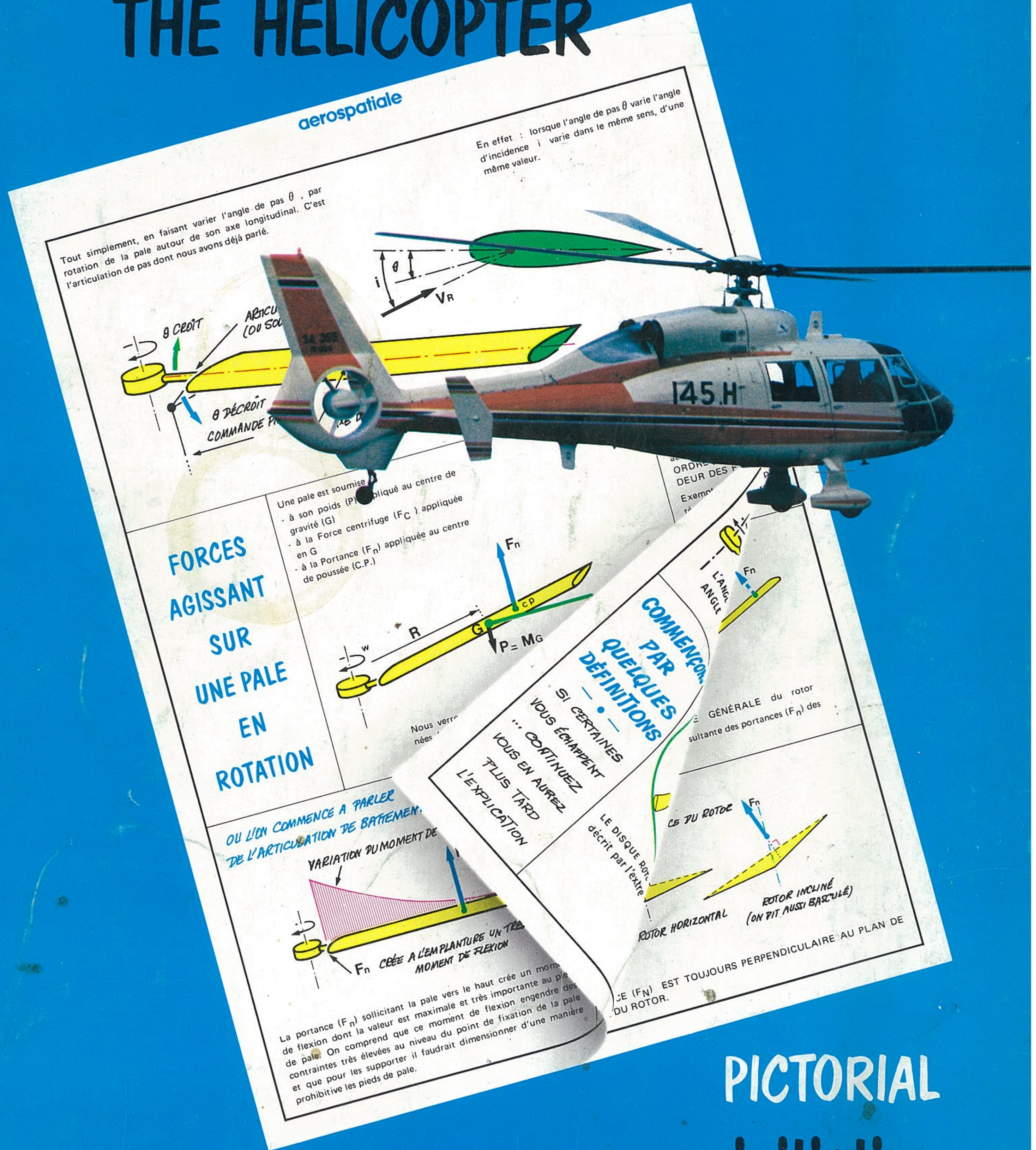
basic theory

of

THE HELICOPTER



PICTORIAL
initiation

aerospatiale – HELICOPTER DIVISION – Product Support Department

Réalisation aerospatiale Suresnes - CTS/R 2408.

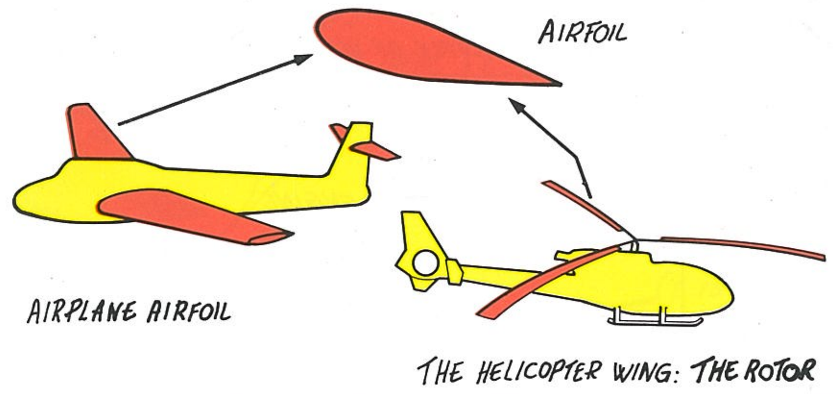
A FEW WORDS OF PREFACE :

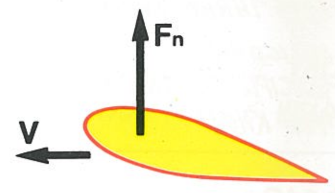
The helicopter, in spite of what may be said, remains a strange machine retaining for the "man in the street" (and sometimes even for the initiated) a somewhat magic and mysterious aspect. In this pages, our wish is to tear off this veil of mystery. But, it is to be well understood that in a few pages it is not possible to explain everything. Therefore we have made a choice dictated by practical considerations. Let us hope it is the right one !!!

We wish you pleasant reading and as you will see, it is not all that complicated.

1. GENERAL — AIRPLANES AND ROTORCRAFT

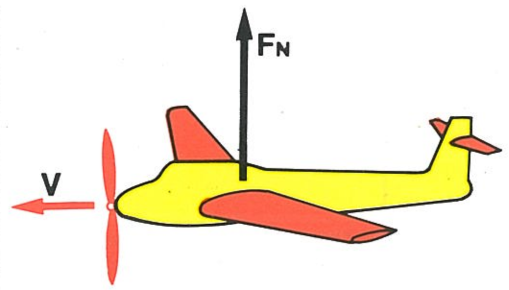
AIRCRAFT LIFT IS PROVIDED BY AIRFOILS CALLED WINGS :



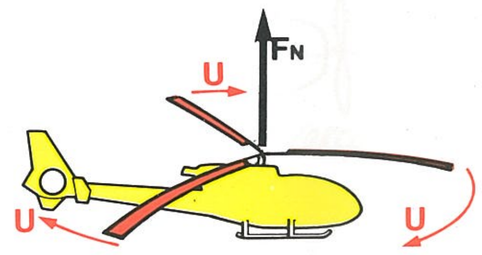


Vertical thrust F_n directed upwards develops on such an airfoil moving through the air at V VELOCITY. It is this aerodynamic force which, in opposition to the aircraft weight, permits "heavier-than-air" aircraft to fly.

THUS, SPEED IS THE ESSENTIAL ELEMENT WHICH ON AN AIRFOIL GENERATES **AERODYNAMIC FORCES** PROVIDING SUSTENTATION SPEED = THRUST



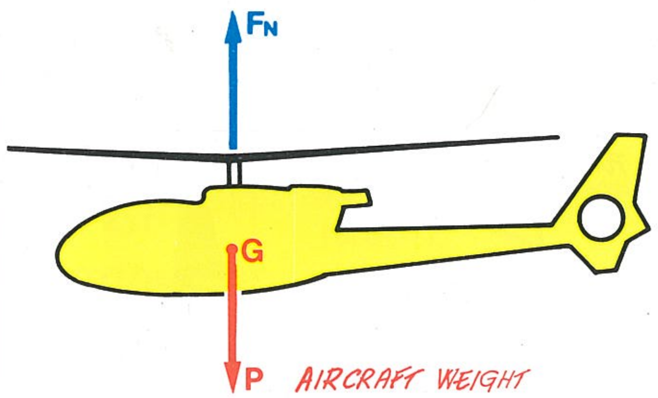
On conventional airplanes, this velocity is provided by a propeller (or a jet engine) providing propulsion AT VELOCITY "V"



On helicopters, the velocity is provided by the rotation of the rotor which is driven at speed U by an engine. The force F_N, called ROTOR LIFT, is normal to the plane of rotation of the rotor.

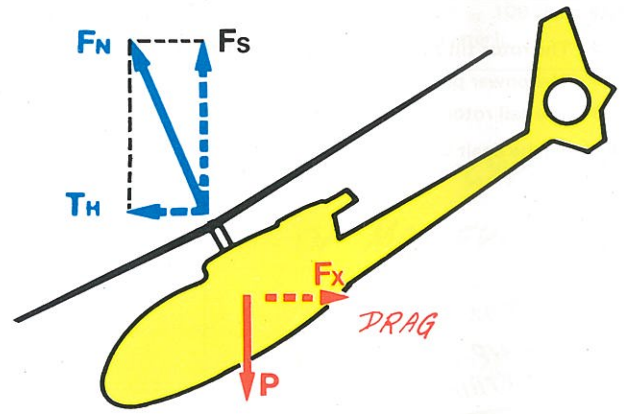
TO SUM UP, TO STAY IN THE AIR :

- THE AIRPLANE MUST MOVE FORWARD AT SPEED V
- THE HELICOPTER DOES NOT REQUIRE SUCH A FORWARD SPEED AS ITS "WING" ROTATES AT SPEED U



The rotating wing enables the helicopter to fly vertically (to climb and descend) or to remain still (hovering). This feature is specific to the helicopter.

F_N	=	P	Hovering
F_N	>	P	Vertical climb
F_N	<	P	Vertical descent



However, the rotor also provides helicopter propulsion. For this purpose, it is sufficient to tilt its plane of rotation using a suitable control. Then, F_N lift consists of two forces :

- F_S (lift) balancing weight P
- T_H (propulsive foce), balancing the aircraft drag F_X and causing forward motion.

ALL AIRCRAFT WHOSE LIFT IS PROVIDED BY ROTARY WINGS, RATHER THAN BY FIXED WINGS, ARE KNOWN AS ROTORCRAFT

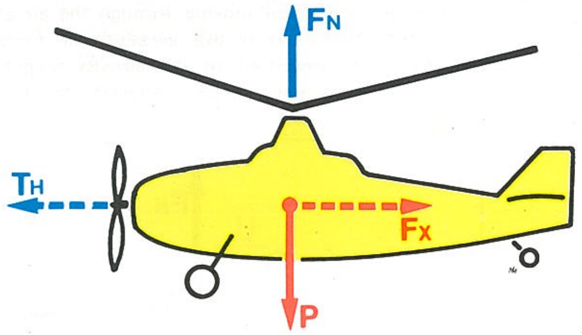
THERE ARE THREE TYPES OF ROTORCRAFT:

- THE HELICOPTER THE PRINCIPLE OF WHICH YOU NOW KNOW
- THE AUTOGIRO
- THE GYRODYNE

THE PRINCIPLE OF WHICH IS SHOWN BELOW

AUTOGIRO

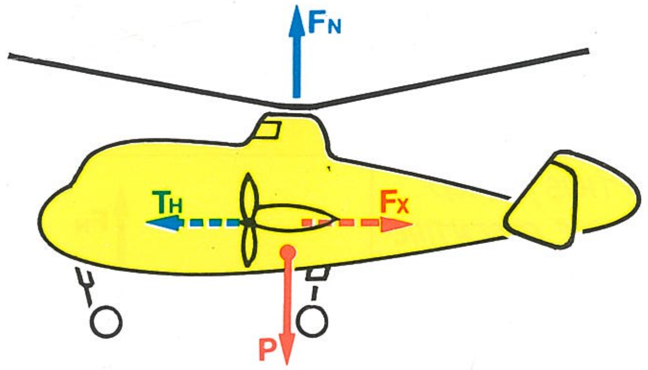
ROTOR FREE ON ITS SHAFT AND ROTATING UNDER THE ACTION OF THE RELATIVE WIND



The rotor is free on a shaft. A propeller drives the aircraft in forward flight. Such motion causes rotor rotation which provides the lift. As a matter of fact, the autogire is an airplane on which fixed wings are replaced by a rotating wing. It is not capable of vertical flight or hovering.

GYRODYNE

ROTOR DRIVEN BY AN ENGINE



The gyrodyne is an autogiro with a powered rotor allowing vertical flight as it is the case for the helicopter.

CONCLUSION :

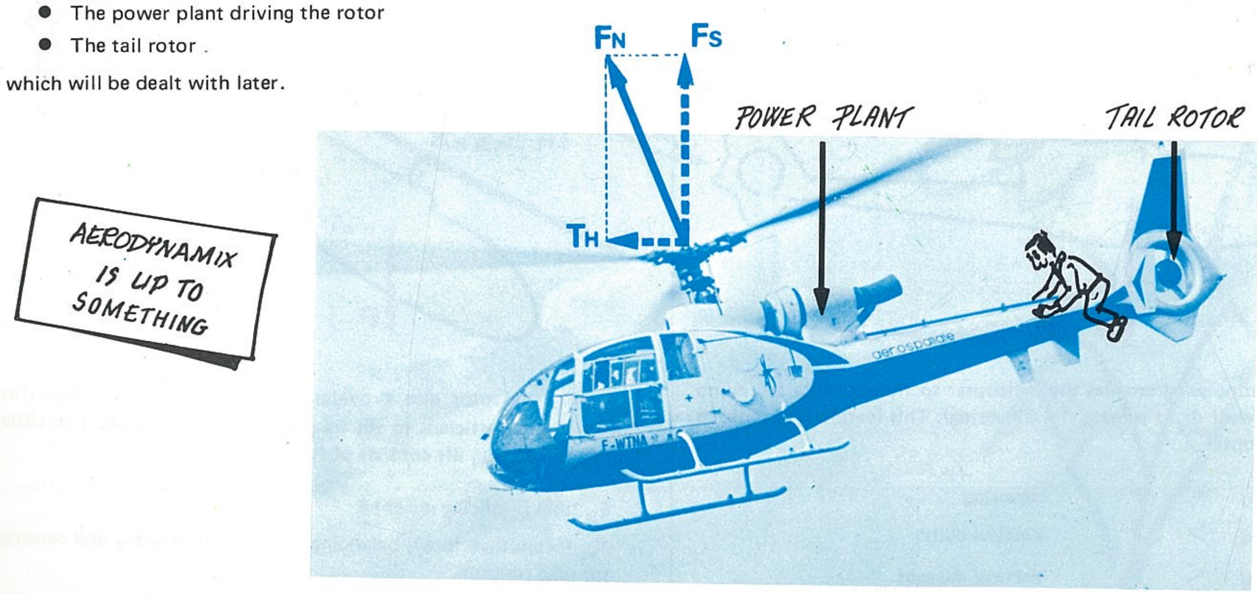
- helicopters : the rotor provides both lift and propulsion.
- autogiros and gyrodynes. The rotor provides only the lift. The propulsion is provided either by a propeller or a jet engine.

HERE IS A HELICOPTER IN FORWARD FLIGHT

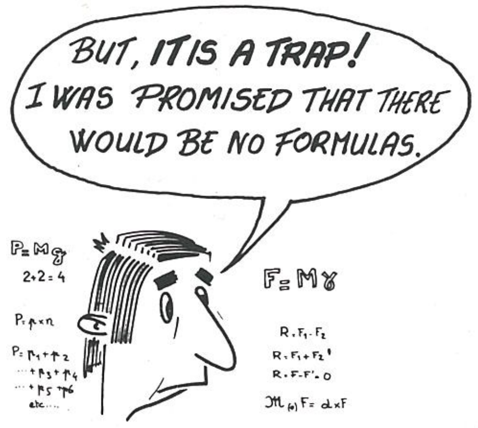
Note :

- The rotor tilt providing a pulling force T_H
- The power plant driving the rotor
- The tail rotor .

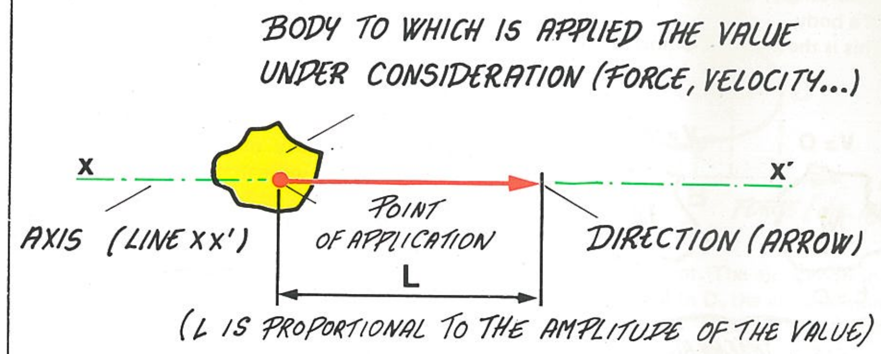
which will be dealt with later.



2. BASIC NOTIONS - MECHANICS AND AERODYNAMICS



VECTORS

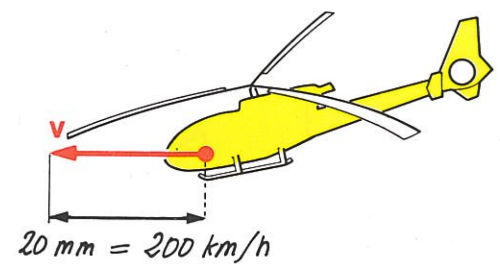


Any physical value (force, velocity, acceleration ....) may be shown as a vector characterized by a point of application, an axis, a direction and an amplitude.

In the case of a force, the origin of the vector is the point of application of the force.

EXAMPLES OF VECTORS

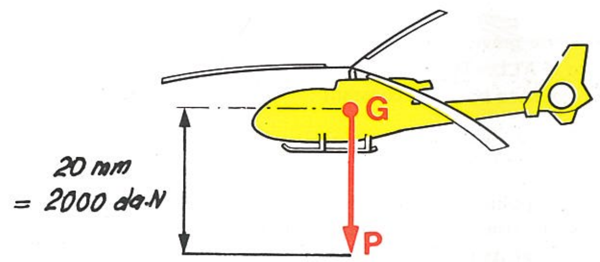
"SPEED" VECTOR



The forward speed v of a helicopter may be entirely characterized by a vector indicating :

- The axis and direction of motion of the aircraft.
- The speed (amplitude of the value)
  Here 1 mm = 10 km/h

"FORCE" VECTOR



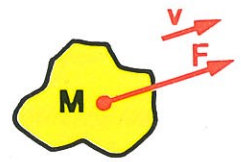
Similarly, weight P of a helicopter, applied to the center of gravity G, is entirely defined by a vector. Here, 1 mm = 100 da.N (The da.N unit for measuring forces will be dealt with later).

2.1 NOTIONS OF MECHANICS

MASS, FORCE, VELOCITY,

All theoretical studies of the helicopter are based on these 3 physical features.

THE ESSENTIAL POINTS WILL NOW BE REVIEWED

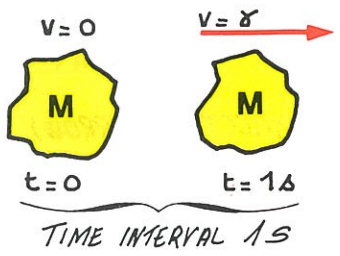


Mass, force and velocity are values that cannot be dissociated :

Thus, the body of mass M, pulled by force F, moves at speed v.

ANY CAUSE CAPABLE OF MODIFYING THE VELOCITY OF A BODY OR OF CAUSING ITS DISTORTION IS CALLED A FORCE

Accordingly, a force is required in order to change the velocity of a body.
This is the principle of inertia.



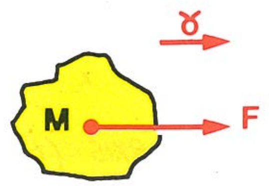
In 1 second, the velocity of body M increases from value 0 to value γ

- γ is the ACCELERATION communicated to the body. It is measured in : meters per second² (or m/s^2)

Changing the velocity of a body consists in increasing or reducing its velocity, i.e., in all cases, in inducing an acceleration γ which may be positive or negative.

This brings us to the basic law of dynamics :

$$F = M\gamma$$



- The inertia of a body is proportional to its mass M : a force F is required to induce acceleration γ in a mass M.

This formula is used for the definition of the unit of measurement of force : THE NEWTON (N)

$$1\ N = 1\ Kg \times 1\ m/s^2$$

1 Newton communicates to a mass of 1 kilogram 1 m/s^2 of acceleration.

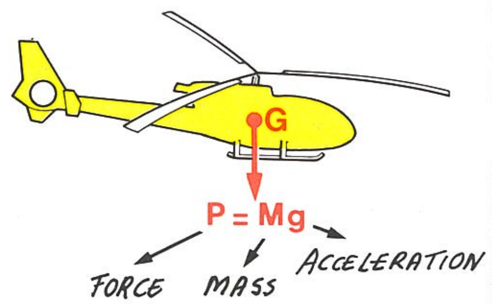
A VERY SPECIAL FORCE:

- **GRAVITY**

Weight is the gravitational force which causes bodies to FALL. The ACCELERATION (g) communicated to bodies is constant :

$$g = 9{,}81\ m/s^2$$

Gravity is applied **to the center of gravity G of bodies (this will be dealt with** later). EXAMPLE : at its maximum mass of 2900 kg, the Dauphin (SA 360) helicopter weighs : P = 2900 x 9,81 = 28449 N or 2844,9 daN.



