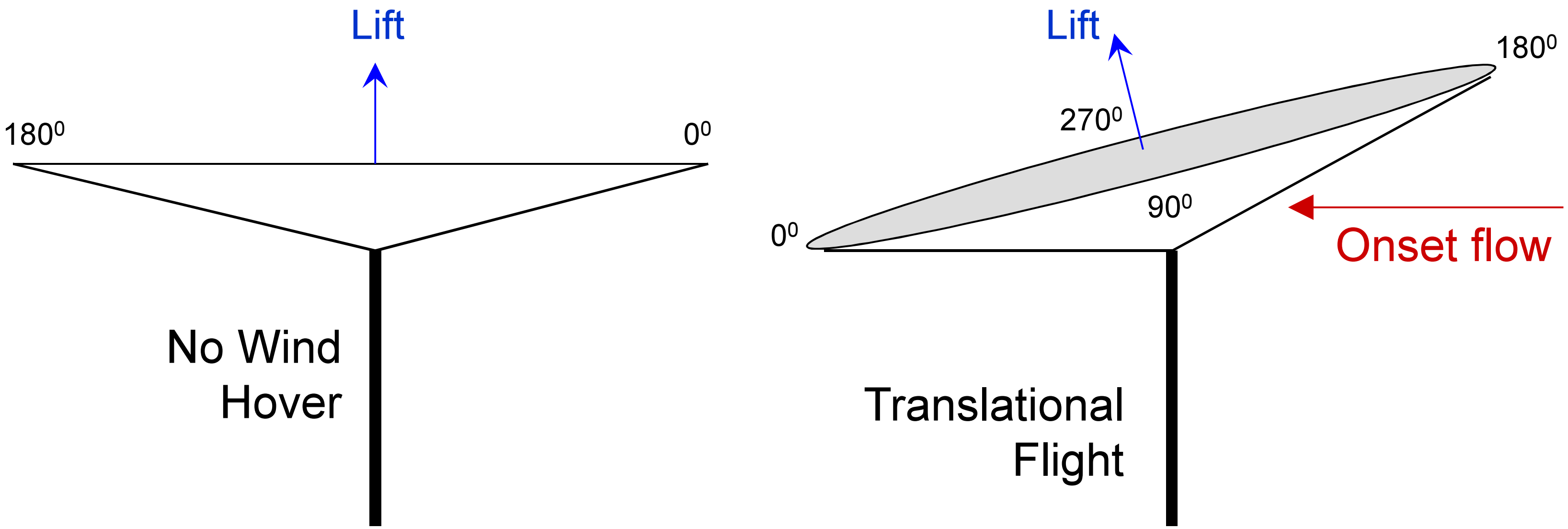
Thus the natural flapping frequency of the blade is $\omega_n = \sqrt{\Omega^2} = \Omega$ rads/sec

The natural frequency is the rotational frequency, so the rotor is in resonance.

Blade Dynamics

This shows that for a blade that flaps about a hinge on the rotor axis, the natural flapping frequency is the rotational frequency. Thus the rotor is in resonance and the phase angle (that is the force-displacement angle) is 90^0

The forcing function (in forward flight) has a maximum and minimum value at $\psi = 90^0$ and $\psi = 270^0$ respectively. It follows then that the displacement has a maximum and minimum value at $\psi = 180^0$ and $\psi = 360^0$ respectively. This means that in forward flight the rotor disc will pitch upwards (in the positive sense).

