Aerodynamics 2- Rotorcraft Aerodynamics

Lecture 7

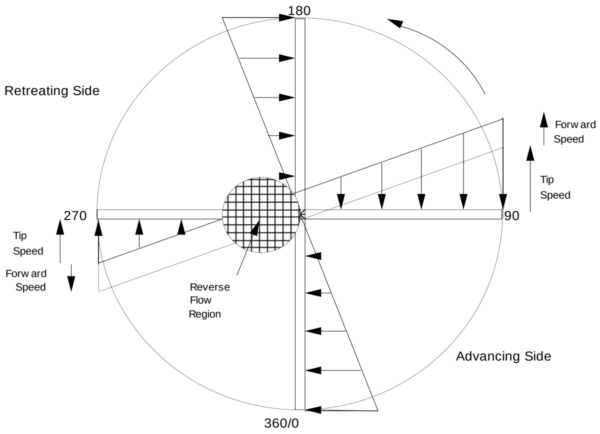
Stability and Control

Department of Aerospace Engineering
University of Bristol

Recap on *(translational flight, flapping & feathering equivalence, induced vel.)*

The helicopter rotor is subjected to asymmetric loading in forward flight due to the resultant velocity components over the advancing and retreating blades. If the rotor is designed to be particularly efficient in hover these problems are greatly exacerbated.

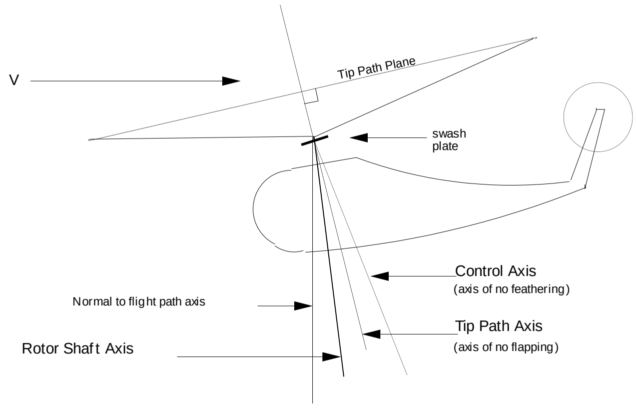
The forward speed of the pure helicopter is ultimately limited by either the effects of flow compressibility on the advancing blade or by retreating blade stall. The choice of rotor tip speed determines which effect is limiting.



There is a region of reverse flow over the inboard section of the retreating blade. The low level of lift generated by the retreating blade is confined to the remaining outer section. This increase the effect of blade tip losses and for lift balance across the disk, the lift from the advancing blade must be greatly reduced. The majority of the rotor lift in forward flight is therefore generated on the leading and trailing sectors of the rotor disk.

The rotor blades are hinged at the centre of rotation and have freedom to flap. Asymmetric loading provides a *once per rev* forcing function to the rotor which happens to have a natural frequency also at *once per rev*. The rotor is therefore in resonance with a phase angle of 90^0.

The application of a force to the rotor results in a corresponding displacement 90^0 further around the azimuth. The asymmetric loading due to forward flight results in a fore and aft tilt of the rotor plane. The presence of blade coning incurs another (longitudinally) asymmetric load that results in a lateral tilt of the rotor plane. The rotor plane is that described by the blade tips and referred to as the Tip Path Plane (TPP). The blade flapping can be prevented by suitable variation of blade pitch around the azimuth.There is a virtual plane in which flapping exists but blade pitch angles remain constant. This is referred to as the No Feathering Plane (NFP) and the axis normal to this plane is known as the Control Axis. The position of the rotor shaft axes is dependent upon the drag of the helicopter airframe as it effectively “hangs” under the rotor.



The induced velocity in forward flight is less than in hover because there is a greater mass flow through the rotor so subsequently less velocity change is required for a given thrust.

therefore $v = \dfrac{\frac{1}{2} C_T \Omega R}{\sqrt{\lambda^2 + \mu^2}}$ If $V = 0,$ then $\mu = 0, \lambda = \dfrac{v}{\Omega R}$ and $v = \Omega R \sqrt{\dfrac{C_T}{2}}$

Rotor Hub - Blade Hinge Arrangements

The type of interface between rotor blade and rotor hub is of profound importance in the control of the aircraft. There are three possible degrees of freedom, orthogonal to each other and referred to as feathering, flapping and in-plane (or lead-lag).