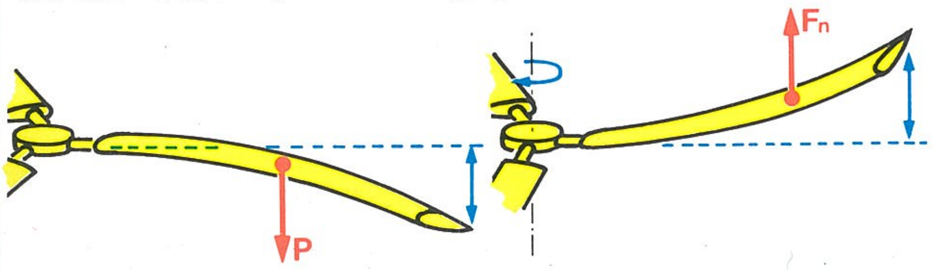
LET US RECALL THE DEFINITION OF A FORCE:

A FORCE IS CAPABLE OF CHANGING THE VELOCITY OF A BODY (AS WAS PREVIOUSLY DEMONSTRATED) OR TO **CAUSE ITS DISTORTION**

(SEE BELOW)

When a force is applied to a RESTRAINED body (not free to move), it cannot act as a motion (Dynamic manifestation) but, instead, through the distortion of that body (static manifestation).

EXAMPLE OF DISTORTION: ROTOR BLADES

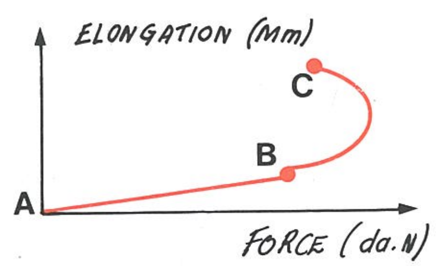


ROTOR STOPPED : Under its weight, the blade is distorted downwards. It is deflected.

ROTATING ROTOR : Under thrust F_n, the blade is distorted upwards.

ELASTIC DISTORTION TO FAILURE. The diagram shows the distortion under TENSION of a steel bar submitted to an increasing force.

- From A to B : elastic distortion.
- From B : Permanent set
- C : Failure of steel bar.

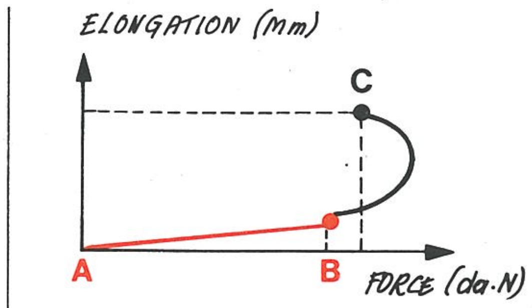


DISTORTION UNDER TENSION

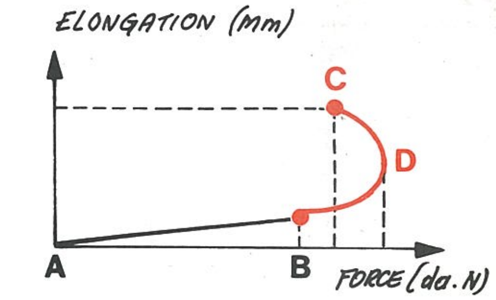
This example of distortion under. TENSION has been selected to show the behaviour of a body stressed by an increasing force. There are other types of distortion under :

- compression.
- shear.
- torque.
- bending.

However, in its principle, the distortion mechanism remains similar. Let us give it a closer look.



In the elastic distortion area (from A to B) the elongation is proportional to the force, if the force is cancelled the body is restored to its initial shape. The point B corresponds to the yield strength of the body. The yield strength is measured in daN/mm²

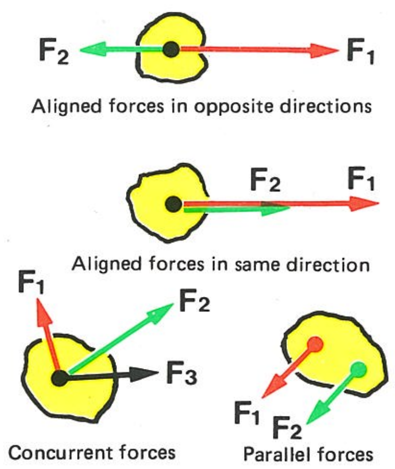


From B, the set is permanent. The elongation increases faster than the force.In D, the cross-section of the steel bar decreases (REDUCTION OF AREA) and elongation continues while the force decreases. The failure occurs at C. The ultimate strength is expressed in daN/mm².

IT WILL BE SEEN LATER HOW FATIGUE PHENOMENA LOWER THE POINT OF FAILURE (FATIGUE LIMIT)

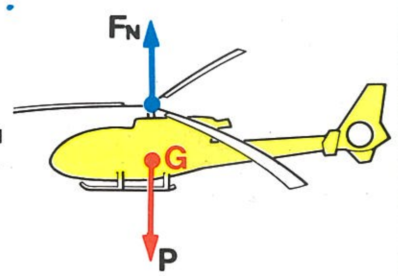
SYSTEMS OF FORCES AND RESULTANTS

Several forces act simultaneously on a same body and constitute a system of forces.

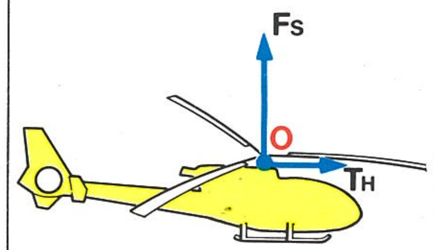


SYSTEMS OF FORCES

TWO EXAMPLES :



Weight P of helicopter and rotor lift F_N are two opposed forces.



Lift force F_S and tension force T_H of rotor are concurrent. Their point of convergence is the rotor center O

A system of forces can be replaced by a single equivalent force producing the same DYNAMIC EFFECT as the system of forces.

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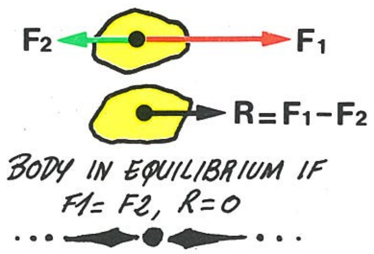
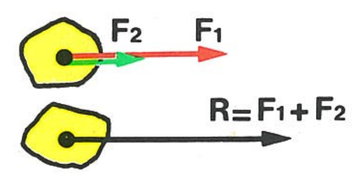
This single force is THE RESULTANT of the system.

RESULTANT R OF 2 ALIGNED FORCES

OPPOSITE FORCES

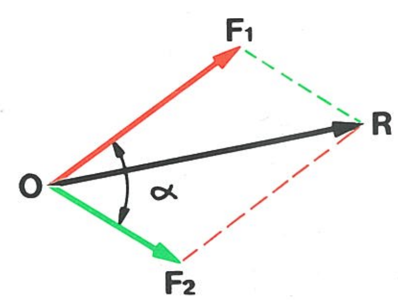


BODY IN EQUILIBRIUM IF F1 = F2, R = 0



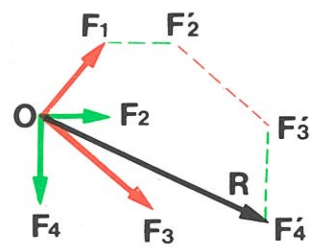
SAME DIRECTION

RESULTANT OF TWO CONCURRENT FORCES



Geometrical construction of resultant : R is the diagonal of the parallelogram constructed from F1 and F2. The smaller the angle α, the larger the resultant R.

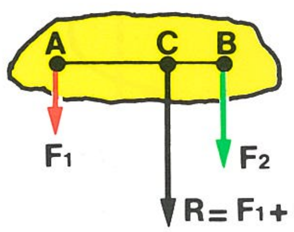
What if the system consists of more than 2 concurrent forces ? Instead of constructing successive parallelograms, it is simpler to draw from F_1.....................



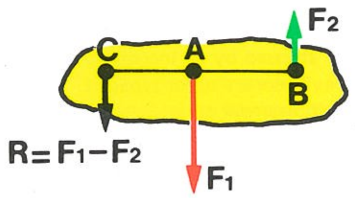
other vectors equipollent to F_2, F_3, F_4 (i.e. F'_2, F'_3, F'_4. . . .)
R is defined by the end of the last equipollent vector.

RESULTANT OF 2 PARALLEL FORCES

• SAME DIRECTION



• OPPOSITE



The point of application C of resultant R is given by the relation :

$F_1 \times CA = F_2 \times CB$

When several forces are replaced by a resultant force R, SUCH FORCES ARE COMPOSED. The composition of forces permits to study their global effect.

Inversely, THE BREAKDOWN OF A FORCE into 2 or several elementary forces permits us to ANALYSE the effect in definite directions representative of the action of such forces.

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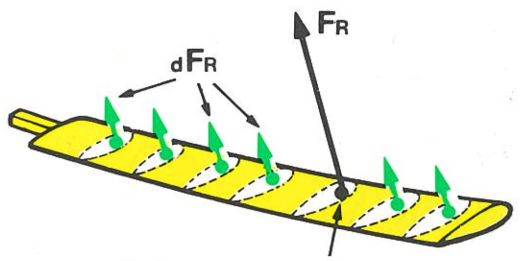
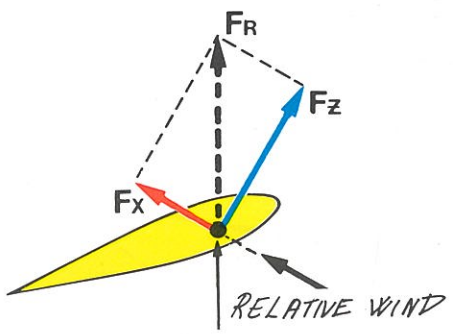
LET US PUT THESE NOTIONS IN CONCRETE FORM



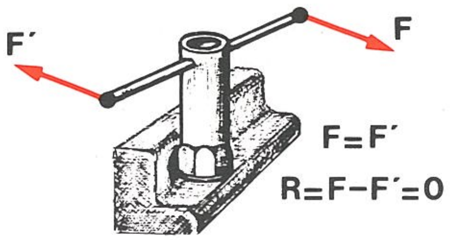
Every component of a rotating rotor blade is acted upon by an elementary aerodynamic force dF_R. All these forces are parallel and codirectional. Their resultant F_R (global effect of elementary forces) is applied to the aerodynamic center of the blade.



For analyzing the effect of F_R on a blade, this force may be broken down into two concurrent forces : F_Z, normal to the direction of the relative wind (lift) and F_X parallel to the relative wind (drag).

A VERY SPECIAL SYSTEM OF FORCES :

TORQUE



2 parallel forces (F - F') which are equal and opposite constitute :

A TORQUE

A torque has no resultant (R = 0).

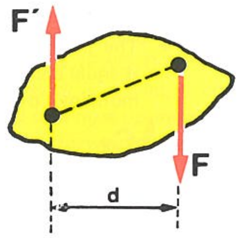
It causes the rotation of bodies free to rotate and distorts (twists) bodies prevented from rotating.

MOMENT OF A FORCE

•

A SINGLE force may, in some cases, cause the ROTATION of a body, in the same way as torque.

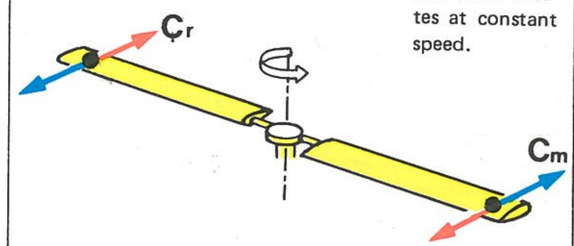
THE EFFICIENCY of a torque is characterized by its MOMENT (M) :
M = d x F (d is the lever arm of the torque)



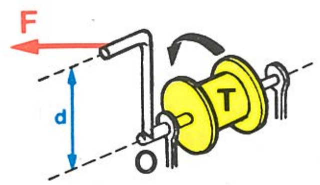
The MOMENT of a torque is measured in Newton meter (m.N). Usual multiple : The deca Newton meter (m.daN).

Two torque stresses with the same moment are equal. To balance (cancel) a torque it should be opposed by a torque with the same moment.

Cm = Cr.
The rotor rotates at constant speed.



Example : A rotor at stabilized r.p.m.
– Cm engine torque drives the rotor.
– Resisting torque Cr is equal and opposite.THE ROTOR IS IN EQUILIBRIUM.

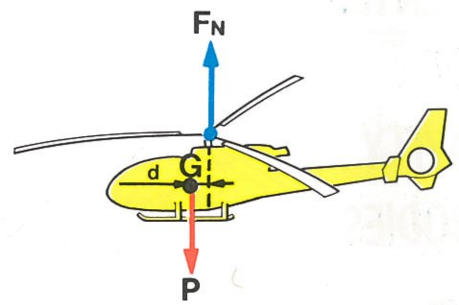


The force F, applied to the crank-arm, rotates drum T around its fulcrum O. The effect of the force in relation with point O is proportional to length d of the lever arm.

This effect is called THE MOMENT OF THE FORCE (M (o) F) ; it is measured in m.N or m.daN.

M (o) F = d x F

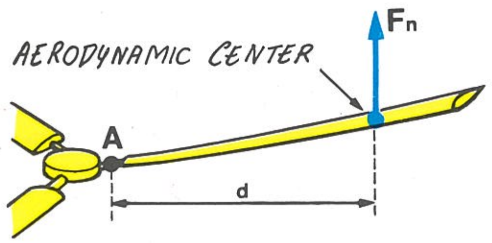
EXAMPLE



Lift F_N of rotor has, in relation with the center of gravity G of helicopter, a moment :

d x F_N tending to tilt the aircraft forward. The aircraft tilts until. d = O (F_N and P are then aligned and the moment is zero).

OTHER EXAMPLE



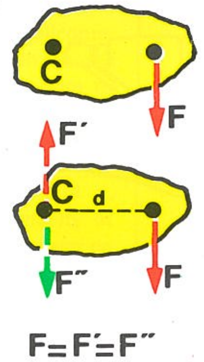
The blade thrust (F_N) creates a BENDING moment .

d x F_N

acting upon attachment point A of the blade where it induces very significant loads.

The more rigid the blade, the higher are these loads. The device (flexible hinge) used to reduce this bending moment so as to render it consistent with the strength of the materials utilized will be explained later.

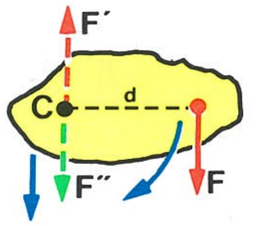
DO NOT CONFUSE THE MOMENT OF A FORCE WITH TORQUE



Let us analyze the effect of force F. It is possible, without changing the external condition of the body to which it is applied, to construct from C two forces (F', F'') equal, opposed and parallel to F (such that F = F' = F''). The resultant of F' and F'' is zero (F' − F'' = 0) and therefore the two systems are equivalent.

1 FORCE = 1 TORQUE + 1 FORCE

This explanation permits to analyse the effect of force F which, as it may be seen.......



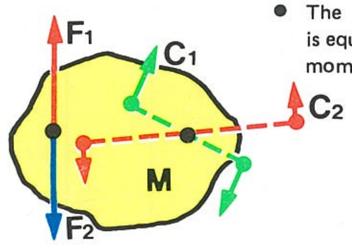
.... rotates the body around C (effect of torque F, F') and drives the body along F'' (effect of force F'')

IN CONCLUSION, IT MUST BE REMEMBERED THAT **A FORCE CANNOT BALANCE A TORQUE**

Now, it is time to deal with the equilibrium of bodies. A BODY FREE TO MOVE IS IN EQUILIBRIUM WHEN ITS SPEED DOES NOT CHANGE (it may be stationary or in motion).

THE BODY M IS IN EQUILIBRIUM AS :

- $F_1 = F_2$ and, therefore, R = 0.
- The moment of torque C_1 is equal and opposite to the moment of torque C_2.



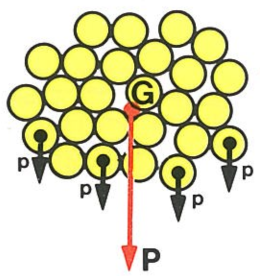
EQUILIBRIUM CONDITIONS OF FREE BODIES :

- Zero resultant of forces applied (R = 0)
- Zero torque resultant.

THE CENTER OF GRAVITY OF BODIES

A NOTE WORTHY POINT

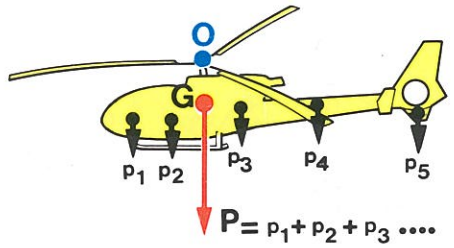
A body consists of heavy elementary particles.



Number of particles n.
P = p x n

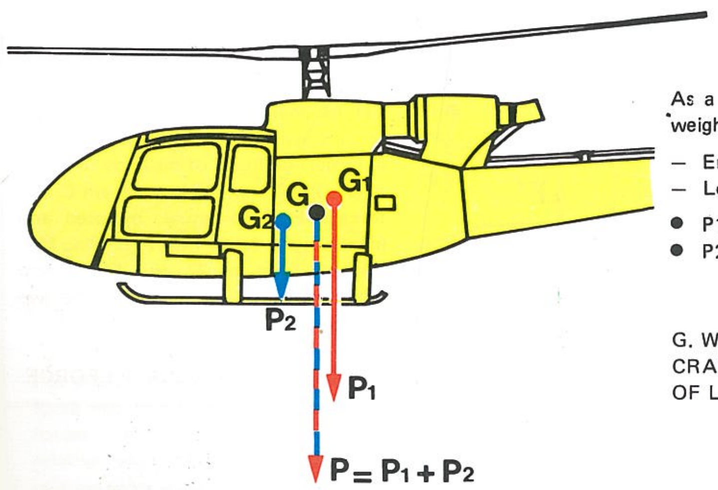
If elementary weights p are composed (composition of parallel forces), a resulting force P (weight of body) applied to point G (CENTER OF GRAVITY OF BODY) is obtained.

The situation is similar for a helicopter which consists of heavy assemblies and equipment.



If the weights (p1, p2, p3...) of these assemblies and equipment are composed, total weight of aircraft P, applied to center of gravity G is obtained.
The pattern of the various masses is designed so that G is aligned with the center of rotor O.

HOWEVER, WHILE THE CENTER OF GRAVITY OF A SOLID BODY IS FIXED, THAT OF A HELYCOPTER MAY MOVE.



As a matter of fact, the total weight (P) of aircraft is the resultant of 2 weights :

- Empty weight (P1). Weight of unloaded helicopter. P1 is applied to G1.
- Load (P2) : Crew-passengers-freight-fuel... P2 is applied to G2.

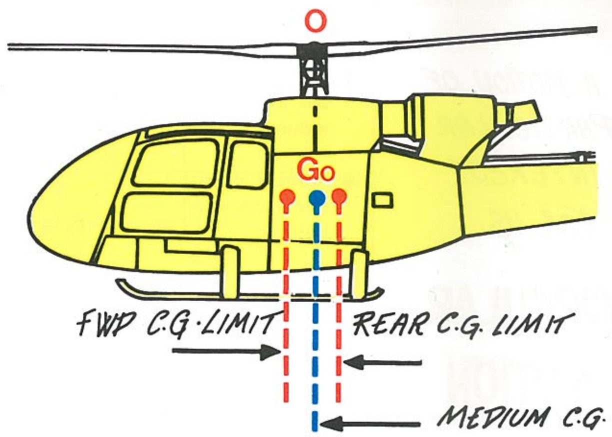
- P1 is constant in amplitude and position : accordingly, G1 is fixed
- P2 may vary in amplitude and position : accordingly, G2 is mobile.

G. WHERE THE RESULTANT P = P1 + P2 (TOTAL WEIGHT OF AIRCRAFT) MOVES IN RELATION WITH THE WEIGHT AND POSITION OF LOAD P2.

THIS GIVES RISE TO THE NOTION OF

HELICOPTER C.G. LOCATION

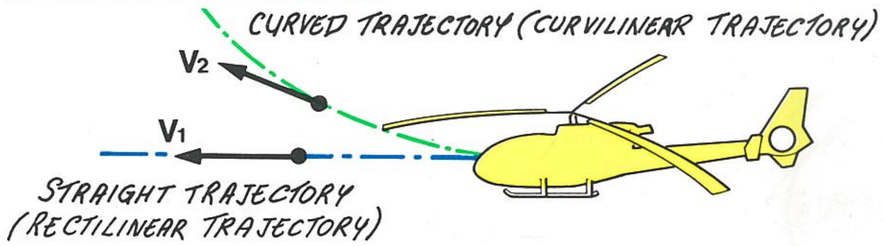
- In relation with the medium center of gravity Go (Go being aligned with rotor center O), the total weight of the aircraft may be applied forward (FWD C.G) or to the rear (Rear C.G.). When the center of gravity is moved, it creates in flight a nose down moment (FWD C.G.) or a nose up moment (rear C.G.). Such moments, which tilt the aircraft forward or rearward, adversely affect comfort (aircraft attitude) and, if they are too great, they may become dangerous for flying the aircraft. It is for this reason that helicopter manufacturers specify C.G. limits not to be exceeded.



HAVING EXPLAINED FORCES, WE WILL NOW DISCUSS THEIR DYNAMIC EFFECT

MOTION AND VELOCITY

A MOTION IS DEFINED BY A TRAJECTORY AND A VELOCITY



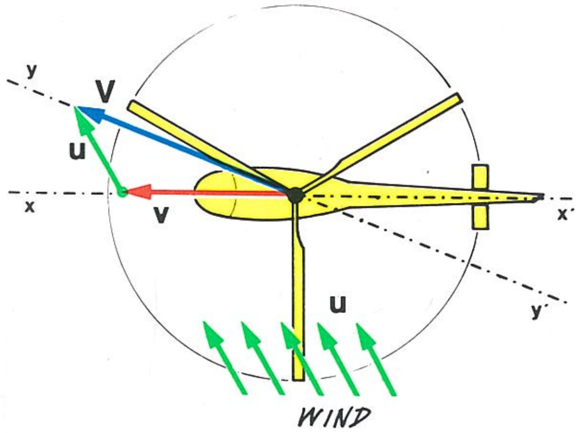
The velocity of a body is expressed in meters per second (m/s) or in kilometers per hour (km/h) :

$$V = \frac{\text{space}}{\text{Time}}$$

A velocity can be, like a force, shown as a vector indicating the direction of displacement (arrow) and the velocity value (length of the vector).