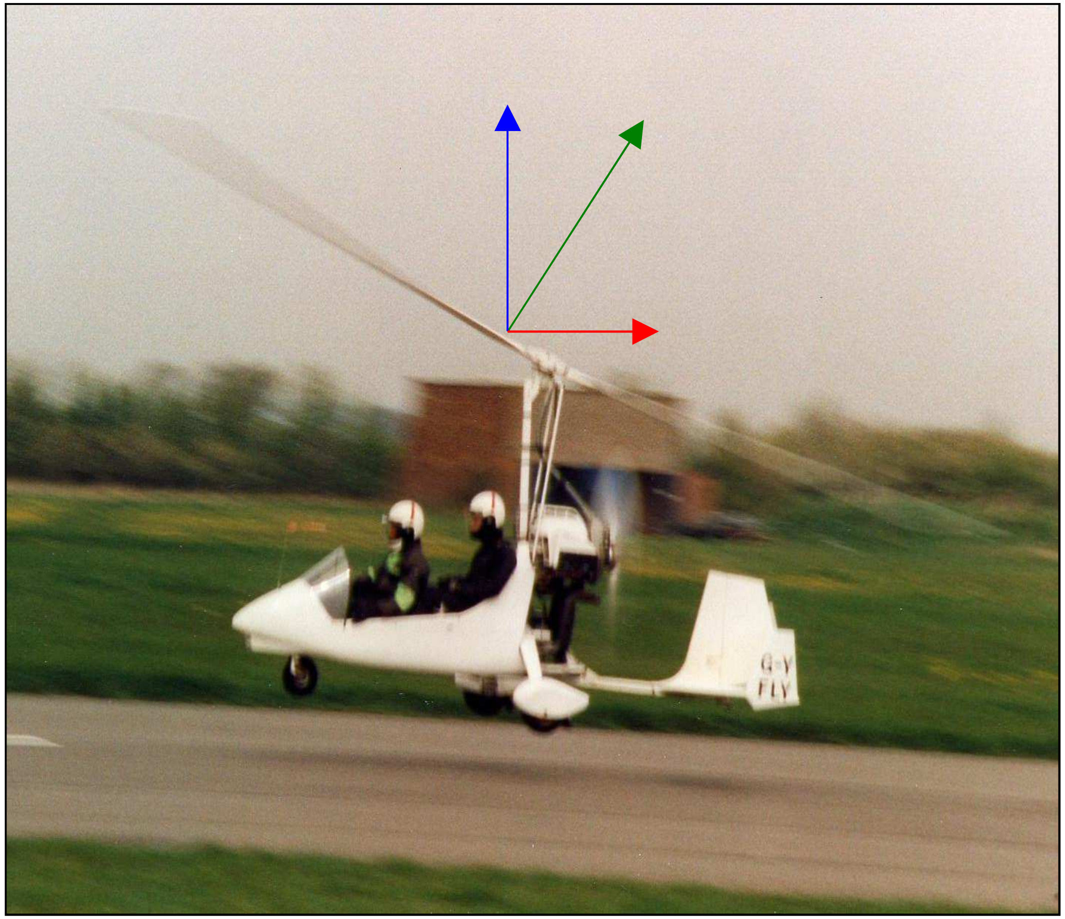


View from Starboard Side (ψ=90^0)

Blade Dynamics

For the autogyro, the tilt back of the rotor disc is conducive to normal operations.

However as the forward speed increases, tilt back becomes excessive. The rotor will produce too much thrust for the lift component required and the drag component will limit maximum speed.



Autogyro Rotor Control

Early control of the rotor was by orientation of the aircraft, to which the rotor shaft is rigidly attached as seen here on a Cierva C.8 Mk IV

Direct control was introduced in 1931 (Cierva C.19 Mk.V) whereby the autogyro pilot has direct control of the rotor disk inclination, quite literally in early designs.

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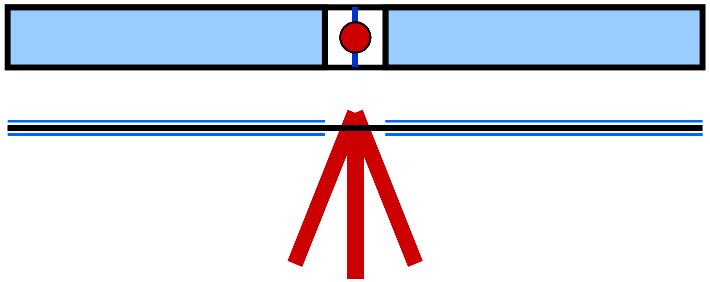
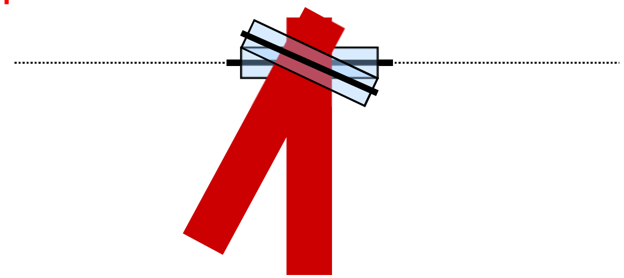
Flapping~Feathering Equivalence

So, the autogyro had a flapping hinge and no feathering hinge but by directly tilting the rotor disk the effective pitch of the blades varied cyclically around the rotor azimuth – this was in effect a cyclic pitch control.





The powered rotor (helicopter) cannot be manually tilted with such ease.

The fully articulated rotor head, controlled across the stationary / rotational interface by a swash plate, can apply collective and cyclic changes of pitch.