All helicopter rotors have a feathering hinge so that the blade pitch can be changed in flight (cyclically and collectively). For the autogyro such a hinge may not exist as flapping equivalence prevails.

The blades of all rotorcraft have some degree of freedom in flap. The teeter rotor or fully articulated rotor (with discrete hinges) provide total freedom in flap. The Sikorsky ABC aircraft has a “rigid” rotor but generally modern helicopters have “stiff” rotors with an effective flapping hinge and plenty of inherent damping.

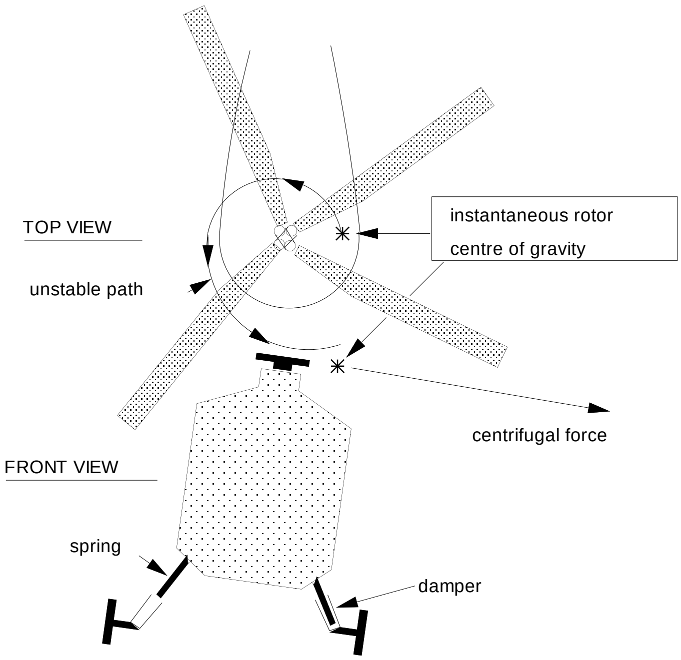
The in-plane hinge may be a discrete hinge or an effective hinge as part of a “stiff” rotor system. There may be no lead~lag hinge and such is the case for all two-bladed teeter rotors.

The need for the feathering and flapping hinge has already been discussed in Lecture 5, but the need for a lead-lag hinge is not so obvious. It would not be required if the blade could not flap. The flapping blade incurs an in-plane acceleration and deceleration due to the Coriolis forces. This imposes severe fatigue stress loads on the blade-hub attachment which would lead to failure. The two-bladed teetering rotor minimises this effect by using the effect of blade coning which is fixed) in conjunction with an underslung teeter hub. The lower resulting level of in-plane vibration is absorbed in a torsionally resilient rotor shaft.

The introduction of the lead-lag hinge was made by Juan de la Cierva who invented the flapping hinge (he thought that if one hinge was good, two must be better). It worked well in the air but on the ground gave rise to a new and destructive problem - Ground Resonance.

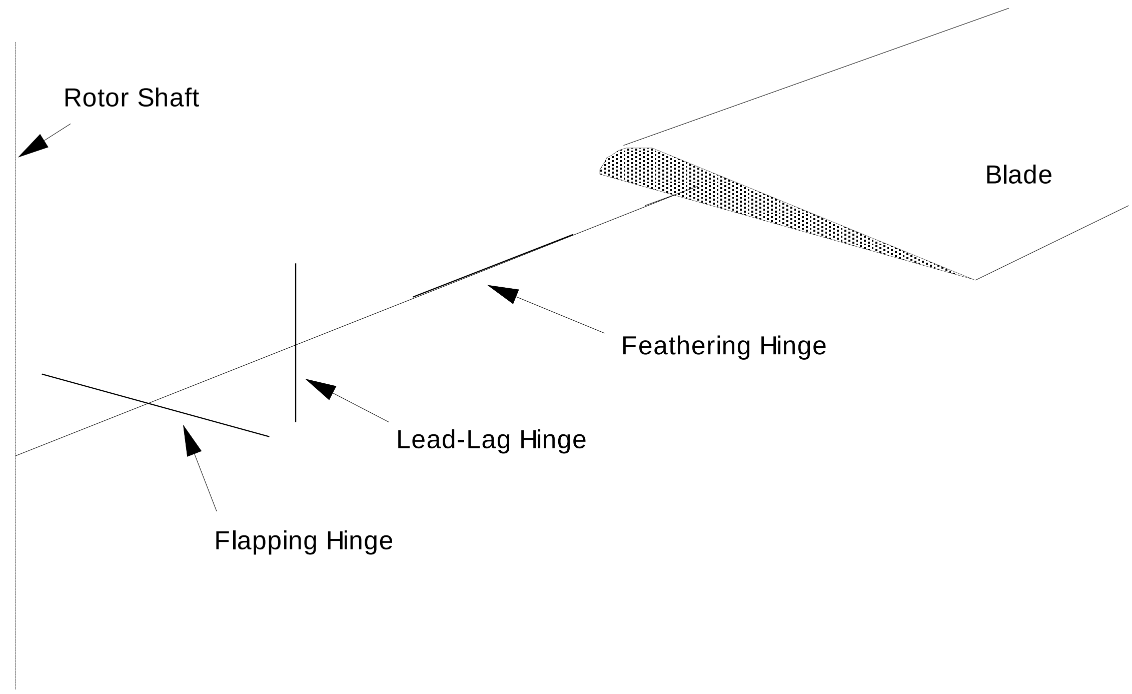
Ground Resonance.