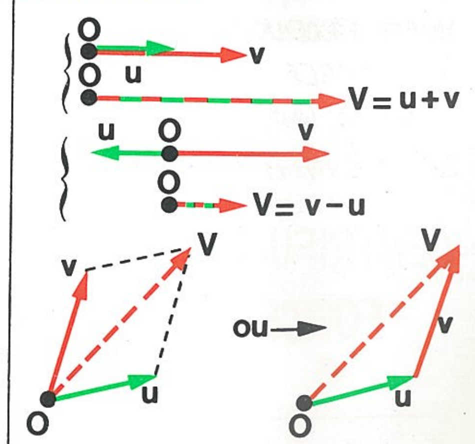
A motion is called UNIFORM when the speed or velocity is constant. In all other cases, the motion is said to be ACCELERATED : The velocity varies (increases or decreases) under the action of a force system (other than null) applied to the body in motion.

A BODY MAY BE SUBMITTED TO A SINGLE MOTION OR TO SIMULTANEOUS MOTIONS.



Example : The helicopter moves at velocity v in the axis x x'. It is deflected from its trajectory by a wind having a velocity U (drift). The resulting motion is given by the composition of vectors v and u. V is the resulting velocity of the helicopter which moves on the resulting trajectory y y'. v is the driving velocity, u the relative velocity and V the resulting velocity.

COMPOSITIONS OF VELOCITIES : VELOCITY VECTORS ARE COMPOSED LIKE FORCE VECTORS

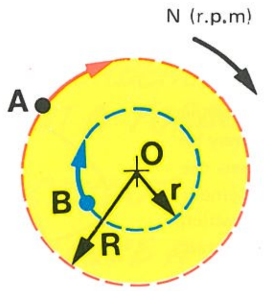


A MOTION OF PARTICULAR INTEREST FOR US

CIRCULAR MOTION

All points of a body in rotation are animated with a circular motion. Their trajectory is a CIRCLE.

- Point A describes a circle of radius R.
- Point B describes a circle of radius r.



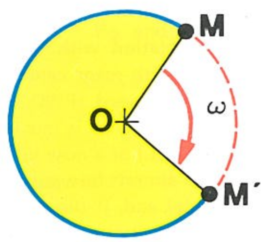
THE ROTATIONAL SPEED (N) of a body is measured in r.p.m. (revolutions per minute).

ANGULAR VELOCITY (ω)....

$$\omega = \frac{\pi N}{30}$$

1 rev. : 2 π radians
N (r.p.m) = 2 π N

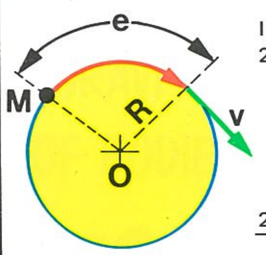
$$\omega = \frac{2 \pi N}{60} = \frac{\pi N}{30}$$



Rotational velocity is also expressed in terms of the center angle swept by radius OM of the rotating body. This is angular velocity which is measured in radians per second. (rd/s)/

... AND CIRCUMFERENTIAL VELOCITY

$$v = \omega R.$$



In one turn, M covers 2 π R (meters)
In N (r.p.m.) it covers :
2 π RN (meters)

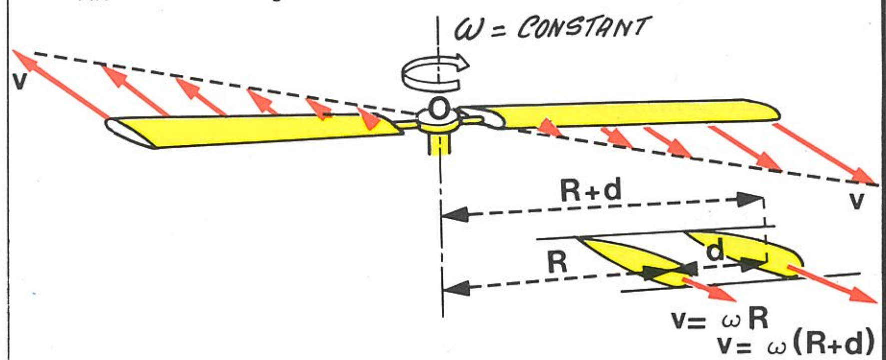
and in 1 second. :

$$\frac{2 \pi RN}{60} = \frac{\pi RN}{30} = \omega R$$

The circular velocity (v) is the distance (e) covered in 1 second by a moving body M having a circular trajectory. It is measured in meters per second (m/s)

CIRCUMFERENTIAL VELOCITY IS PROPORTIONAL TO RADIUS (AND TO ANGULAR VELOCITY ω)

AN EXAMPLE : diagram of velocities for a rotor rotating at constant speed.

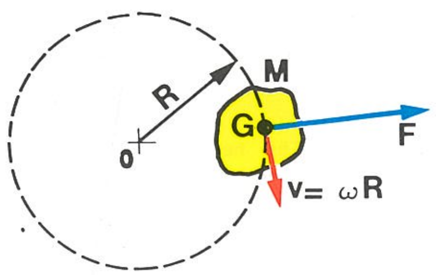


The circular velocity of blade components increases, from the root to the tip, according to their gyration radius R.

FORCES PRODUCE MOTION (YES) BUT THERE IS A MOTION CIRCULAR MOTION WHICH PRODUCES A FORCE HAVING VERY SIGNIFICANT EFFECTS:

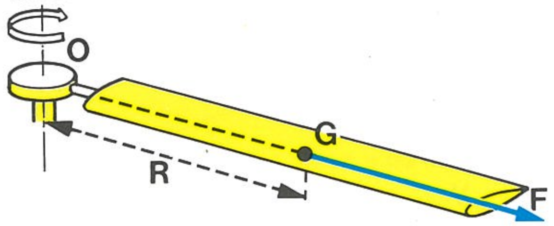
CENTRIFUGAL FORCE

$$F = M\omega^2 R$$



It is demonstrated that a body of mass M having a circular motion of R radius and a speed «v» is submitted to a CENTRIFUGAL FORCE $F = \frac{MU^2}{R} = M\omega^2 R$. This force is applied to the center of gravity G of the body.

The centrifugal force is directed toward the outside of the trajectory. Its action line passes through center of rotation "O"



Here is an idea of the amplitude of the centrifugal force applied to a rotor blade :
(case of a SA 330 helicopter blade).
M = 70 kg – N = 265 r.p.m.– R = 4,03 m

$$F = 70 \times \left(\frac{3{,}14 \times 265}{30}\right)^2 \times 4{,}03 = 217.015 \text{ N}$$

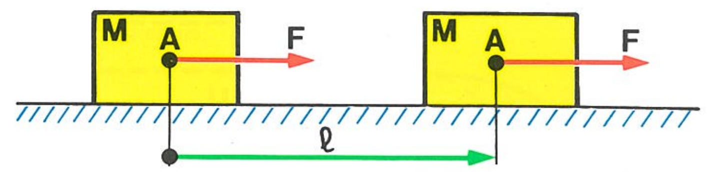
(M, ω^2, R)

THE EFFECT THAT SUCH A FORCE MAY PRODUCE AT THE BLADE ROOT IS EASILY IMAGINED.

FORCE AND MOTION PRODUCE

WORK AND POWER

The force F moving a body M produces WORK



WORK

- A force F which moves its point of application "A" over a distance ℓ produce work :

W = F x ℓ

Work is measured in Joules (J)

1 J = 1 N x 1 m

POWER

- If work W is produced in t seconds, the power developed is :

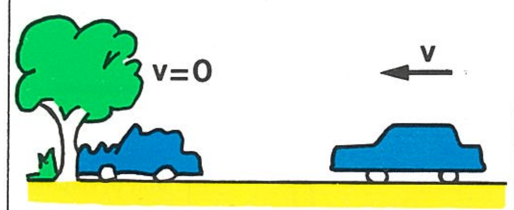
$$P = \frac{W}{t}$$

Power is measured in Watts (W).

A PECULAR FORM OF WORK, "CANNED WORK" OR

KINETIC ENERGY

A body (solid, liquid or gaseous) set in motion stores an energy called KINETIC ENERGY.

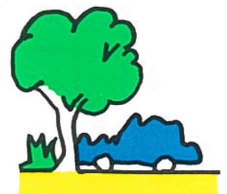


If such body suddenly stops, it releases all its kinetic energy under the form of work (here : distortion, failure...).

When the velocity of the body increases, its kinetic energy increases (it is supplied with work).
When the velocity of the body decreases, its kinetic energy decreases (it releases work or heat).

Kinetic energy is expressed (W)

$$W = \frac{1}{2} MV^2$$



Example : a vehicle having a mass M = 700 kg runs at 90 km/h (25 m/s). Its kinetic energy is

$$W = 1/2 \times 700 \times 25^2 = 218750 \text{ J.}$$

This is the quantity of energy released during the accident.

2.2. NOTIONS OF AERODYNAMICS

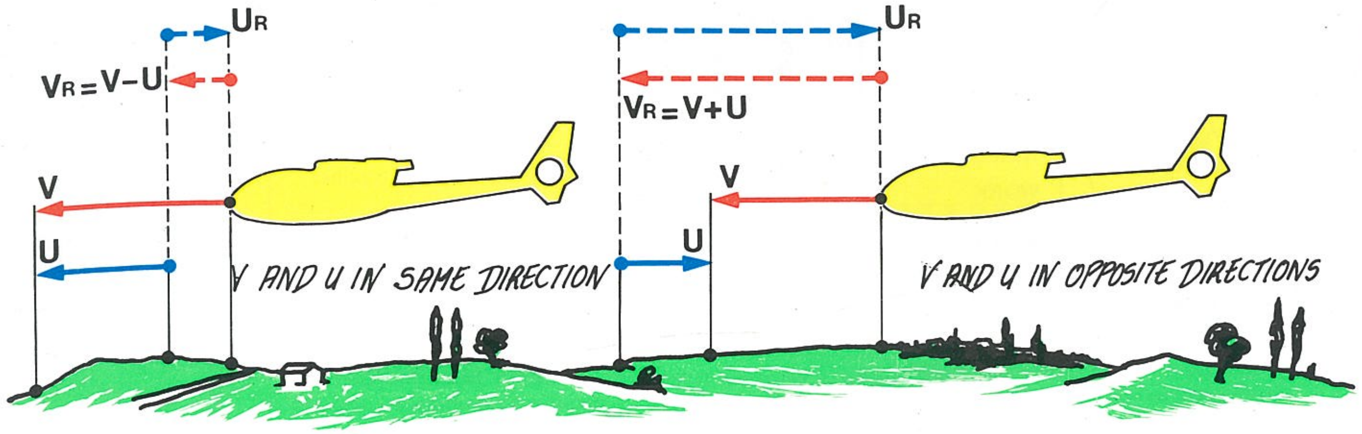
THE AIR IN MOTION

In aerodynamics, there appears the notion of relative motion. As a matter of fact, for studying the aerodynamic behaviour of a body, its motion must be considered NOT IN RELATION WITH THE GROUND (absolute motion) but IN RELATION WITH THE AIR (relative motion). Thus, we shall speak of relative velocities : Velocity of a body in relation with the air or air velocity in relation with the body (the two being equal and opposite).

LET US ILLUSTRATE THESE DEFINITIONS

V = Helicopter velocity relative to the ground
VR = Relative speed of helicopter

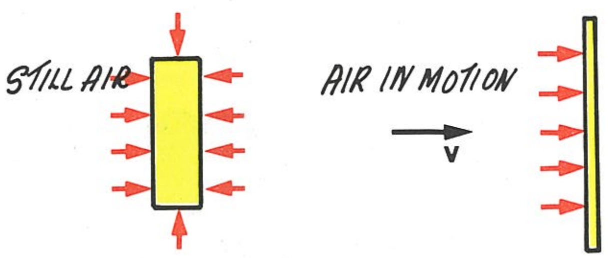
U = Velocity of the air (wind) relative to the ground
UR = Relative speed of air (relative wind)



AIR IN MOTION AND DYNAMIC PRESSURE

The air (like all gases) develops energy which acts as pressure :

- STATIC Pressure (P_S) : EXPANSION ENERGY
- DYNAMIC Pressure (P_d) : KINETIC ENERGY OF AIR IN MOTION.



Static pressure acts in all directions.

Dynamic pressure acts in the direction of velocity.

BUT, WHAT IS PRESSURE ?

Pressure is the force of a gas acting on the unit of area.

$P = \frac{\text{Force}}{\text{Area}}$ The unit of pressure is the Pascal (Pa) $1 \text{ Pa} = \frac{1 \text{ N}}{1 \text{ m2}}$

Here is another definition of pressure :
Pressure is the energy of a gas contained in the unit of volume :

$P = \frac{\text{Energy}}{\text{Volume}}$ $1 \text{ Pa} = \frac{1 \text{ J}}{1 \text{ m}^3}$

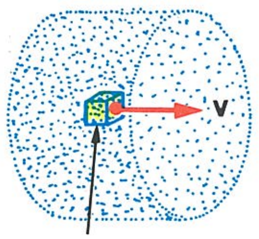
KINETIC ENERGY AND DYNAMIC PRESSURE OF AIR

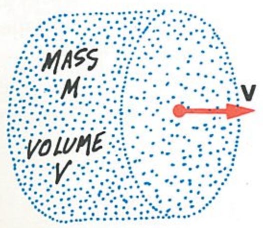
The kinetic energy of a mass of air M occupying a volume V and having a velocity v is :

$W = 1/2 \, M.V^2$

or, as $M = \rho V$ (ρ being the mass of the unit of volume) :

$W = 1/2 \, \rho V.V^2$





The kinetic energy of the unit of volume is called dynamic pressure (Pd), or :

$P_d = 1/2 \, \rho \frac{V.V^2}{V} = 1/2 \, \rho V^2$

Accordingly, a mass of air in motion possesses both static energy (static pressure P_S) and dynamic energy (dynamic pressure P_d).

The sum of these energies represents the total energy (or total pressure P_t).

- STILL AIR = STATIC PRESSURE (P_S)
- AIR IN MOTION = TOTAL PRESSURE (P_t)

$$P_t = P_S + P_d = P_S + 1/2 \, \rho v^2$$

THE TOTAL PRESSURE (P_t) OF A GAS IS CONSTANT

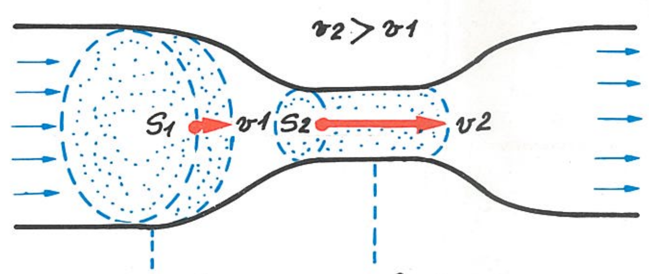
(Provided the gas receives or supplies neither heat nor work).

$P_t = P_S + P_d =$ Constant, which means that if a gas gains energy under the form of speed (increase of dynamic pressure), it loses an equal quantity of energy in the form of static pressure, and vice versa.

OR :

When the dynamic pressure increases, the static pressure decreases.

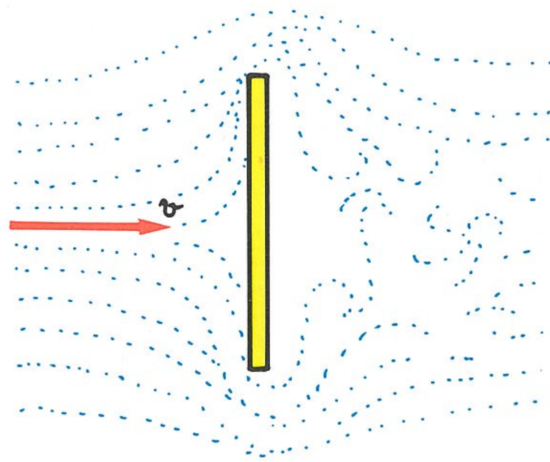
EXAMPLE : Variation of static and dynamic pressures in a variable cross-section duct. The airflow (Q = SV) being constant, the airspeed (v) increases when the cross-section (S) decreases.



$$\underbrace{1/2 \, \rho v_1^2}_{Pd\,1} + P_{S1} = \underbrace{1/2 \, \rho v_2^2}_{Pd\,2} + P_{S2} = \text{CONSTANT}$$

THE CROSS-SECTION DECREASES ($S_2 < S_1$). THE SPEED INCREASES ($V_2 > V_1$) - THE DYNAMIC PRESSURE INCREASES ($Pd_2 > Pd_1$) AND THE STATIC PRESSURE DECREASES BY AN EQUAL AMOUNT

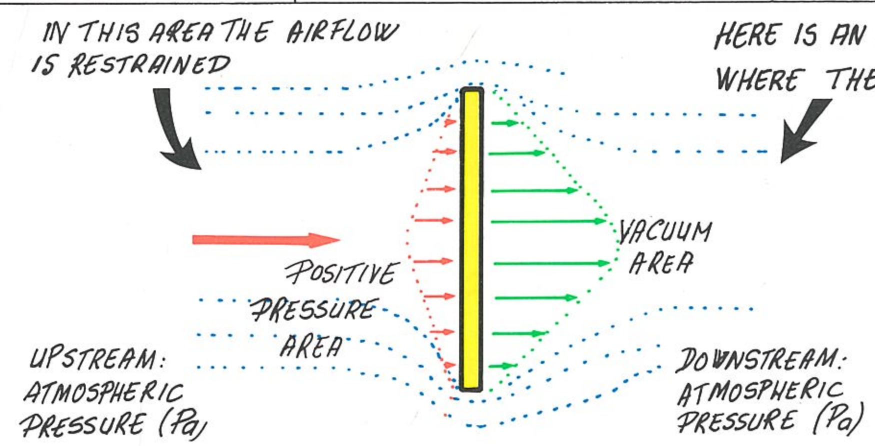
WIND RESISTANCE



A body forms an obstacle to the relative wind and restrains its motion. This is wind resistance. Air opposes the motion of bodies. A plate placed normal to the airflow (relative wind) restrains and deviates the mass of air which strikes it.
This phenomenon is demonstrated by the AERODYNAMIC SPECTRUM : The air-flow is materialized by smoke.

IN THIS AREA THE AIRFLOW IS RESTRAINED

HERE IS AN AREA OF RELATIVE VACUUM WHERE THE AIRFLOW INCREASES



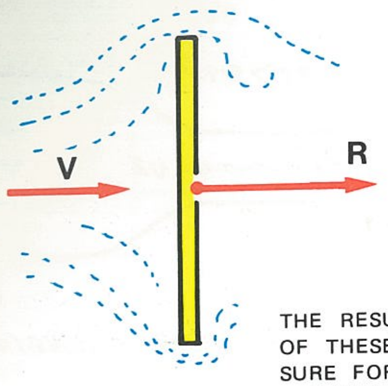
Vectors represent the relative static pressure $P_S - P_a$).
This pressure is negative in the vacuum area.

LET US HAVE A CLOSER LOOK AT THIS !

- On the forward surface of the plate, where the airflow decreases, the dynamic energy is converted into static pressure. The pressure exerted on the forward surface exceeds the atmospheric pressure ($P_s > P_a$).
- On the rear surface of the plate, there is a relative vacuum area where the airflow increases. The dynamic pressure increases and the static pressure decreases.

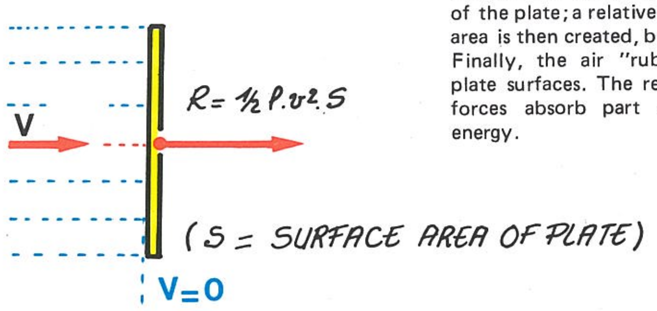
$P_s < P_a$: VACUUM

Thus, the forward surface of the plate is submitted to a pressure which tends to push it and the rear surface to a vacuum tending to aspirate it.



THE RESULTANT OF THESE PRESSURE FORCES IS THE WIND RESISTANCE : R

VALUE OF R



..... But, the airflow is deflected and the mass of air flows at a speed which is reduced but not null, along the sides of the plate; a relatively large vacuum area is then created, behind the plate. Finally, the air "rubs" against the plate surfaces. The resulting friction forces absorb part of the kinetic energy.

If the airflow striking the plate was not deflected, its entire kinetic energy would be converted into pressure and the expression of R would be.

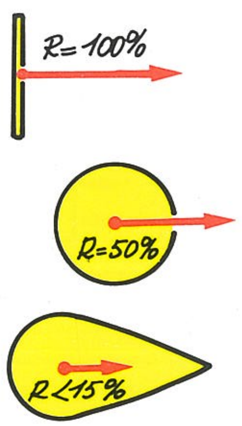
$R = 1/2\ \rho \cdot v^2 \cdot S$ ($1/2\ \rho\ v^2$ = dynamic pressure) .....

Considering these effects, the basic expression of R becomes :

$R = 1/2\ \rho \cdot v^2 \cdot S \cdot K$

K : being a factor covering :

- The body's shape (the body's shape has an effect on the airflow and, therefore on the value of the pressure loads).
- The body's surface condition (i. e. the friction forces).