Thus the pitch can be cyclically changed to prevent the blades from flapping (in translational flight) and also address the problem of lift asymmetry.

Coning angle ▼ ▼ Rotor flap-back (longitudinal) angle

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

Blade pitch angle $\theta = A_0 - A_1 \cos\psi - B_1 \sin\psi - A_2 \cos 2\psi - B_2 \sin 2\psi - \ldots\ldots$

Collective Pitch angle input ▲ ▲ ▲ Lateral Cyclic Pitch angle input

Longitudinal Cyclic Pitch angle input will counter lateral rotor tilt

Flapping~Feathering Equivalence

Direct control

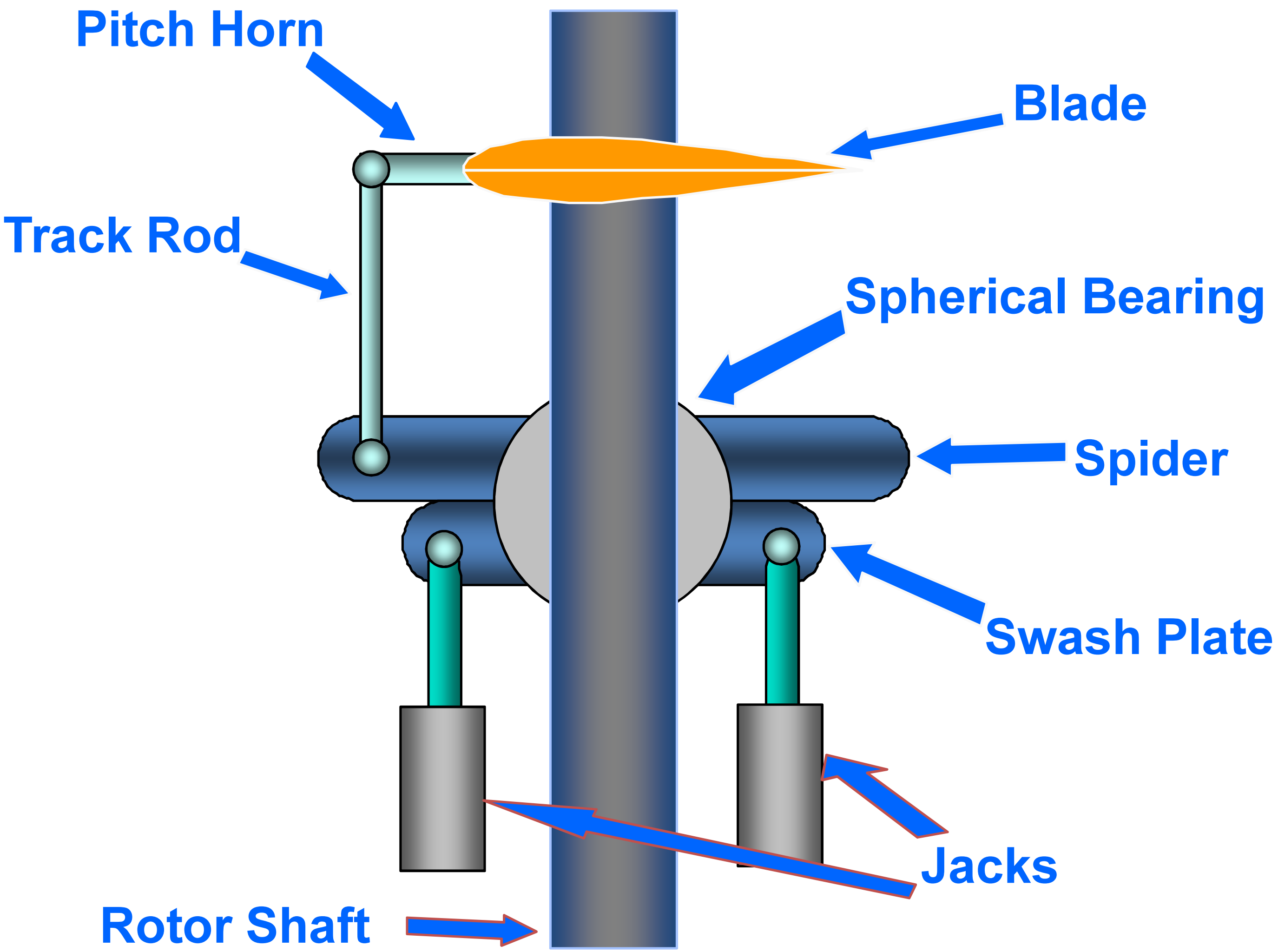
(autogyro rotor)