In the same way that the rotor in flap was shown to be in resonance, so is the rotor in-plane. Unlike the flapping teeter blade, if the lead-lag hinge is coincident with the rotor shaft, the restoring force is zero. This is however a hypothetical case since the rotor would simply spin in the bearing and the rotor remain stationary. As the hinge off-set increases so does the spring term but it is always less than that for flapping. As a consequence the restoring force is less for small hinge off-sets so that the motion of a wayward blade is not so readily restored. In flight this is not generally a problem but on the ground if the rotor system is in resonance with the spring~damper of the undercarriage, the rotor C. of G. displacement will rapidly spiral outward and turn the aircraft on to its side instantaneously.



Blade Hinge Arrangement

The avoidance of ground resonance requires that the lead-lag hinge be as far outboard as possible so that the rotor's in-plane natural frequency is too high to couple with the undercarriage. This is not generally practicable (although there are always exceptions e.g. Brantly/Hynes H-5). The hinge is usually located inboard and lead-lag dampers are fitted. The normal hinge arrangement is shown below, though there are variations.



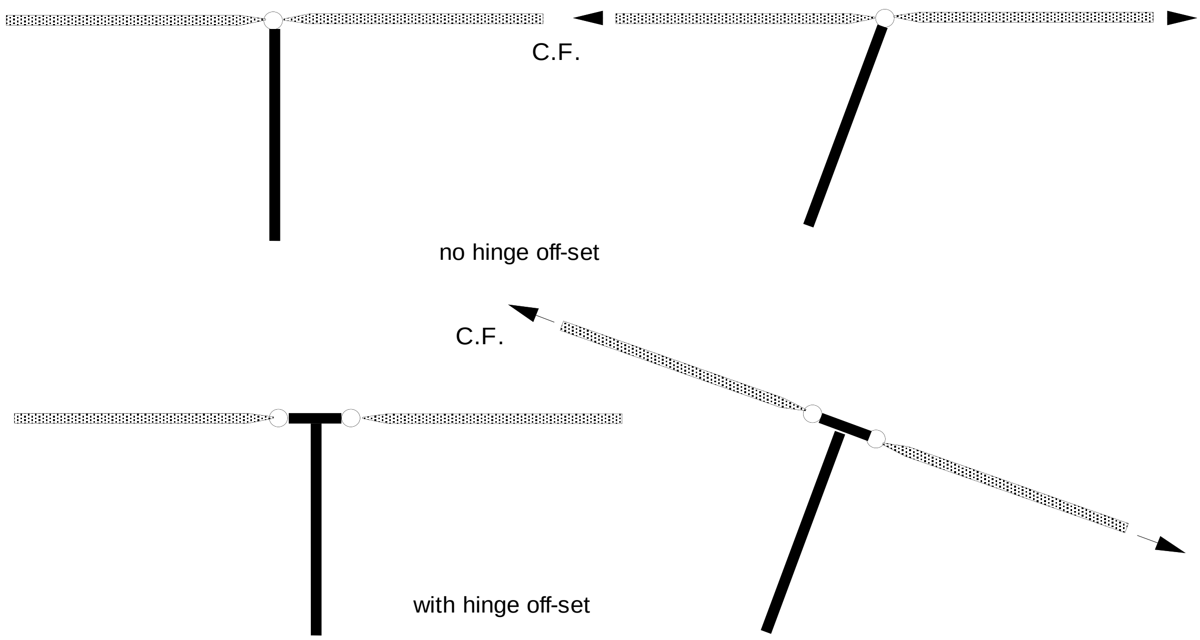
The feathering hinge is the most outboard as this avoids any undesirable cross-coupling effects. The lead-lag hinge is the next most outboard hinge for the reasons given above (as far as possible from the shaft). The flapping hinge is either coincident with the rotor shaft or some distance out. The latter is known as “flapping hinge off-set” and this has the most influence on the general handling of rotorcraft.