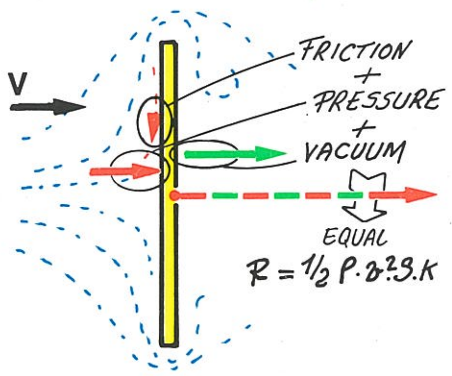


Let us illustrate the effect of the body's shape on wind resistance R.

If the wind resistance is rated at 100 percent in the case of a circular plate.

.....The wind resistance is only rated at 50 percent for a sphere having the same diameter, and drops below 15 percent for a stream-lined body.

LET US SUM UP...



AND CONCLUDE :

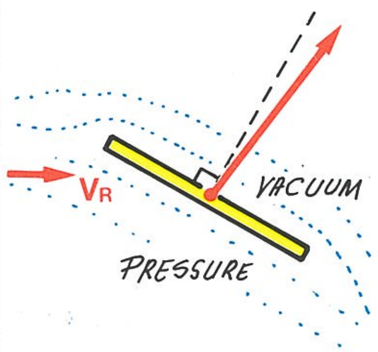
$$R = 1/2\ \rho \cdot v^2 \cdot S \cdot K$$

The air resistance is proportional :

- to the air density ρ
- to the square of wind velocity v^2
- to the body's surface S
- to the factor K covering the body's shape and surface condition.

HOW TO OBTAIN A LIFTING SURFACE

Wind resistance is a necessary evil. As a matter of fact, although it opposes the movement of bodies, it contains an energy which may be mastered and directed.

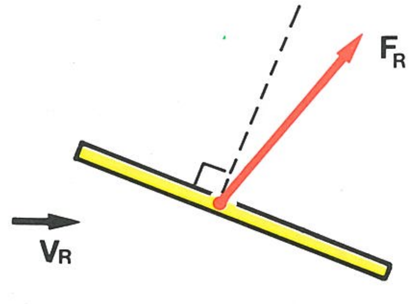


$$R\ (\text{ou}\ F_R) = 1/2\ \rho \cdot v^2 \cdot S \cdot K$$

Without forgetting to our previous conclusions, let us tilt the plate with respect to the relative wind v_R we shall still note :

- A pressure area
- A vacuum area.

However, the resultant R (which will henceforth be called F_R. (The resultant aerodynamic force) is directed upwards.

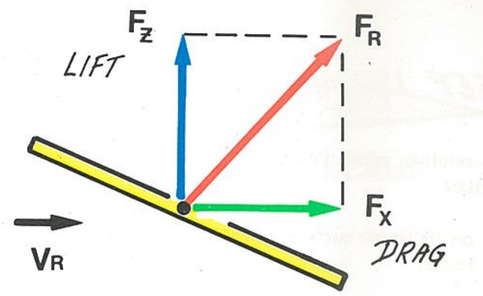


Note that the aerodynamic resultant (F_R) is not normal to the plate as the pressure forces would tend to place it, but tilted rearward under the action of the friction forces.

ANALYSIS OF FR

F_R may be broken down into two forces :

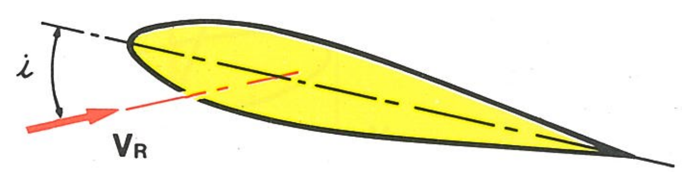
- F_Z, normal to the relative wind V_R. This is liftcap which raises the plate.
- F_X, parallel to the relative wind. This is DRAG, which restrains the plate's motion.

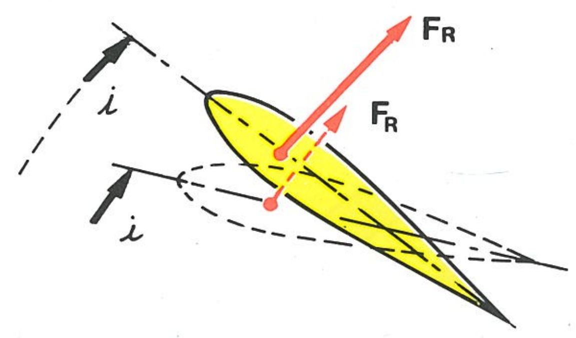


This is the principle of airfoil surfaces, i.e. of surfaces capable of converting the relative speed of air into a lift force. Now, we shall deal with airfoils specially designed in the wind tunnel for increasing lift and reducing drag.

FROM "FLAT" AIRFOILS TO STREAMLINED AIRFOILS

Helicopter rotor blades and airplane wings are airfoils specially designed for developing lift forces. To obtain lift the airfoil must be inclined with respect to the relative wind. The angle "i" of the relative wind with respect to the airfoil is called ANGLE OF ATTACK.



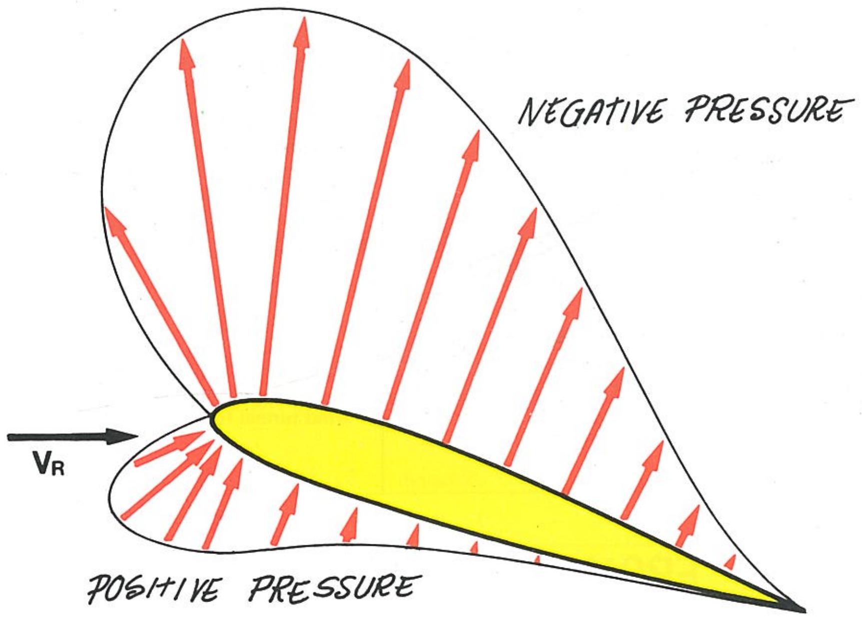


The value of the angle of attack "i" affects the amplitude of aerodynamic resultant F_R : if i increases, F_R increases.

This new notion leads us to reconsider the factor K, which, in the expression already given of F_R does not cover the body's position relative to the relative wind, and to substitute a factor C_r introducing this effect. The resulting final expression of F_R is :

$$F_R = 1/2\ \rho \cdot v^2 \cdot S \cdot C_r$$

Diagram of positive and negative pressures acting on an airfoil.



KEEP IN MIND

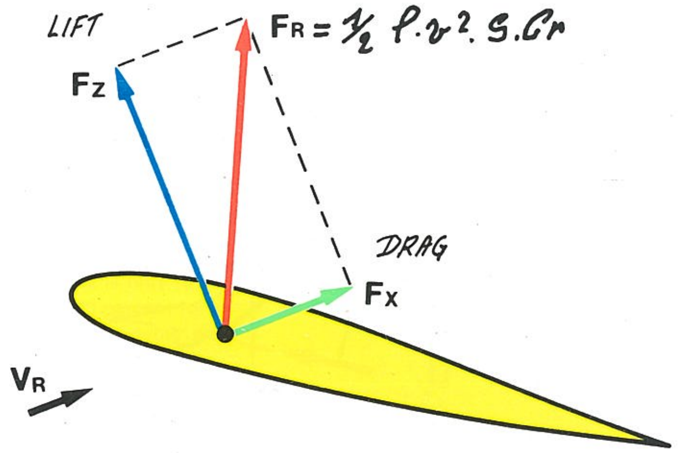
In relative wind (V_R), an airfoil is submitted :

- on its upper surface, to negative pressure forces
- on its lower surface, to positive pressure forces

  whose resultant, called AERODYNAMIC RESULTANT (F_R) consists of two forces which may be measured in a wind tunnel :

  – LIFT (F_Z), normal to the relative wind. It is a force acting in the right direction : it supports the airfoil.

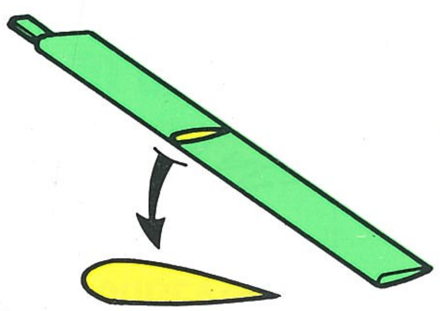
  – DRAG (F_X), parallel to the relative wind. It is a harmful force : it restrains the airfoil and absorbs energy uselessly.



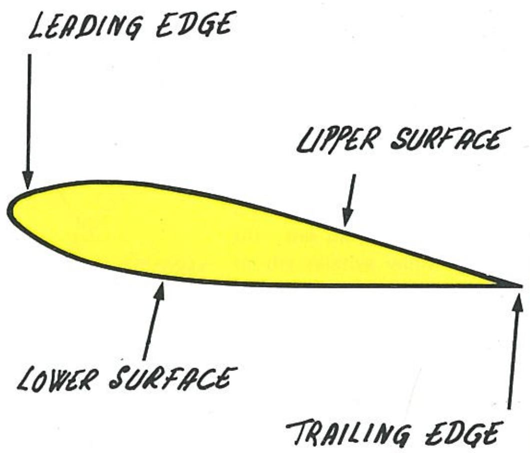
Keep also in mind that the negative pressure forces acting on the upper surface of the airfoil have a major effect (Refer to the pressure diagram). Indeed, they provide 70 percent of the lift.

LET US TALK ABOUT AIRFOILS

PROFILE OF A HELICOPTER ROTOR BLADE

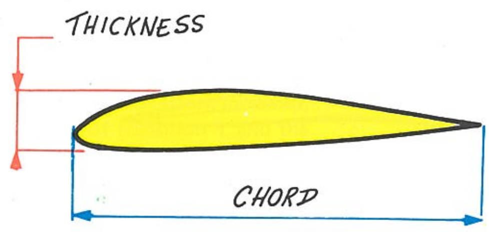


The profile of an airfoil (rotor blade-airplane wing) determines its aerodynamic behaviour.



MAIN COMPONENTS OF AN AIRFOIL.

DEFINITIONS RELATING TO AIRFOILS



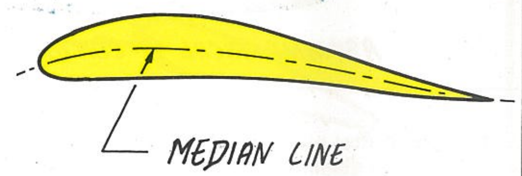
The ratio : $\frac{\text{THICKNESS}}{\text{CHORD}}$

is called "THICKNESS RATIO"

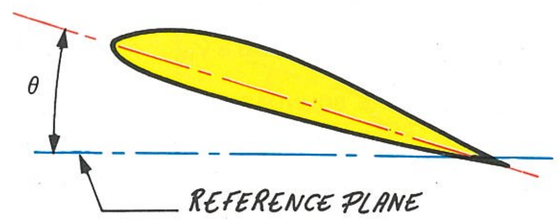
The thickness ratio is expressed in percentage of the chord.
(Example : 12 percent thickness ratio).

The REFERENCE CHORD is the line drawn between the leading and trailing edges. It acts as a base for the definition of the airfoil shape.

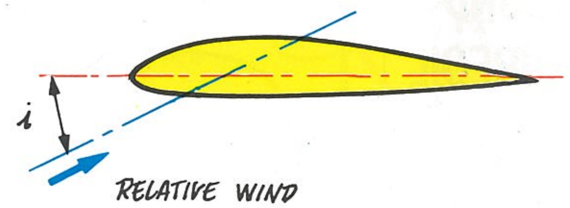
The MEDIAN LINE is the geometric locus of points equidistant from the upper and lower surfaces.



PITCH ANGLE AND ... ANGLE OF ATTACK



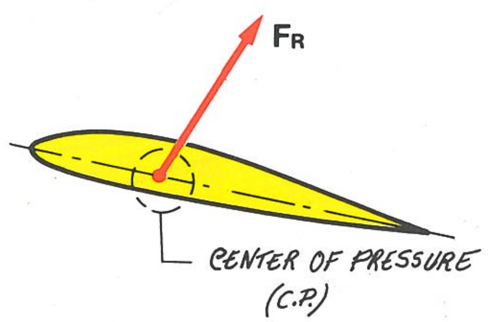
The pitch angle (θ) is the angle formed by the airfoil chord with a fixed reference plane. For a helicopter blade, this plane of reference is normal to the rotation axis of the rotor.



The angle of attack (i) is the angle formed by the airfoil chord with the direction of the relative wind.

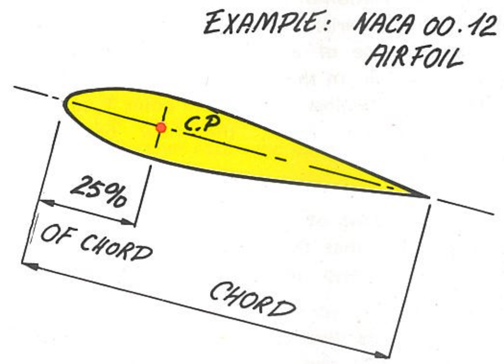
THE CENTER OF PRESSURE

It is the point where the aerodynamic resultant force F_R is applied.



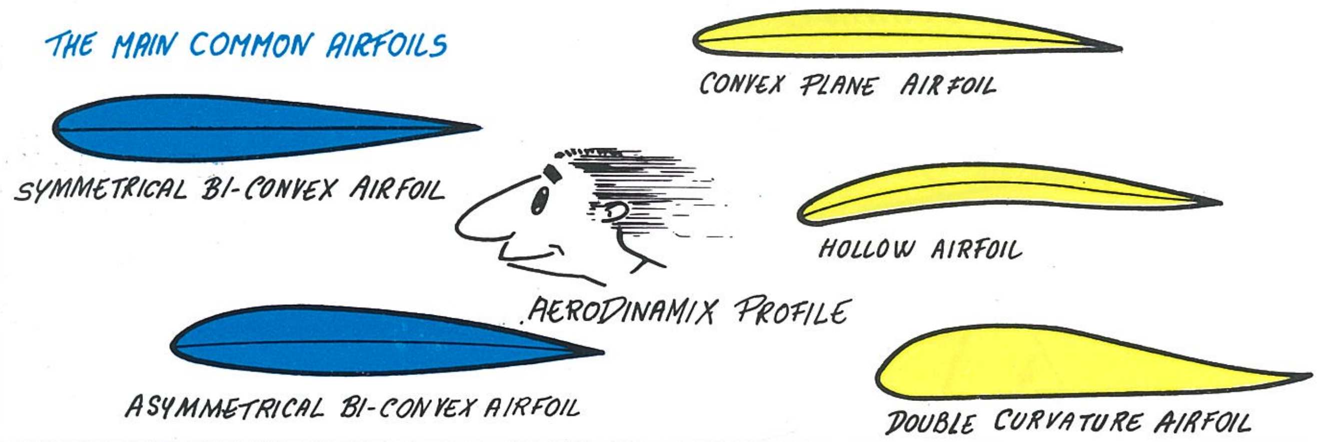
The location of the center of pressure (C.P.) with respect to the airfoil chord varies according to the type of airfoil under consideration and for asymmetrical airfoils with respect to the angle of attack (i).

In the case of symmetrical airfoils (whose median line coincides with the chord) :



The center of pressure is fixed (independently of the angle of attack) and located at 25 percent of the airfoil chord.

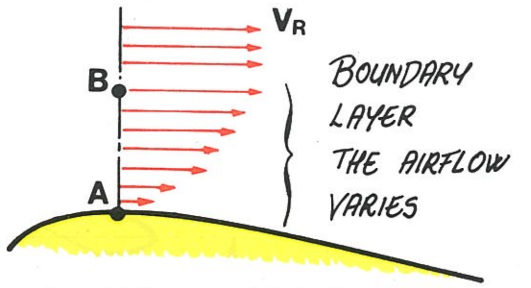
THE MAIN COMMON AIRFOILS



The symmetrical bi-convex airfoil is, the airfoil par excellence for metal helicopter rotor blades for the following reasons : Ease of manufacture and constant stability : as a matter of fact, the fixity of the center of pressure, coinciding with the blade hinge axis, avoids any unwanted moment. The new techniques of production (composite blades) allow asymmetrical bi-convex airfoils which have better aerodynamic qualities.

THE AIR FLOW AROUND AN AIRFOIL

BOUNDARY LAYER



In the immediate vicinity of an airfoil the viscosity of air produces a braking of air molecules resulting from friction forces.

In A, air molecules adhere to the airfoil. The speed of air flow is zero.

From A to B, friction forces decrease and the air velocity increases.

In B, the air flow is no longer affected by friction. Its speed is V_R.

THE BOUNDARY LAYER IS THE AIRFILM OF THICKNESS AB WHERE THE FLOW VELOCITY VARIES.

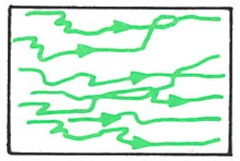
FUNCTION OF BOUNDARY LAYER : THE STATIC PRESSURE FORCES WHICH CREATE ON AN AIRFOIL THE RESULTANT AERODYNAMIC FORCE (F_R) CAN HAVE EFFECT ONLY WHEN THERE IS A BOUNDARY LAYER STICKING TO THE AIRFOIL

LAMINAR AND TURBULENT FLOWS

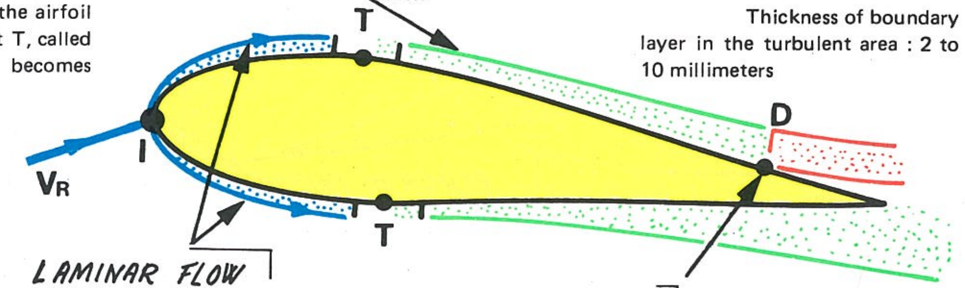
The examination of the aerodynamic spectrum (air flow materialized by smoke) demonstrates the existence of a boundary layer over the whole airfoil. In the first section of the airfoil the flow is laminar. Then, from point T, called the transition point, the flow becomes turbulent.

I is the point of impact. It is from there that the air flow is divided in two parts by the airfoil.

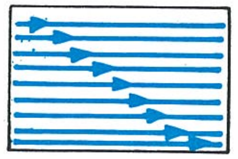
TURBULENT FLOW.
The trajectory of the airflow layers jets is disordered but the general direction of flow remains that of the laminar flow.



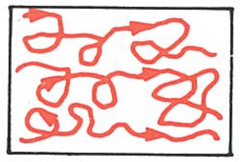
Thickness of boundary layer in the turbulent area : 2 to 10 millimeters



The airflow layers are parallel to each other. Thickness of boundary layer in laminar flow area is some 1/10 of millimeter.



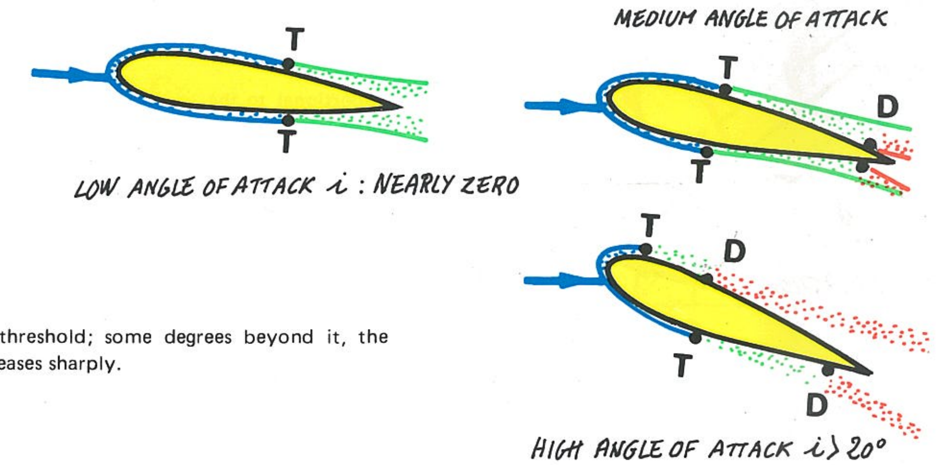
SEPARATION OF BOUNDARY LAYER.
Under some conditions the flow may become whirling. THE BOUNDARY LAYER BECOMES SEPARATED FROM THE AIRFOIL.



EFFECT OF THE ANGLE OF ATTACK ON AIRFLOW

When the angle of attack increases, the point of transition T and the point of separation of the boundary layer D move towards the leading edge. The displacement of these points is not very significant up to a relatively high angle value (variable according to the type of airfoil but generally exceeding 20°).