Swash Plate control

(helicopter rotor)

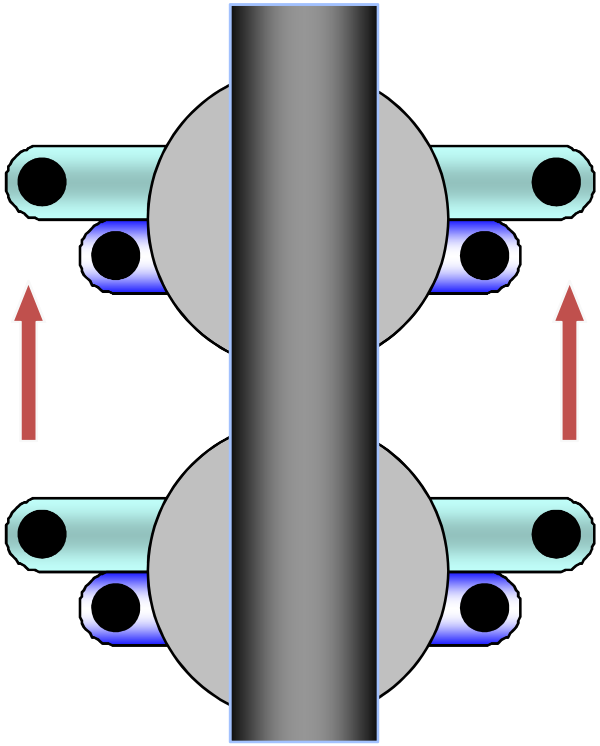
Flapping~Feathering Equivalence

Swash Plate Mechanism

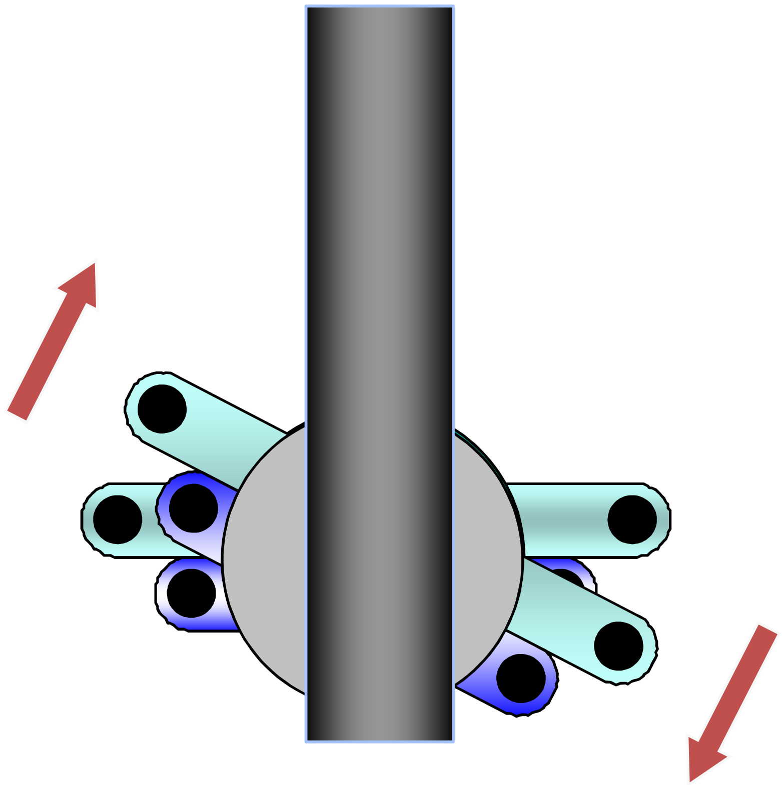


Flapping~Feathering Equivalence

Swash Plate Mechanism



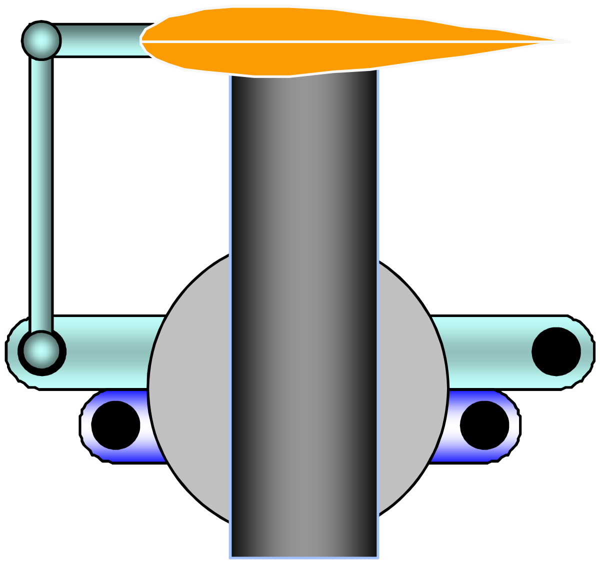
Collective Pitch