With no flapping hinge offset, the rotor cannot impart any moment into the airframe. A pilot commanded tilt of the rotor (via cyclic control input) will incline the thrust vector relative to the rotor shaft and a rolling or pitching motion of the airframe results. With the hinge off-set there will be a strong couple generated on the rotor mast by virtue of the blade CF forces and this will be in addition to the inclination of the thrust vector.

The flapping hinge off-set provides the rotorcraft with greater agility and control. In the “over the top” manoeuvres when the aircraft is at zero ′g’, there is no thrust and for a rotor without hinge off-set there is momentarily no control either.

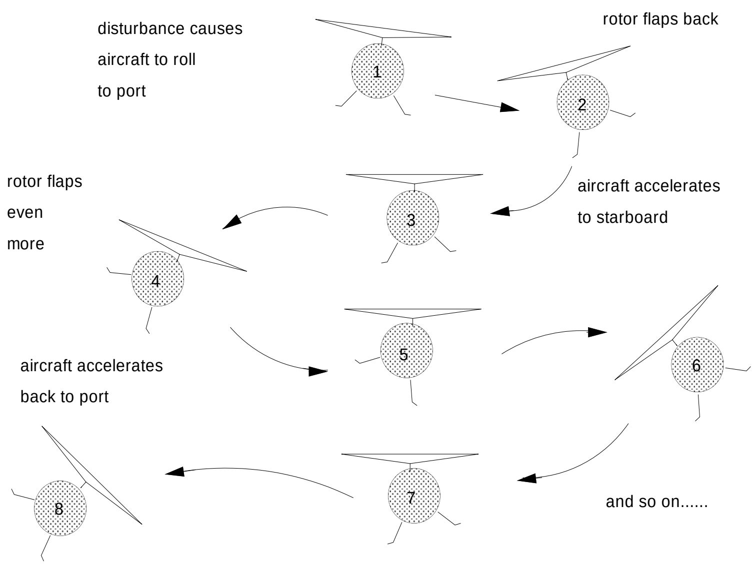
Rotor Control

Considering a teetering rotor (ie. without hinge off-set), a disturbance of the rotor shaft (the helicopter) cannot directly influence the rotor because there is no physical mechanism through which a moment can be transmitted. Operating in a vacuum the rotor would remain in its original plane. Operating in air however the shaft disturbance is equivalent to a cyclic pitch input and the rotor will realign itself normal to the shaft. A rotor with an off-set hinge will however follow any disturbance more directly as shown below.



Effect of Shaft Tilt in a Vacuum

Unless there is a cyclic pitch command from the pilot, any disturbance of the rotor shaft (the helicopter) will effectively change the cyclic pitch input until the rotor realigns itself by the means described above. This “following on” of the rotor makes for a dynamically unstable aircraft. The tilted rotor will start to accelerate the aircraft in the direction of tilt. As the aircraft gains translational speed the rotor will tilt back, away from the direction of motion and provide a retarding force to reduce the velocity of the rotor. The inertia of the aircraft increases the tilt back of the rotor such that the aircraft accelerates backwards at an even greater velocity than it did forwards. This cycle of events then repeats itself with increasing amplitude, until the pilot puts a stop to it.



The problem is that the rotor follows the tilt of the control axis, which (in the absence of pilot input) will move with the rotor shaft. It was soon observed by Arthur Young (of Bell Helicopters) that a pre-disturbance reference was required and this could be achieved by means of an intermediate platform. It is called the “Bell Stabilising Bar” and comprises of a small rotor orthogonal to the main rotor and consisting of two bars with bob-weights at the tips.It acts like a gyroscope and is installed in the control system so that its motion produces stabilising cyclic-pitch inputs if the helicopter is disturbed. Other similar systems evolved.