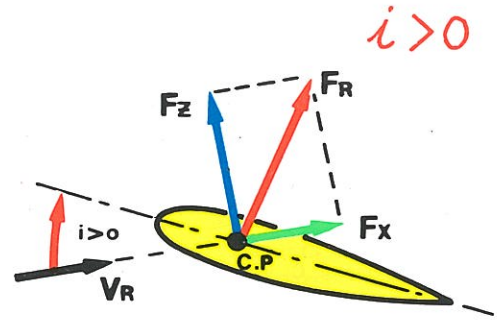
A critical airflow area begins at this threshold; some degrees beyond it, the boundary layer is separated and lift decreases sharply.

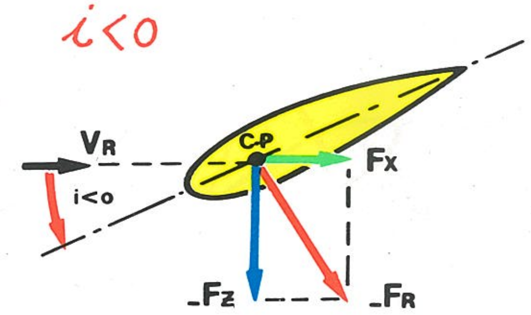


THIS IS KNOWN AS STALLING

ANALYSIS OF THE AERO-DYNAMIC RESULTANT F_R

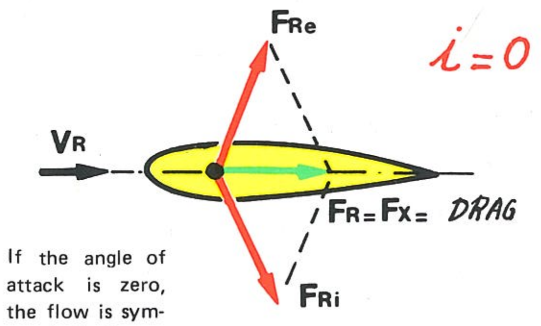
EFFECT OF THE ANGLE OF ATTACK ON THE DIRECTION OF F_R





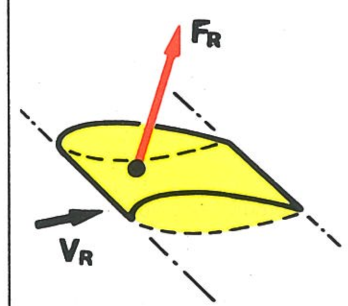
We have seen that the aerodynamic resultant F_R, applied at the center of pressure (C.P.) is inclined rearwards and directed upwards when the angle of attack is positive (i.e. when the relative wind V_R attacks the airfoil on its lower surface).

If the angle of attack i is NEGATIVE, the phenomenon is inverted : F_R is directed downwards and the airfoil is pulled downwards by a force - F_Z which may be called NEGATIVE LIFT.



If the angle of attack is zero, the flow is symmetrical (for a symmetrical airfoil) on the upper and lower surfaces. The pressure forces on the upper and lower surfaces are equal and admit 2 symmetrical resultants (F_{Re} and F_{Ri}). In this case, the general resultant (F_R) is parallel to the airflow. This is drag. The lift is null.

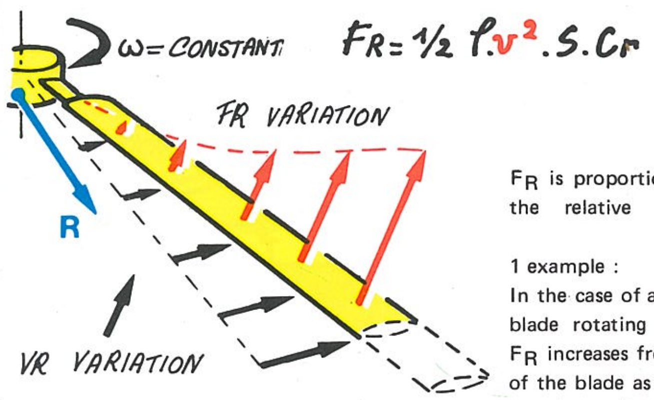
FACTORS AFFECTING THE VALUE OF F_R



Let us consider a blade section of a helicopter rotor and examine every term of the expression :

$$F_R = 1/2 \, \rho \, v^2 . S . C_r$$

F_R is proportional to ρ (air density). As ρ depends on the atmospheric pressure and the ambient temperature. F_R varies with these two data. Particularly, F_R decreases when the altitude increases.



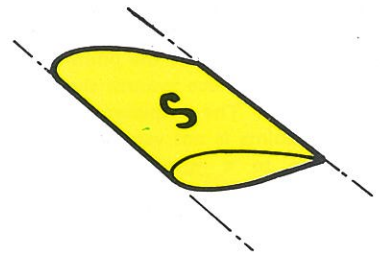
F_R is proportional to the square of the relative wind velocity V_R.

1 example :
In the case of an UNTWISTED rotor blade rotating at constant velocity, F_R increases from the root to the tip of the blade as V_R increases with the rotation radius R. This variation of F_R is troublesome. The applicable remedy is :

BLADE TWIST

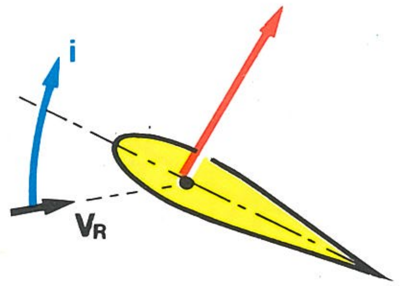
FR = 1/2 ρ.v².S.Cr

F_r is proportional to the surface area S of the blade section.



Value S is constant for a blade having a given profile.

FR = 1/2 ρ.v2.S.Cr



THE VALUE OF FR DEPENDS ON THE ANGLE OF ATTACK i

F_R is proportional to factor C, which reflects :
- the shape of the body (profile)
- the condition of the body's surface
- THE BODY'S ATTITUDE WITH RESPECT TO THE RELATIVE WIND (ANGLE OF ATTACK)

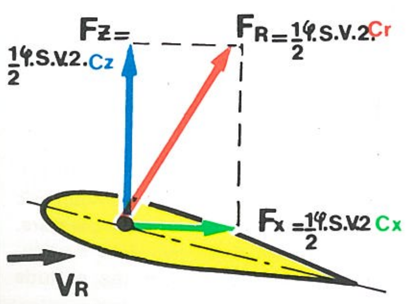
KEEP IN MIND : for a given blade, C_r varies in terms of the angle of attack "i" only.

CONCLUSION: THERE IS ONLY ONE WAY TO CONTROL FR: TO VARY THE ANGLE OF ATTACK

The way this is achieved on a helicopter will be examined later.

EFFECT OF ANGLE OF ATTACK VARIATION ON LIFT (Fz) AND DRAG (Fx)

EXPRESSION OF Fz AND Fx

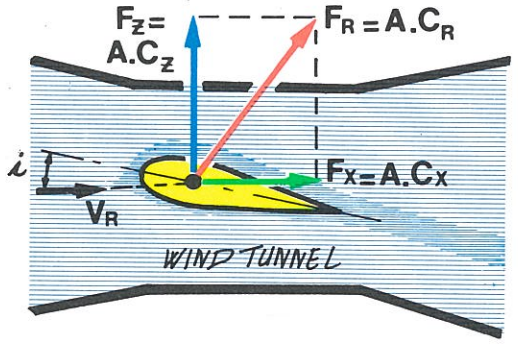


Lift (F_Z) and drag (F_X) are calculated using the basic formula of wind resistance and a shape and position factor determined in a wind tunnel.

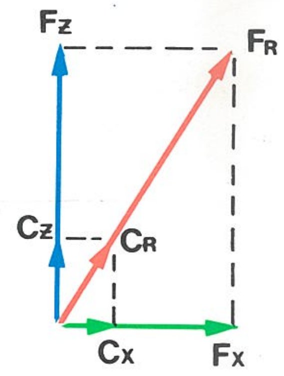
- Cz IS THE LIFT FACTOR
- Cx IS THE DRAG FACTOR

In the wind tunnel, C_Z and C_X are determined using aerodynamic scales measuring the drag and lift values. The test conditions are such that the term 1/2 ρ .S. V^2 . . . . . REMAINS CONSTANT .

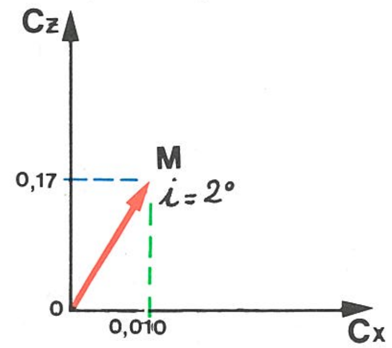
i.e. : 1/2 ρ S v2 = A



The 3 following parameters, LIFT (F_z), DRAG (F_x) and aerodynamic resultant (F_R) depend only on the factors C_Z, C_X and C_R which vary with respect to angle of attack "i" only.



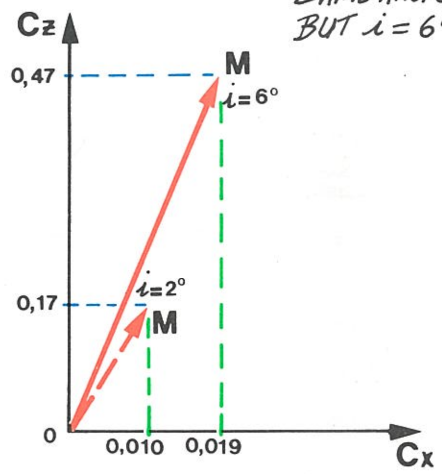
Accordingly, to design the aerodynamic features of an airfoil, it is sufficient to determine, for every angle of attack "i", the C_Z and C_X data and to plot them on a graph.



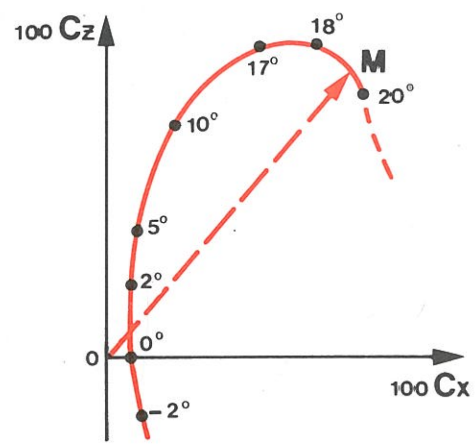
Example : Case of a symmetrical bi-convex airfoil, for i = 2°.

Factor C_r, is represented in size and direction by vector OM.

SAME AIRFOIL BUT i = 6°



POLAR CURVE OF AN AIRFOIL



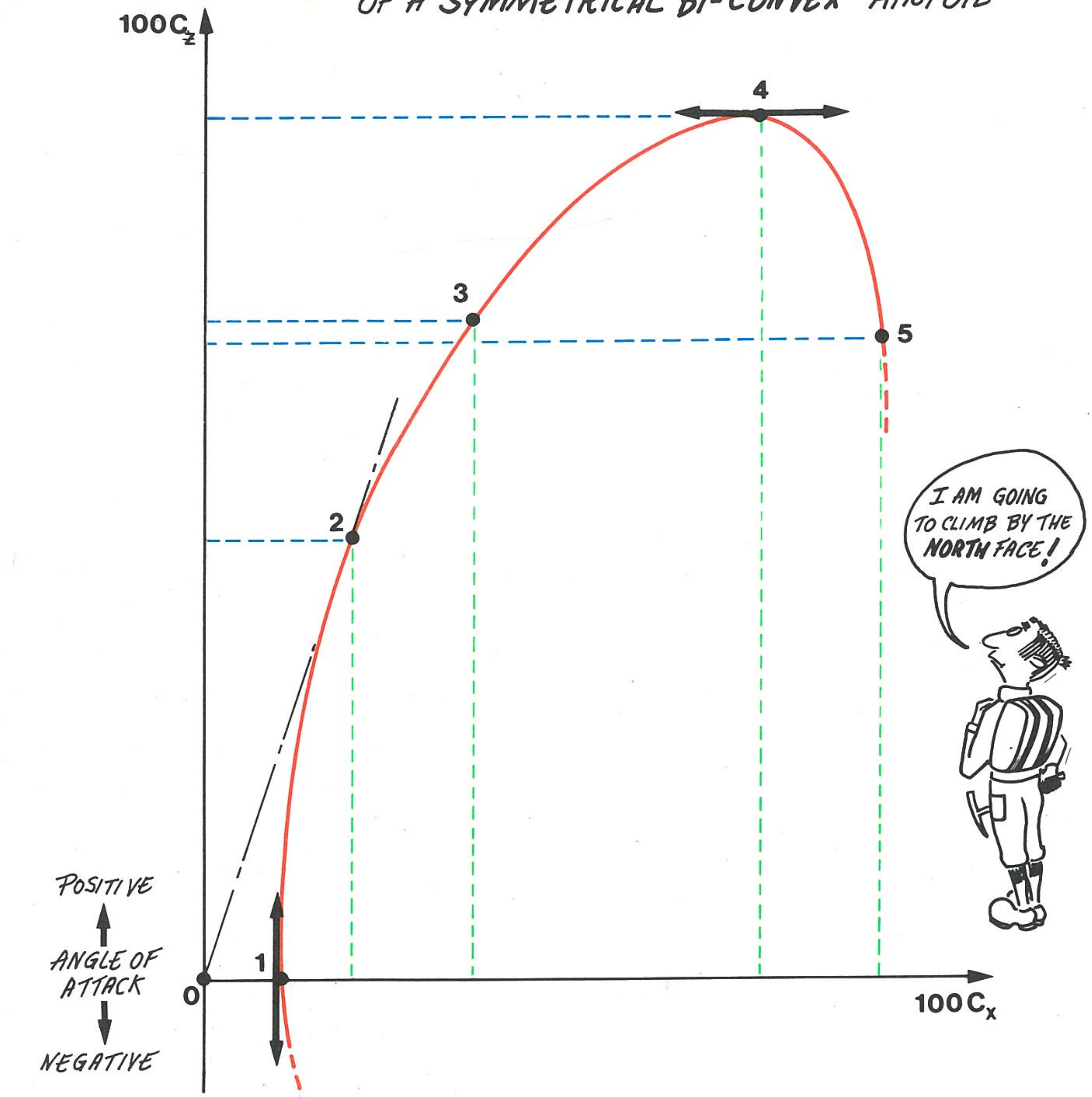
If all points M determined this way are connected, a curve called the airfoil polar curve is obtained. This curve show how, for a given airfoil, the lift and drag vary in terms of the angle of attack.

As C_Z and C_X values are low, for the purpose of making easier the reading of the curve, C_Z and C_X are multiplied by 100. Furthermore, as C_X is much smaller than C_Z, the scale of C_X is 10 times greater than that of C_Z.

This curve is called polar as it is defined by the end of vectors OM originating from the same pole (origin O).

THE SIGNIFICANT POINTS ON THE POLAR CURVE OF AN AIRFOIL

GENERAL SHAPE OF THE POLAR CURVE OF A SYMMETRICAL BI-CONVEX AIRFOIL



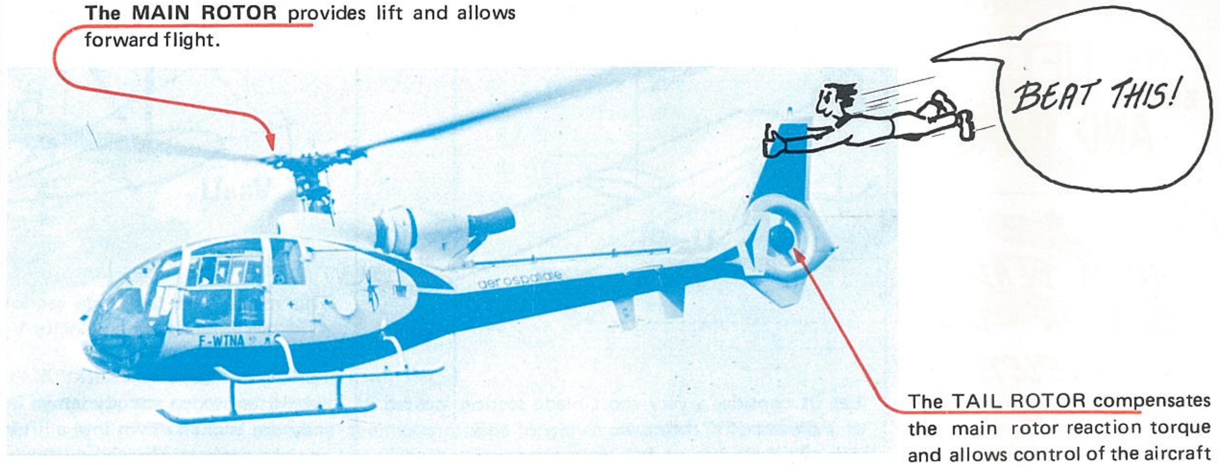
THE ANGLE OF ATTACK INCREASES FROM POINT 1 TO POINT 5.

- in 1 — The angle of attack is zero. Lift is null and drag is minimum
- in 4 — The lift is maximum
  - from 1 to 4, lift and drag increase,
  - beyond point 4, any increase in the angle of attack produces a reduction in lift (critical area)
- in 5 — This is the stalling angle. The boundary layer separates and the lift decreases sharply.
- in 2 — This the point of maximum lift - to-drag ratio
  - at this point, the angle of attack provides maximum lift for minimum drag. The lift-to-drag ratio is defined by the ratio $\frac{C_Z}{C_X}$
- in 3 — This is the point of best lift to drag ratio of the airfoil. This is the optimum angle of attack for a helicopter blade. At this angle, the ratio $\frac{C_X^2}{C_Z^3}$ is minimum.

3. BLADE AND ROTOR

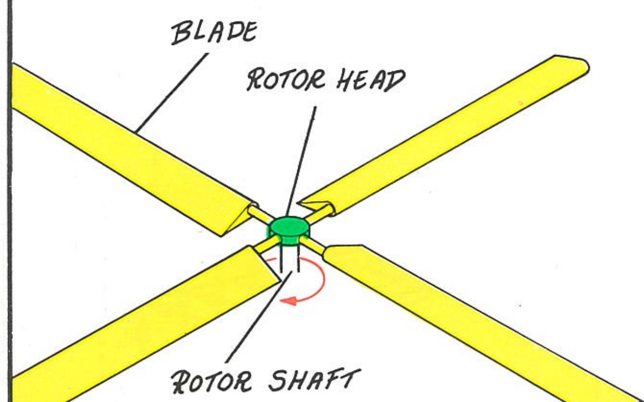
GENERAL

The MAIN ROTOR provides lift and allows forward flight.



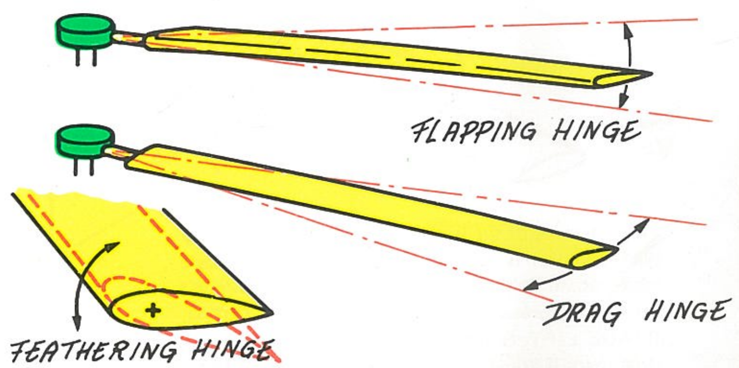
The TAIL ROTOR compensates the main rotor reaction torque and allows control of the aircraft about its yaw axis.

THE ROTOR IS THE MAIN HELICOPTER COMPONENT.



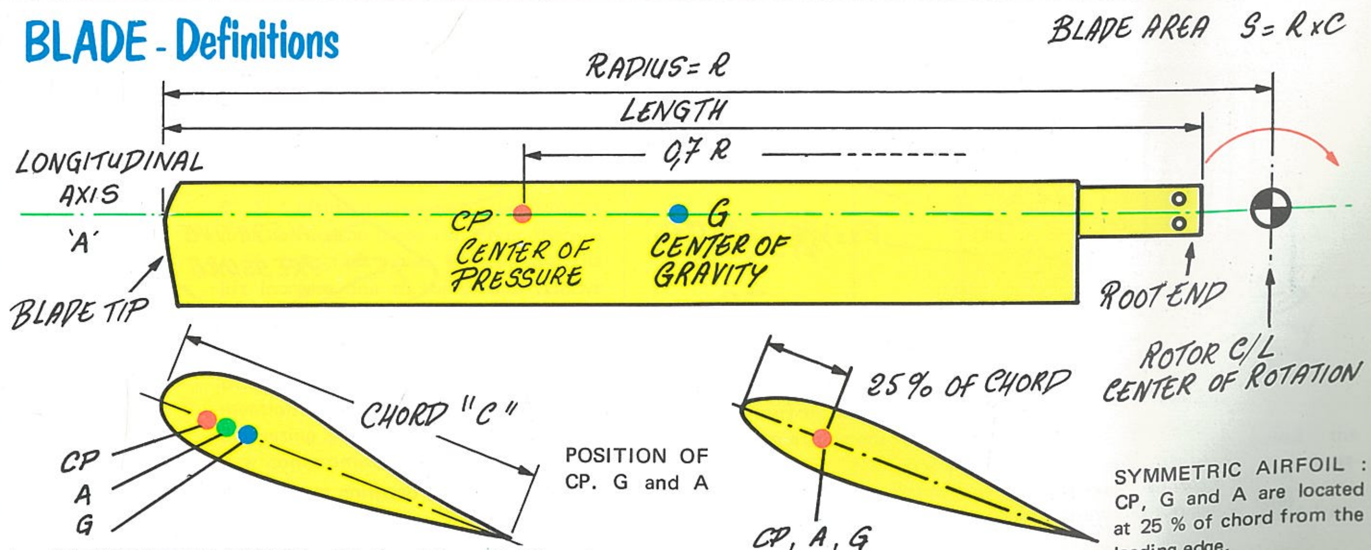
A rotor is composed mainly of :
- a ROTOR SHAFT driven by the power plant.
- a ROTOR HEAD linking the rotor shaft and blades.
- BLADES (two or more).