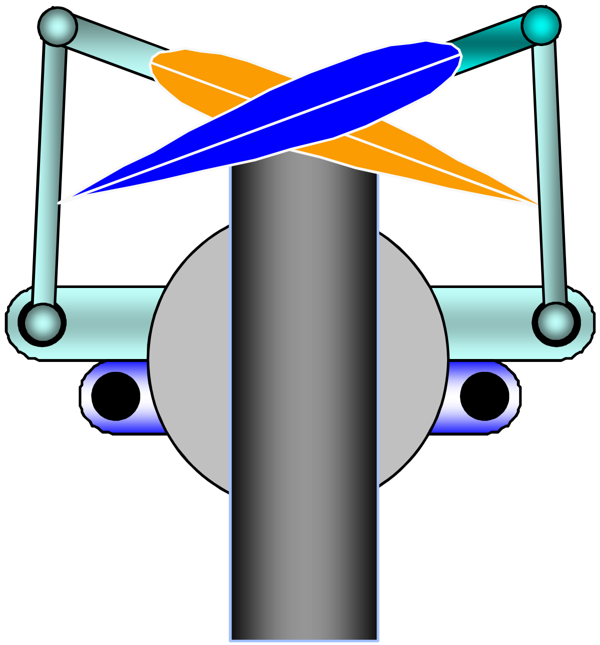


Cyclic Pitch

Flapping~Feathering Equivalence

Swash Plate Mechanism

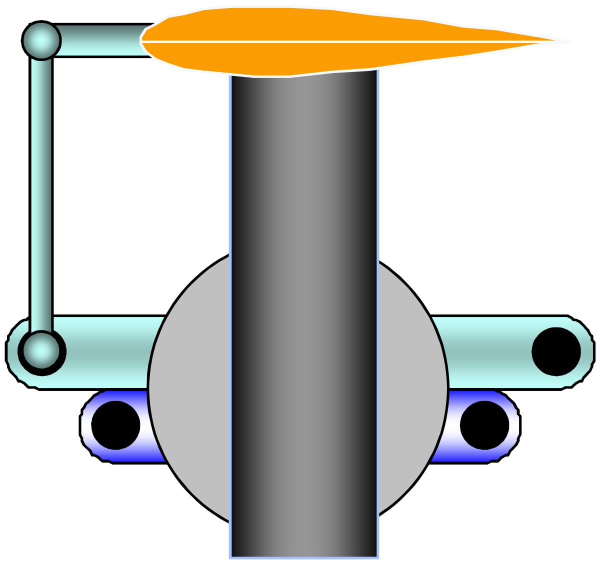


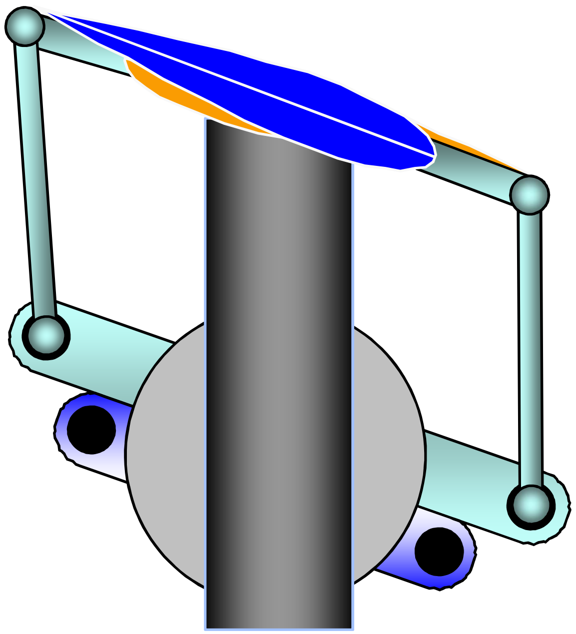


Collective Pitch

Flapping~Feathering Equivalence

Swash Plate Mechanism





Cyclic Pitch

Swash Plate Control – Articulated Hub