The blades are linked to the rotor head by HINGES (or FLEXIBLE SECTIONS) allowing blade motions :
- In the vertical plane (flapping hinge)
- In the rotation plane (drag hinge)
- about the longitudinal axis (feathering hinge)



WE ARE GOING TO REVIEW ROTOR AERODYNAMICS AND MECHANICS, WITH PARTICULAR EMPHASIS ON THE NEED FOR HINGES (OR FLEXIBLE SECTIONS).

BLADE - Definitions



POSITION OF CP, G and A

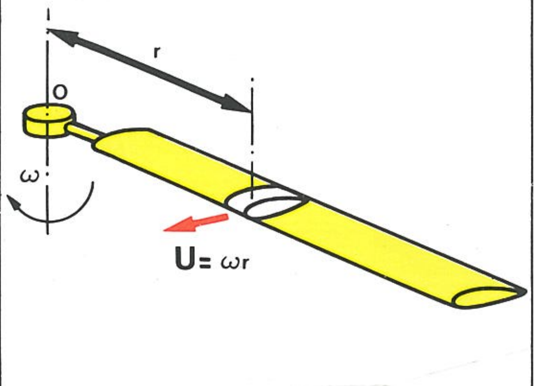
DISSYMMETRIC AIRFOIL : CP, G and A are at different locations.

SYMMETRIC AIRFOIL : CP, G and A are located at 25 % of chord from the leading edge.

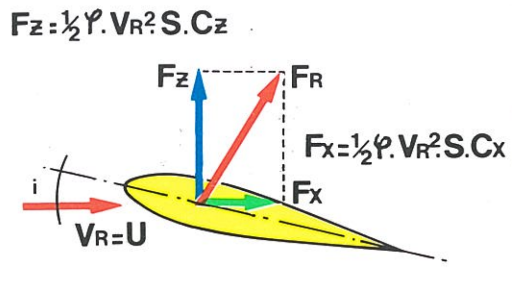
BLADE LIFT AND DRAG

•

FROM BLADE SECTION TO A COMPLETE BLADE



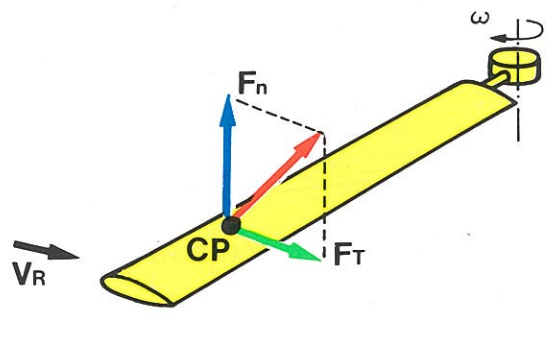
Let us consider a very short blade section located at a distance "r" from the centre of rotation "O". The rotor operating at constant speed "ω", the blade section circumferential speed is U = ωr.



This means that the blade section is operating in a relative wind having a velocity V_R = U.

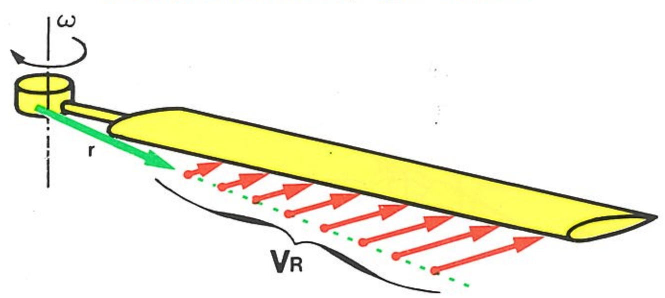
For a given angle of attack "i" the blade section is submitted to an aerodynamic load "F_R" which may be broken down into a lift load "F_Z"; acting at right angle to V_R and a drag load "F_X" parallel to V_R.

TOTAL LIFT AND DRAG OF BLADE



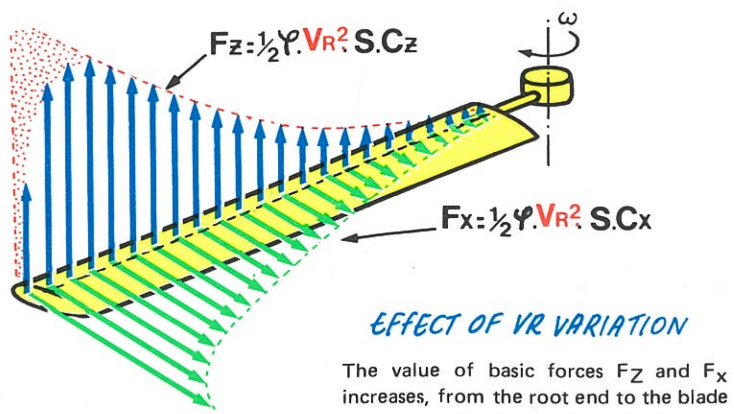
The resultant of the basic lift loads applied to every blade section is a load F_n, parallel to the basic loads, equal to their sum and applied to the blade's centre of pressure "C.P." This is the TOTAL BLADE LIFT. Similarly, the resultant of the basic drag loads is equal to their sum. This is the TOTAL DRAG "F_T"

VARIATION OF RELATIVE VELOCITY VR ALONG THE BLADE



From the root end to the blade tip, the blade section radius of rotation "r" INCREASES. The CIRCUMFERENTIAL SPEED (or relative velocity "V_R") of blade sections increases proportionally to the radius :

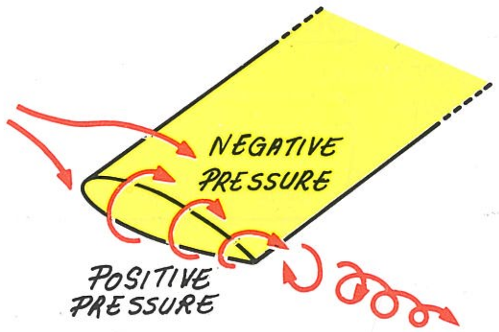
$V_R = \omega r$.



EFFECT OF VR VARIATION

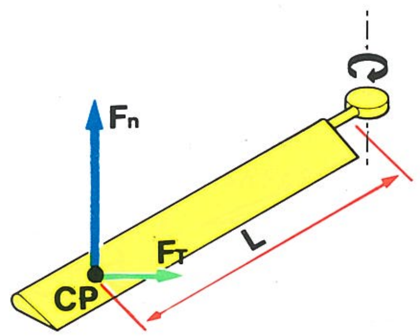
The value of basic forces F_Z and F_X increases, from the root end to the blade tip, with the square of the relative velocity V_R.

At the blade tip, there is a decrease in lift caused by the tip losses which tend to balance the pressure between the lower and upper surfaces.



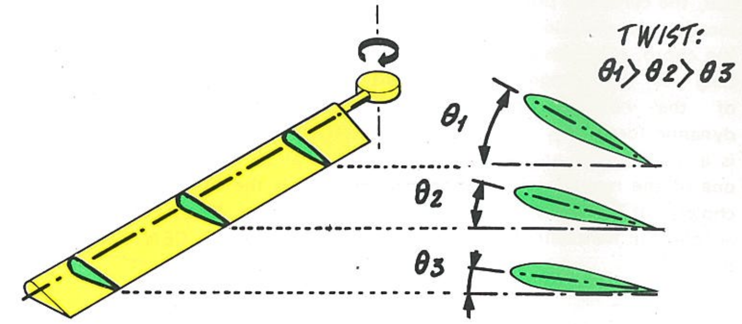
The tip losses, occuring at the blade tip, cause a decrease in lift and an increase in drag.

WHY ARE BLADES TWISTED?

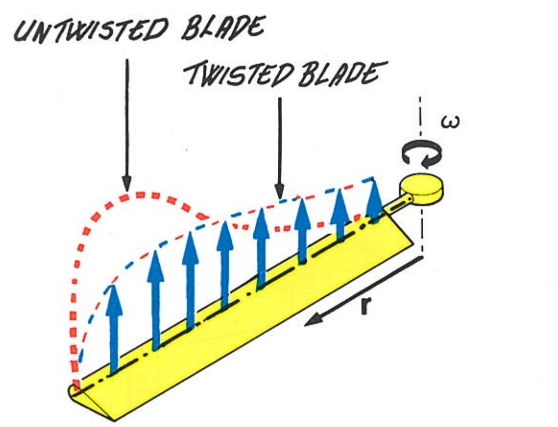


Due to the increase in lift and drag basic forces, from the root end to the blade tip, the center of pressure (C.P.) is located near the blade tip. Therefore, bending moments (F_n x L" and F_T x L") are applied to the root end but ; from the blade strength point of view these moments are excessive.

To achieve a better load distribution and reduce the bending moments, the blades are twisted, that is "distorted" about their longitudinal axis so that they operate at a high angle of attack near the rotor head and at a low angle of attack towards the blade tip where relative velocity (V_R) is high.

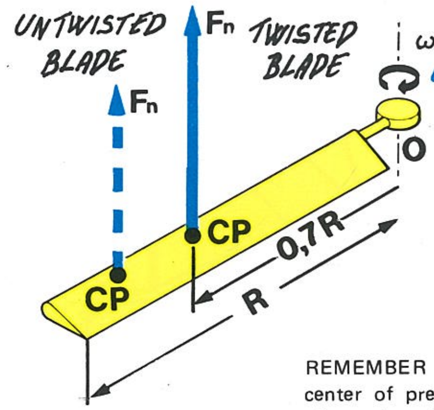


The angle θ decreases progressively from the root end to the blade tip.
This decrease results in a progressive reduction in lift and drag values.



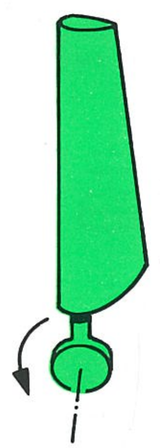
This shows a comparison of the lift distribution along the radius, on twisted and untwisted blades.

COMPARISON OF CENTER OF PRESSURE (C.P.) LOCATION ON TWISTED AND UNTWISTED BLADES.



REMEMBER : When a blade is twisted, the center of pressure (C.P.), is nearer the center of rotation (O), thus the bending moments at the root end are reduced.

We will see later how blade twist improves rotor behaviour in autorotation.



Another way of achieving an even lift distribution along the blade.

THE TRAPEZOIDAL BLADE

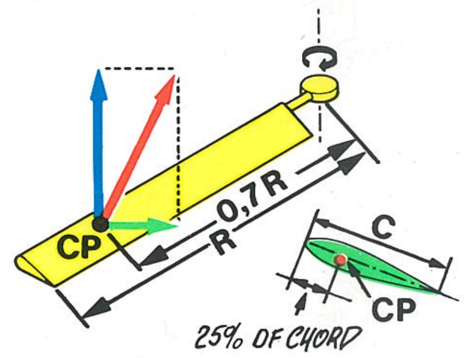
(used on some tail rotors)

- The lifting surface decreases from the root end to the blade tip. Thus, there is a lift reduction which compensates the lift increase due to the greater relative velocity (V_R).

But, there are other means. Let us mention the varied blade profile and decreasing thickness. And often a blade is a compromise between these various solutions.

THE BLADE CENTER OF PRESSURE

The blade center of pressure (C.P.) is the point where aerodynamic forces are applied.



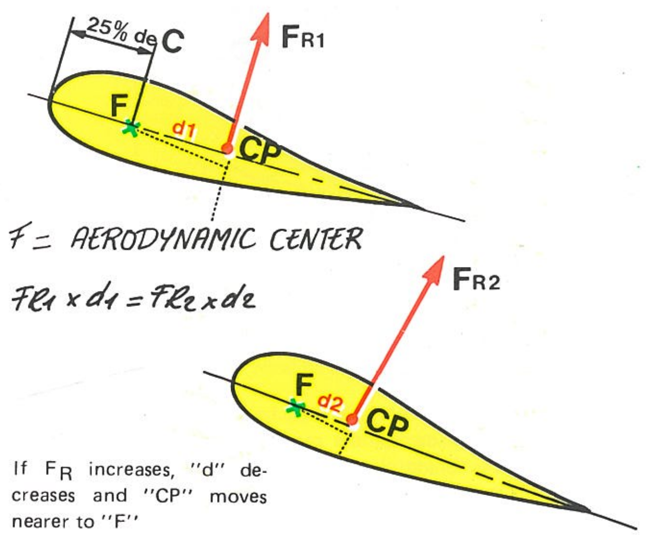
On a SYMMETRIC BI-CONVEX airfoil, the center of pressure location is FIXED. It is located at 0.7 R from the center of rotation (R being the rotor radius) and at 25% of the chord from the leading edge.

THE DISSYMETRIC AIRFOIL AND THE VARIATION IN CENTER OF PRESSURE LOCATION

We are going to see that on a DISSYMMETRIC airfoil, the center of pressure location is variable along the chord, it moves according to the magnitude of the resultant aerodynamic force "F_R". This is a disadvantage and it is one of the reasons for the choice of SYMMETRIC airfoils for helicopter blades.

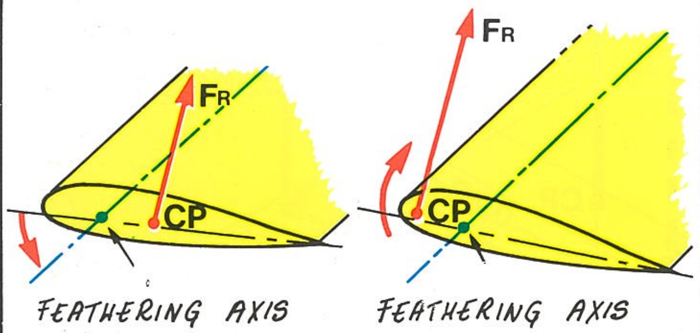
When F_R increases, the center of pressure moves towards the leading edge. In the wind tunnel, the analysis of the center of pressure location change has revealed a FIXED point which has a noteworthy characteristic. This fixed point is called the AERODYNAMIC CENTER (F), it is located at 25 % of the chord. Its characteristic is the following : THE MOMENT OF F_R RELATIVE TO THE AERODYNAMIC CENTER IS CONSTANT.

$M = F_R \times d$ = CONSTANT



If F_R increases, "d" decreases and "CP" moves nearer to "F"

EFFECT OF CENTER OF PRESSURE CHANGE

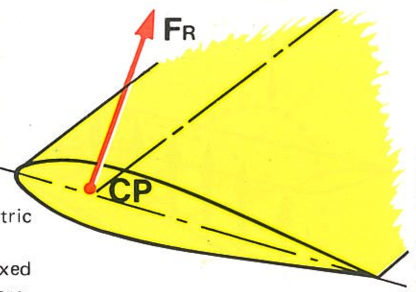


IF CP is located aft of the feathering axis, F_R produces a NOSE DOWN moment tending to decrease the angle of attack.

On the other hand, if CP is forward of the feathering axis, F_R produces a NOSE-UP moment tending to increase the angle of attack.

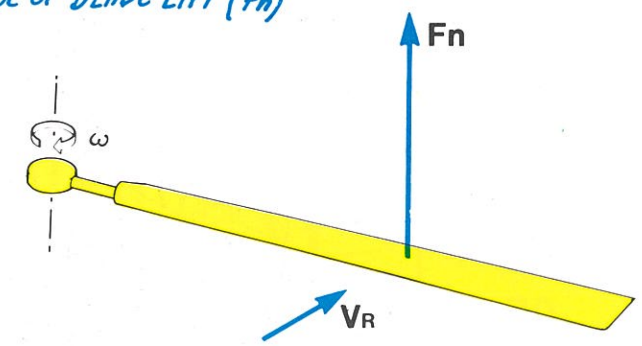
As we have seen, when F_R increases, the center of pressure moves towards the leading edge ; therefore, in all cases, the effect of F_R is to decrease the NOSE DOWN moment or to increase the NOSE-UP moment, that is, finally to increase the angle of attack.

DISSYMMETRIC AIRFOILS ARE UNSTABLE



On the other hand, symmetric airfoils are STABLE.
The center of pressure is fixed and coincides with the aerodynamic center and the feathering axis.

CONTROL OF BLADE LIFT (F_n)



Considering the lift equation $F_n = 1/2\, \rho \,.\, V_R^2 \,.\, S.\, Cz$, it can be seen that, in flight, there are only two factors allowing lift control (that is to handle the aircraft) :

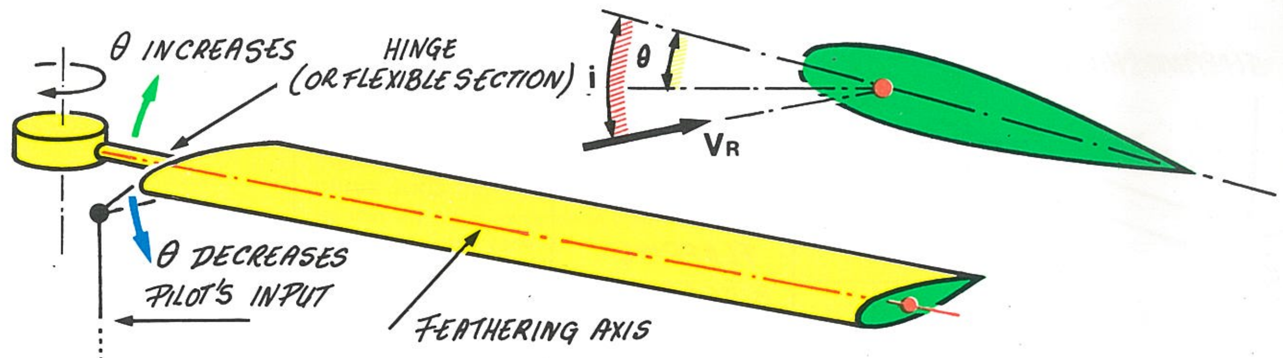
- V_R either the blade circumferential velocity or ω the rotor speed.
- C_z (lift factor) which depends on the angle of attack.

The other factors depend either on atmospheric pressure and temperature (ρ), or on the blade area and profile. But, as helicopter rotors operate at constant speed (governor), there remains one way only to control lift : VARIATION OF THE ANGLE OF ATTACK. Let us recall that when the angle of attack increases, the lift increases also.

HOW IS THE ANGLE OF ATTACK CONTROLLED?

Simply, through variation of the blade pitch angle θ achieved by rotating the blade about its feathering (longitudinal) axis. This is the feathering hinge, already mentioned.

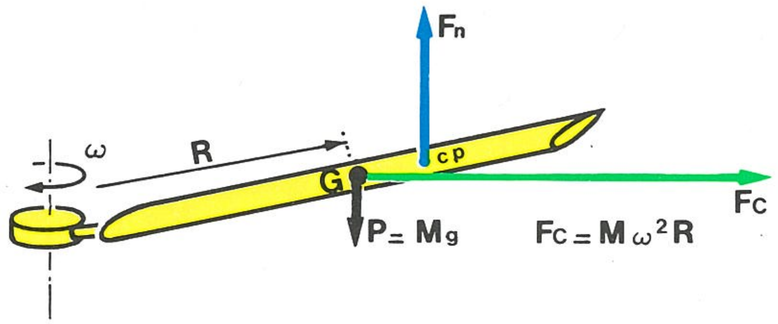
When the blade pitch angle θ varies, the angle of attack "i" varies also by the same amount and in the same direction.



FORCES ACTING ON A BLADE IN ROTATION

A blade is subjected to :

- its weight (P) applied to the centre of gravity (G).
- centrifugal force (F_C) applied at G.
- lift (F_n) applied at the cèntre of pressure (C.P.)



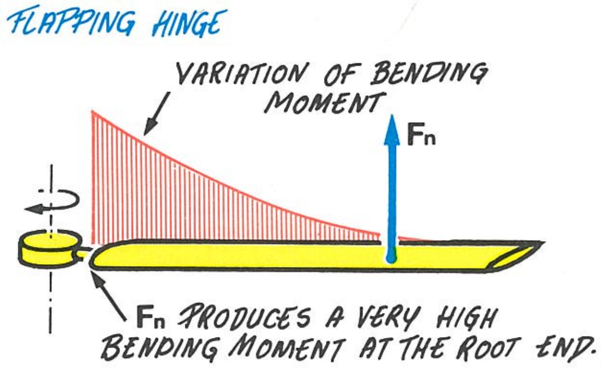
We will see later that there are also alternating inertia forces (CORIOLIS forces) acting on the blade in the rotation plane.

The blade weight is negligible relative to the other forces.
AMPLITUDE OF FORCES :
SA 330 helicopter taken as an example).

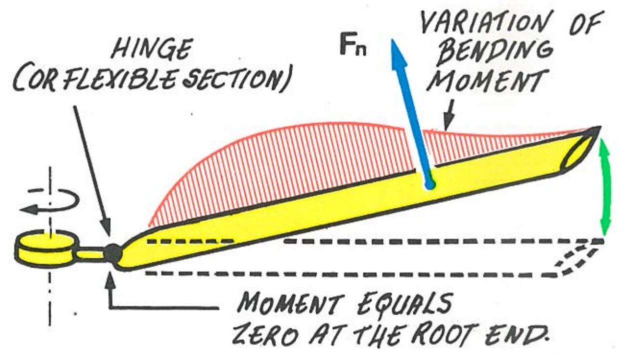
- F_C, about 22000 daN.
- F_n, about 1800 daN (in autorotation)
- weight (P) : 69 daN.

To clarify your ideas, we recall that : 1 daN = 1,02 kg.f.

WHERE WE START TO TALK ABOUT THE FLAPPING HINGE

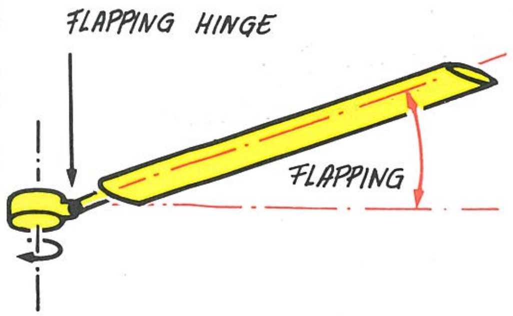


Lift (F_n) tending to pull the blade upward produces a bending moment, which is very strong and greatest at the blade root end. It may be seen that this bending moment generates very high stresses at the blade attachment points and to withstand them the blade root would require excessive dimensions.



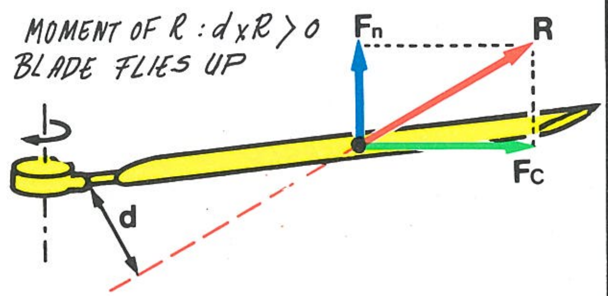
To cancel the bending moment at the root end (that is, to reduce the stresses), the blade is hinged in the vertical plane. It is to be noted that the hinge may be a physical item (hinge pin) or apparent (flexible section : interposition between the blade and the rotor head of a very flexible material, such as "glass-fiber-resin" composite).

It may be seen that such a hinge; which allows the blade an upward motion (called : FLAPPING), cancels the bending moment at the blade attachment by substituting a motion.



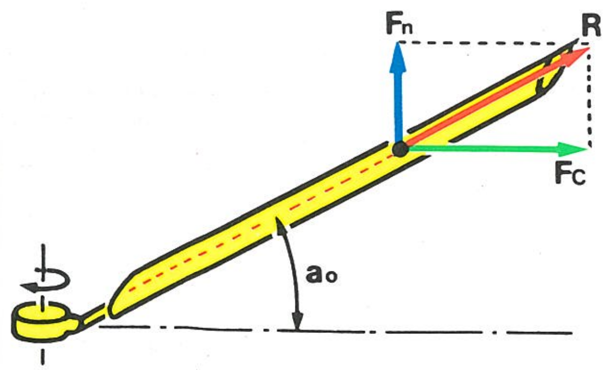
WE WILL SEE THAT THE BLADE'S VERTICAL FLAPPING PLAYS A VERY SIGNIFICANT AERODYNAMIC ROLE. IN FACT, WITHOUT FLAPPING HINGES THE HELICOPTER CANNOT FLY

BLADE EQUILIBRIUM



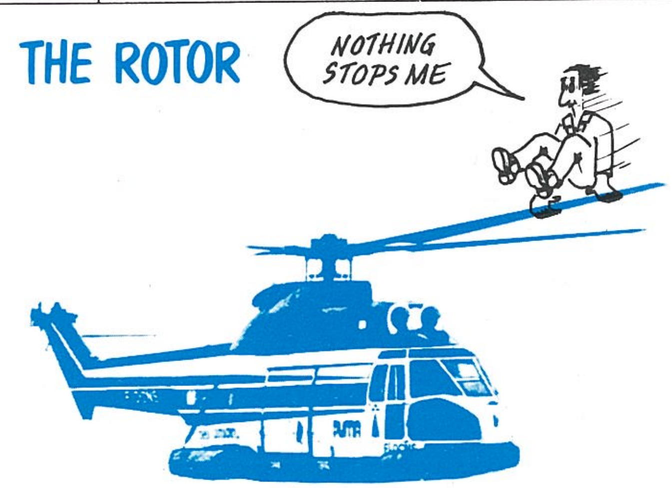
The blade, free to flap upwards, flies up under the action of R (resultant of F_n and F_c).
(to simplify the explanation, it is assumed that the center of gravity and the centre of pressure are coinciding).

The motion stops when the blade is aligned with R, the moment of which about the hinge axis is then equal to zero.



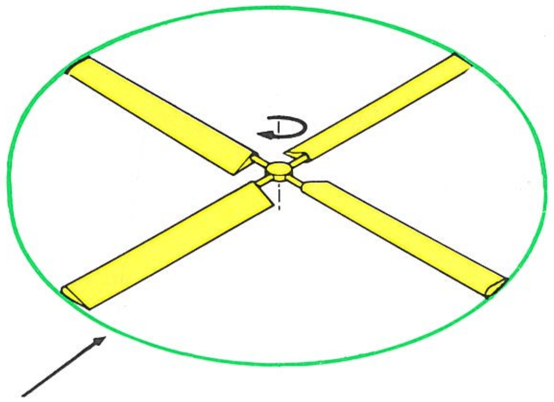
THE ANGLE Ao IS CALLED CONING ANGLE

THE ROTOR



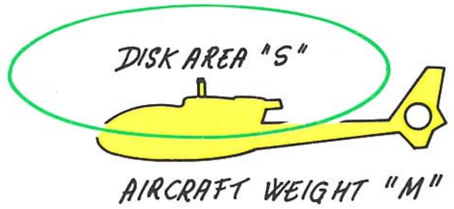
LET US BEGIN WITH SOME DEFINITIONS

IF SOME OF THEM ARE NOT CLEAR, CONTINUE READING; THE EXPLANATION WILL BE GIVEN LATER



THE ROTOR DISK is the circle described by the blade tips.

THE DISK LOADING (OR WING LOADING) ...



..... is the ratio $\frac{M}{S}$, expressed in Kg/m^2.

THE SOLIDITY FACTOR "σ"
is the ratio between the blade area (s) and the disk area (S)
$\sigma = \frac{s}{S}$

Some actual values as an indicator.

Taking the DAUPHIN helicopter as an example :

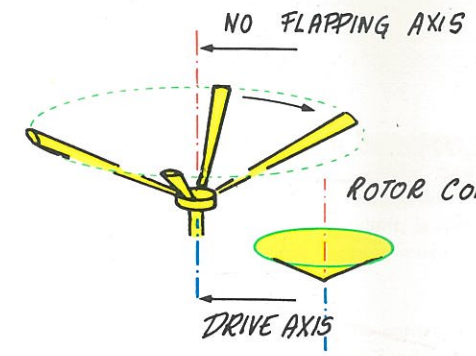
- Disk area : S = 103.87 m^2
- Disk loading : $\frac{M}{S} = \frac{2900}{103{,}87} = 27{,}91$ Kg/m^2
- Blade area : 2.012 x 4 = 8.048 m^2.
- Solidity factor : $\theta = \frac{s}{S} = \frac{8.048}{103.87} = 0.0774$

THE ROTOR CONE

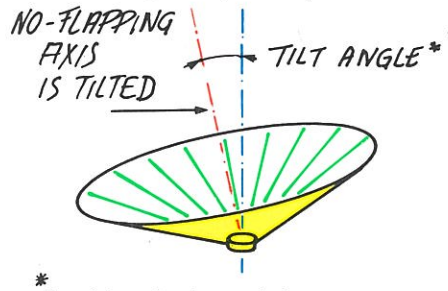
- The blades subjected to lift and centrifugal force describe a very wide cone : THE ROTOR CONE.
- The cone axis is called

THE NO-FLAPPING AXIS

In hover (and zero wind), the "no flapping" axis coincides with the DRIVE AXIS (rotor shaft). We will see that any cyclic variation in blade lift results in rotor cone tilt.



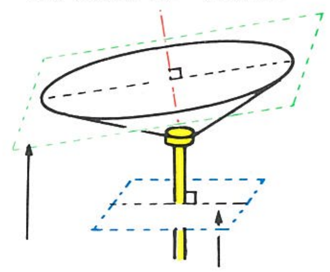
ROTOR TILTING



* For this angle, the symbols are :

- a_1 = longitudinal tilting
- b_1 = lateral tilting.

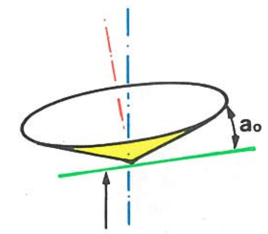
REFERENCE PLANE



PLANE OF ROTATION (OR ROTOR PLANE) perpendicular to the no-flapping axis.

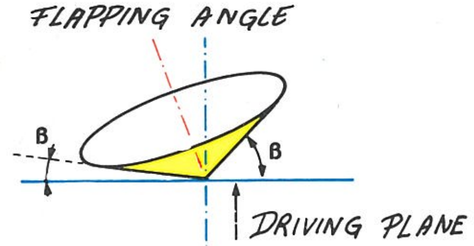
DRIVE PLANE, perpendicular to the rotor shaft.

CONING ANGLE



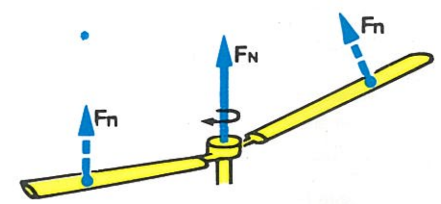
This is the angle between the blade and the plane of rotation (or with a plane parallel to the plane of rotation.)

FLAPPING ANGLE

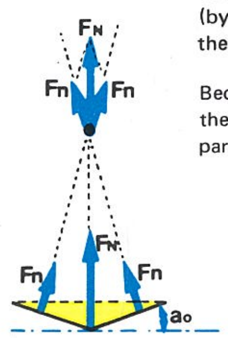


This is the angle between the blade and the drive plane. It may be seen that this angle varies over a complete blade revolution.

THE TOTAL ROTOR LIFT (F_N)



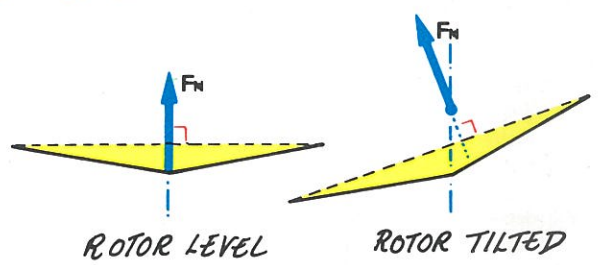
The TOTAL ROTOR LIFT (F_N) is the resultant of the lift of blades (F_n).



Composition of blade lift (F_n) (by displacement of forces along their line of action).

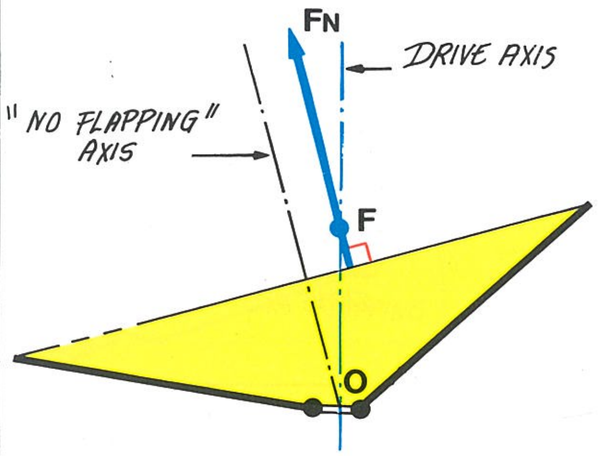
Because of the coning angle (a_0), the blade lift forces (F_n) are not parallel.

DIRECTION OF ROTOR LIFT



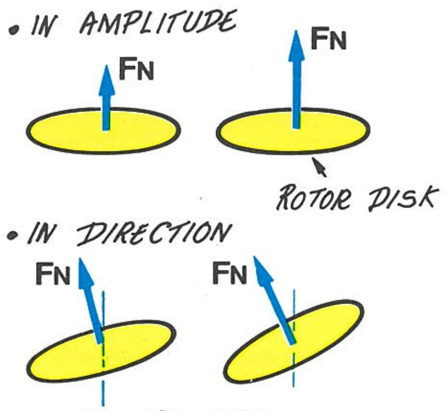
LIFT (F_N) IS ALWAYS PERPENDICULAR TO THE ROTOR PLANE OF ROTATION.

ROTOR LIFT APPLICATION POINT



Lift (F_N) is applied at a virtual point "F", called the AERODYNAMIC CENTER located above the center of rotation. "O" If the plane of rotation is perpendicular to the drive axis, lift (F_N) coincides with this axis. If the plane of rotation is tilted, F_N intersects the drive axis. The aerodynamic centre "F" is located at the point of intersection.

HOW DOES "F_N" VARY ?



VARIATION OF FN IN AMPLITUDE

- F_N, resultant of blade lift forces (F_n) varies with these forces, that is according to the terms of the following equation :

$$F_n = 1/2\,\rho \,.\, V_R^2 \,.\, S \,.\, C_Z \,.$$

- It is useful to establish (as we have already done) the variable and the constant terms.

THE VARIABLE TERMS ARE :

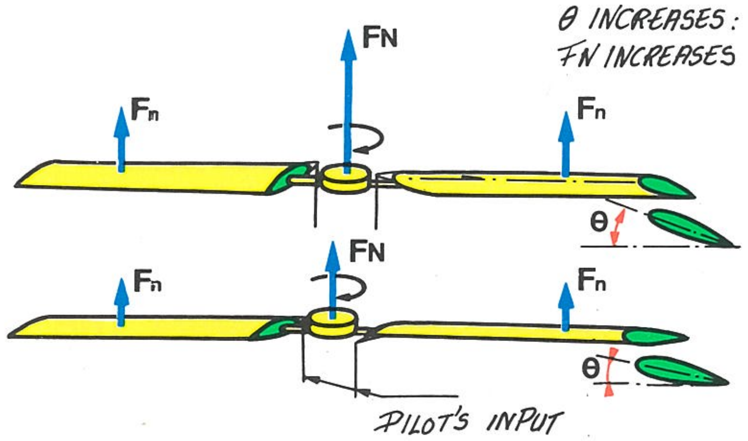
- The angle of attack (i) (part of C_Z)
- The air density ρ
- The relative velocity (V_R) of the air

THE CONSTANT TERMS ARE :

- The blade area (S)
- The profile and surface condition (part of C_Z).

Only the variable terms i, V_R and ρ, which have an effect on F_N amplitude, are of interest to us.

EFFECT OF THE ANGLE OF ATTACK



F_N varies with the angle of attack (and therefore with the pitch angle θ). Using a control, the pilot can vary simultaneously the pitch of each blade. This is the collective pitch variation, which we will come to later).

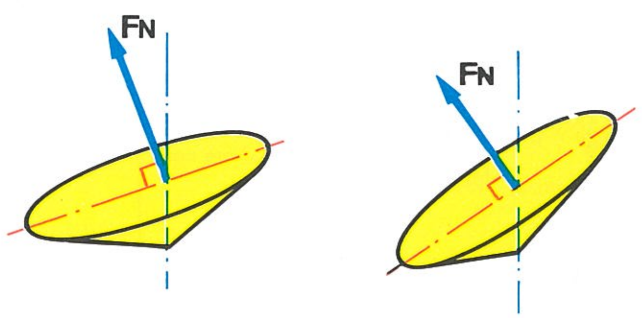
EFFECT OF THE RELATIVE VELOCITY (V_R) AND DENSITY (ρ) OF THE AIR

REMEMBER THAT

- F_N is proportional to V_R^2, which with the rotor operating at constant speed, depends on forward speed only. Therefore, a higher pitch (θ) is required in hover than in forward flight.
- Like ρ, F_N decreases as the altitude or the temperature increases. To maintain constant lift, with increasing altitude or temperature, the pilot has to increase the blade pitch (θ).

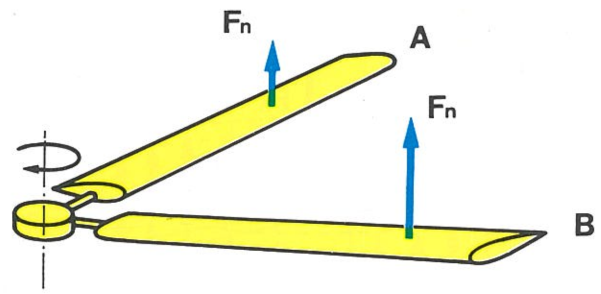
VARIATION IN DIRECTION OF F_N

To obtain a variation in direction of F_N, it is necessary to tilt the rotor plane, since F_N is always perpendicular to that plane.



The tilting of the rotor plane changes the direction of F_N.

We will see that IN ALL CASES, rotor plane tilt is caused by a dissymmetry in the lift of blades at their various positions in azimuth.

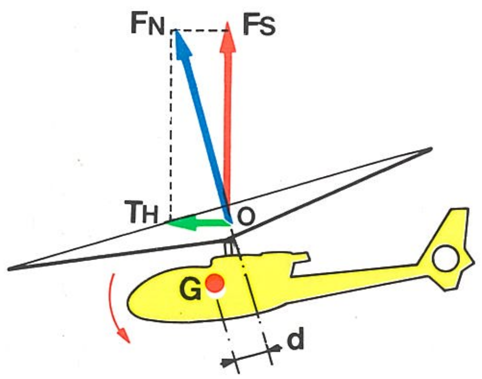


LIFT DISSYMMETRY MAY BE NATURAL OR CONTROLLED.

- Natural dissymmetry is due to variations in the relative wind velocity (V_R). This dissymmetry, somewhat inconvenient, is compensated automatically by the blades's vertical flapping motion, (we are going to talk about this).
- The dissymmetry initiated by the pilot allows the control of the rotor plane tilt. The pilot can vary the blade pitch (and hence the lift) according to the blade position in azimuth. This is the cyclic pitch variation, which will be explained in detail.

If when the blade moves from A to B, lift (Fn) varies, there is a LIFT DISSYMMETRY.

ROTOR PLANE TILT AND BRIEF ANALYSIS OF FN EFFECTS

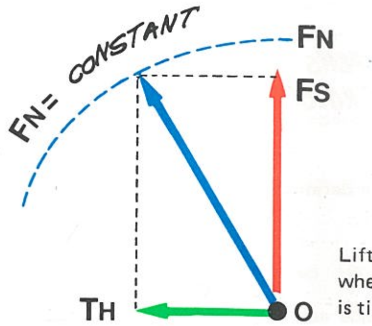


The rotor plane tilting results in the inclination of F_N (which remains perpendicular to it).

- F_N may be then broken down into a vertical lifting force (F_1) which supports the aircraft and a horizontal force (T_H) which ensures forward flight.

It is to be noted that F_N creates, relative to the centre of gravity "G", a moment "d x F_N" tending to incline the aircraft.

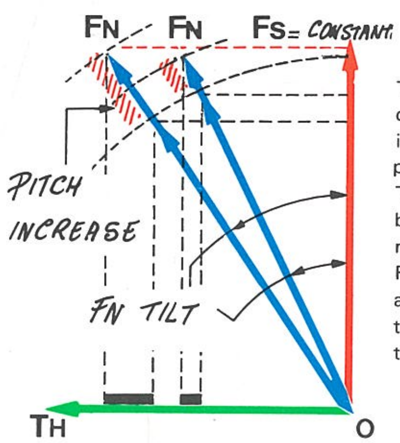
Here, the F_N moment is going to incline the aircraft in the nose down direction until the F_N action line passes through "G" - Remember that the helicopter attitude practically follows the rotor plane.



$F_S < F_N$

Lift is reduced when the rotor is tilted.

Look at this diagram - For a constant lift (F_N), any tilting of the rotor plane means a decrease in the vertical lift force (This force is at its maximum value when the rotor is level, as $F_S = F_N$). Hence, the transition to forward flight entails a reduction of lift, that is a loss in altitude.



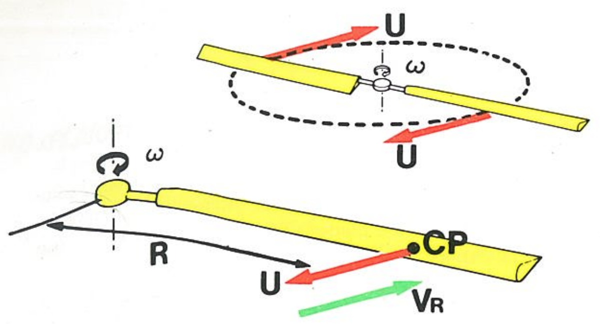
To maintain constant lift in Spite of the F_N tilt, it is necessary to increase F_N by an amount proportional to the spite degree of tilt. The rotor lift increase is achieved by greater blade pitch. It is to be noted that in forward flight lift F_N increases with forward speed and the pilot may then reduce the pitch to keep a constant altitude.

THIS BRINGS US BACK TO THE FLAPPING HINGES

LATERAL LIFT DISSYMMETRY

We shall now see that a FLAP RIGID rotor causes, in forward flight, a lateral lift dissymmetry which, makes it practically UNCONTROLLABLE and also generates very high ALTERNATING stresses which are imcompatible with good fatigue strenght in the materials used.

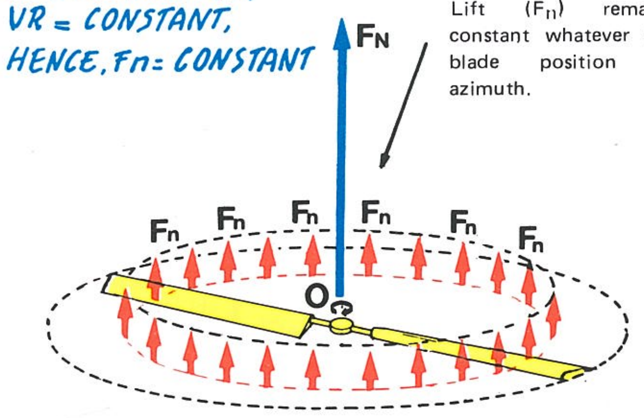
IN HOVERING FLIGHT VR = CONSTANT



In hover, the blade tip speed (U) remains constant, whatever the blade position. At the center of pressure (CP) this speed "U" is equal to ωR, "R" being the radius of the center of pressure trajectory (the rotor angular speed ω is constant).
The air velocity relative to the blade (V_R) is obviously equal, but acting in the opposite direction, to the blade speed "U". Hence, V_R is constant.

IN HOVERING FLIGHT, VR = CONSTANT, HENCE, Fn = CONSTANT

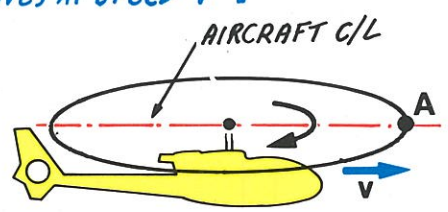
Lift (F_n) remains constant whatever the blade position in azimuth.



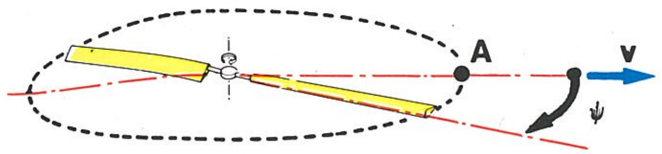
Since V_R is constant, it is obvious that, for a given pitch angle, the blade lift (F_n) is also constant whatever the blade position in azimuth. The lift (F_n) of the various blades is symmetric and the resultant F_N (rotor lift) is applied at the center of rotation "O".

WHAT HAPPENS IN FORWARD FLIGHT WHEN THE ROTOR MOVES AT SPEED "V"?

But first, some definitions.

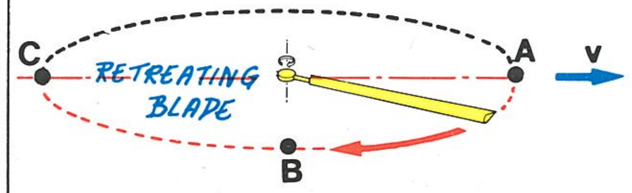


Angle ψ = blade azimuth.

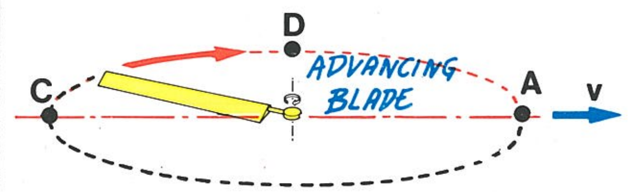


To study aerodynamic CYCLIC phenomena (that is, phenomena reoccurring regularly at each rotor revolution), it is useful to specify the blade position relative to starting point. The angle ψ will be used to state this position (also called "blade AZIMUTH").

ADVANCING AND RETREATING BLADE...

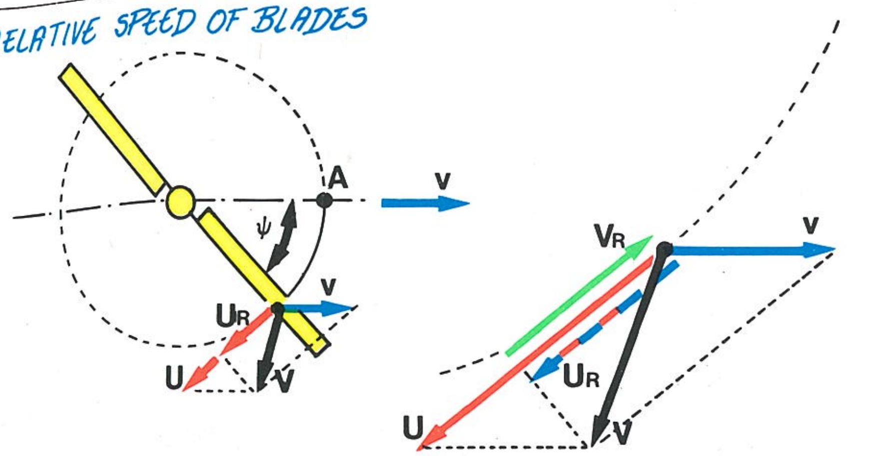


From A to C, the blade retrats in relation to the forward motion ; thus, from A to C the blade is said to be RETREATING.



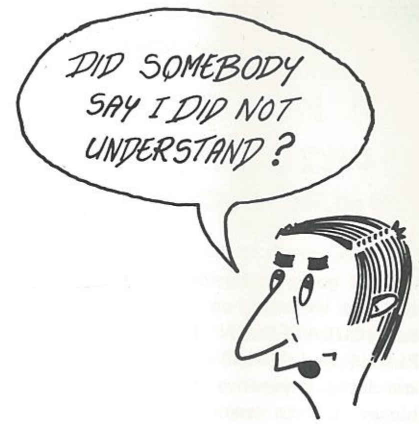
From C to A, the blade advances in relation to the forward motion ; thus, from C to A the blade is said to be ADVANCING.

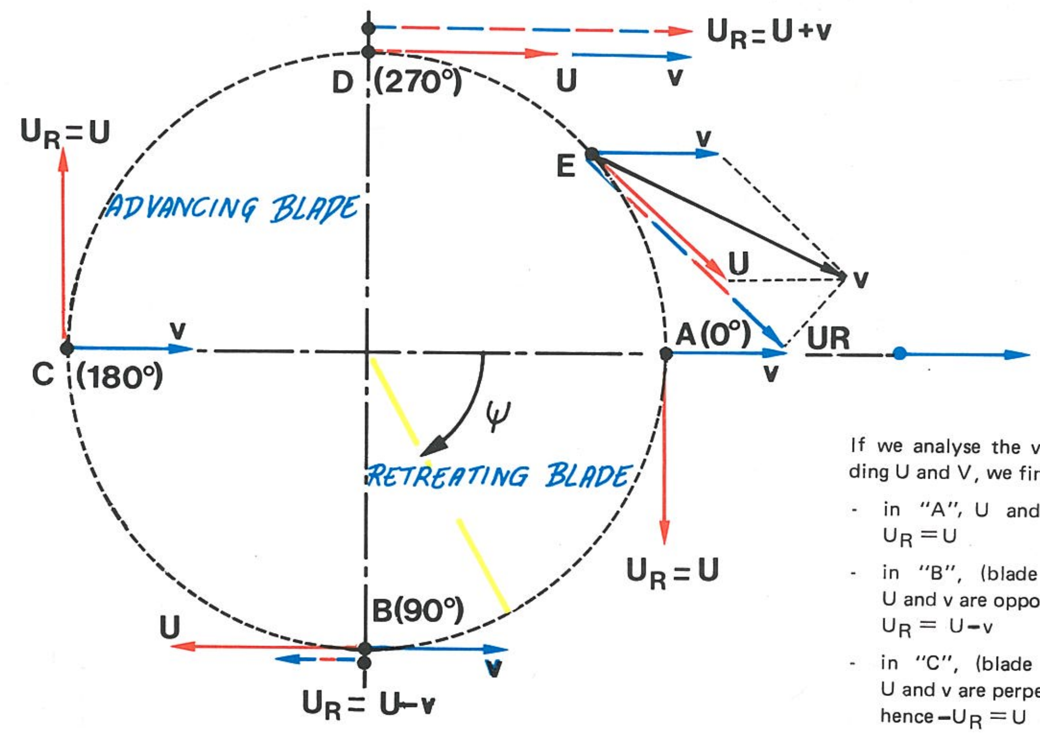
RELATIVE SPEED OF BLADES



In forward flight, the blade tip speed "U" is compounded with the forward speed "v". The resultant speed "V" has a tangential component "U_R", which is the relative blade tip speed. The relative air velocity V_R is, obviously, equal to this speed but opposite in direction. You will see that U_R varies according to ψ (blade azimuth).

VARIATION OF RELATIVE BLADE SPEED (VR) ON A ROTOR IN FORWARD FLIGHT



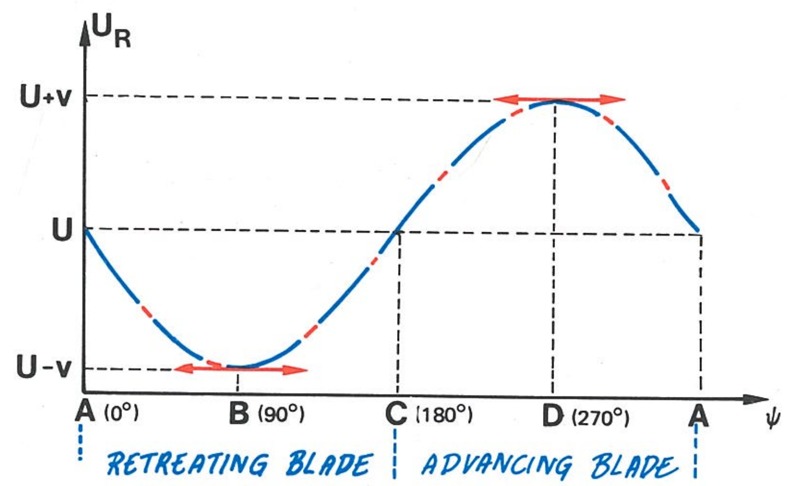


If we analyse the variation of U_R, by compounding U and V, we find that :

- in "A", U and v are perpendicular, hence $U_R = U$
- in "B", (blade has moved 90°), velocities U and v are opposite $U_R = U - v$
- in "C", (blade has moved 180°) velocities U and v are perpendicular : hence $-U_R = U$
- in "D", (blade has moved 270°), velocities U and v are aligned and in the same direction, hence $U_R = U + v$
- in "E", (any point between D an A) : $U < U_R < U + v$ therefore, from D to A, the velocity decreases.

It could be possible to plot the speeds point by point. But the 5 points analyzed are sufficient for understanding that :

- U_R has a maximum value in D (advancing blade)
- U_R has a minimum value in B (retreating blade)
- from D to B, U_R decreases
- from B to D, U_R increases
- U_R has a mean value (u) in A and B.

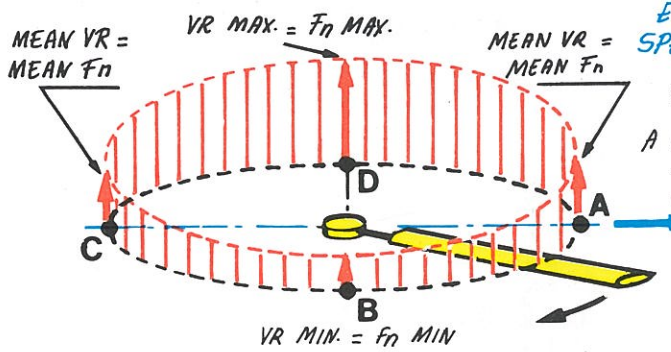


These results may be illustrated by a curve showing the continuous variation of U_R versus ψ

REMEMBER :
$U_R = V_R$

RELATIVE SPEED VARIATION = CYCLIC VARIATION OF BLADE LIFT

We are going to review the effects of this lift variation on a ROTOR NOT ARTICULATED IN THE FLAPPING PLANE, and this will allow you to understand the imperative need for flapping hinges. Let us recall that a blade not articulated in the flapping plane cannot move (flap) upward under the action of the forces applied to it. It constitutes a rigid system with the rotor head and transmits to the latter the loads it is subjected to.



EFFECT OF RELATIVE SPEED (VR) VARIATION

$Fn = 1/2\, \rho . VR^2 . S . Cz$

A VARIATION OF VR CAUSES A VARIATION OF Fn

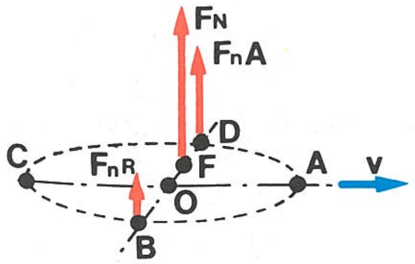
Let us follow one of the rotor blades, operating at speed "v" during a complete rotation, in forward flight.

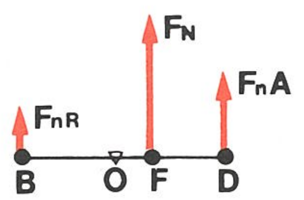
- in "B", speed V_R is at its minimum value ($V_R = U_R = U - v$), lift (F_n) is minimum
- from B to C, F_n increases, it is at its maximum value in "D", where V_R is maximum ($V_R = U_R = U + v$).

  from D to B, F_n decreases. In "C" and "A", F_n is at a mean value.

It can be seen that F_n varies regularly and that at every revolution it has the same value at the same azimuth. It is said that the variation of F_n is cyclic.

FIRST EFFECT OF THE BLADE LIFT VARIATION ON A ROTOR NOT ARTICULATED IN THE FLAPPING PLANE.





$FnR \times FB = FnA \times FD$

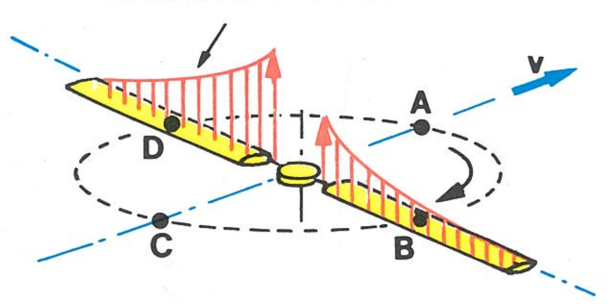
Lift (F_n) variation creates dissymmetry, particularly at positions "B" (where F_n is minimum) and "D" (where F_n is maximum). Obviously in these conditions, the resultant F_N (rotor lift) is no longer applied at the center of rotation "O" but in "F" (advancing blade side). THE MOMENT OF "F_N" IN RELATION TO "O" GENERATES A ROLLING MOTION : LATERAL TILTING OF THE ROTOR AND OF - - - THE AIRCRAFT

LATERAL LIFT DYSSYMMETRY GENERATES A ROLLING MOTION WHICH MAKES IT IMPOSSIBLE TO CONTROL A HELICOPTER EQUIPPED WITH A FLAP RIGID ROTOR

Note that the rolling motion increases as the forward speed (v), because the relative speed dissymmetry (hence, the lift dissymmetry) increases as the forward speed.

SECOND EFFECT OF THE BLADE LIFT VARIATION ON A ROTOR NOT ARTICULATED IN THE FLAPPING PLANE

DISTRIBUTION OF BENDING MOMENT



The lack of flapping hinges creates (as already stated) a very large bending moment at the blade root end. Things get worse when, in forward flight, the blade lift varies at every revolution. Let us follow a blade during its rotation. In "D", where lift F_n is maximum, the bending moment is also at its maximum value. In "B", where lift is minimum, the bending moment is minimum. This means that at every revolution the mechanical stresses, at the blade root end, are going to vary as blade lift "F_n"..... from maximum to minimum to maximum. These stresses which reverse about a mean value are called ALTERNATING stresses.

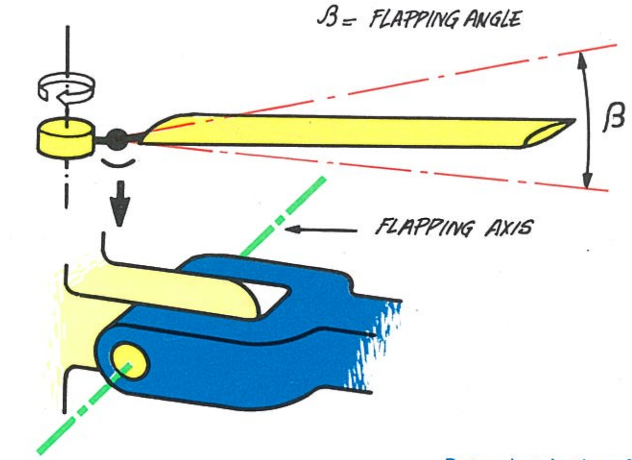
Now, when there are alternating stresses we have FATIGUE of the materials and, therefore a RISK OF FAILURE.

(we will come back to this).

THE FLAPPING HINGE

OR

HOW TO REMEDY THE EFFECTS OF LATERAL LIFT DISSYMMETRY

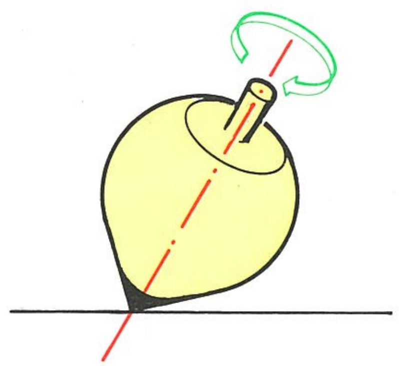


With the flapping hinge, the blade can MOVE in the vertical plane, that is go up or down under the action of the resultant of lift and centrifugal forces, with which it aligns itself (we have studied this). Likewise, we have seen that the flapping hinge cancels the bending moment at the blade root end.

But, what is the effect of the flapping hinge on the rolling moment due to the lateral lift dissymmetry ?

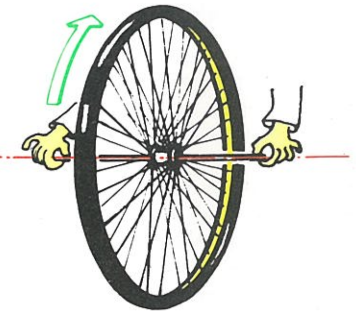
Here we must talk of the gyroscope. Before beginning the study of flapping, let us make a little digression. The blades of a rotor when subjected to a cause (speed or pitch variation) tending to modify their lift, behave like a gyroscope.

THE BLADE'S VERTICAL FLAPPING CAUSES AN AUTOMATIC VARIATION OF THE BLADE PITCH WHICH COMPENSATES THE LATERAL LIFT VARIATION.



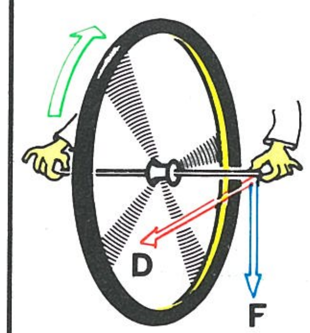
A SPINNING TOP IS A GYROSCOPE

A gyroscope is a rotating body, the rotation axis of which is free to move in all directions.



A bicycle wheel is a gyroscope, provided the hands holding the spindle leave it free to move in all directions.

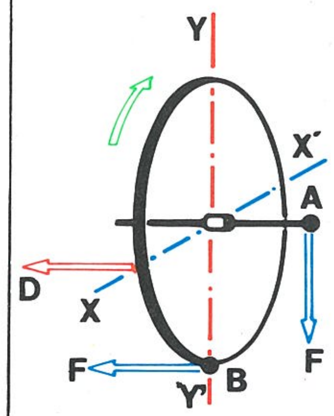
A gyroscope seems to have an independent spirit. It is a strange and provoking beast. It reacts unexpectedly when we attempt to change the direction of its axis.



The bicycle wheel, for example (of course, it should be rotating) : If we attempt to tilt its axis by applying a force "F", a resistance is felt in that direction.

● The wheel does not obey. On the contrary, it reacts immediately, driving the hands holding the spindle in direction "D" which is perpendicular to the direction of force "F". It is just as if force "F" was acting in direction "D"

The axis displacement in direction "D" is called "precession". The phenomenon offsetting the effect (axis displacement) from its cause (force applied on the axis) is due to the gyroscopic inertia forces.

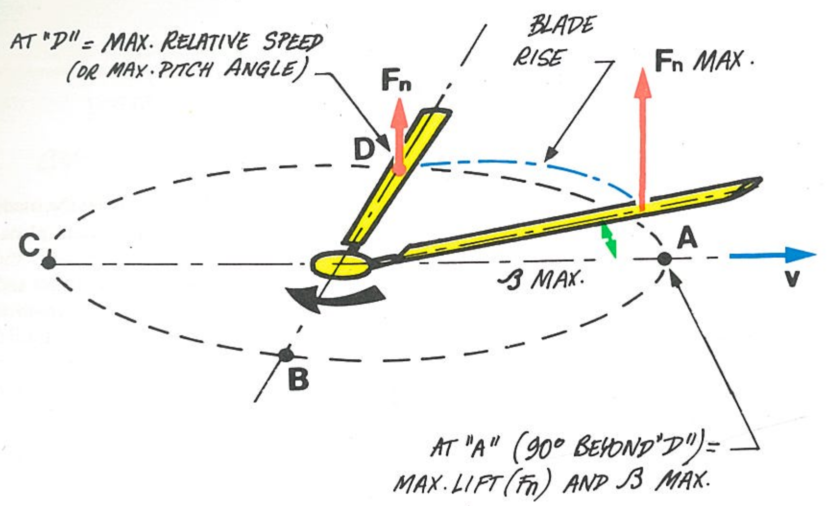


Let us examine this phenomenon :

● F is the action tending to tilt the wheel about the horizontal axis xx'. F may be applied in A or B (it is the same thing).

● D is the counter-reaction of the wheel which is going to rotate about the vertical axis YY' and not about XX' as it should.

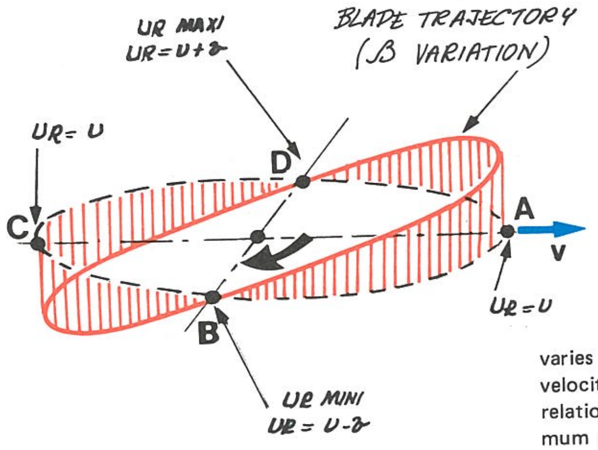
● Both axes 'XX'-FF' are perpendicular to each other, hence, the counter-reaction (the effect) occurs (and always occurs) 90° AFTER the action (the cause).

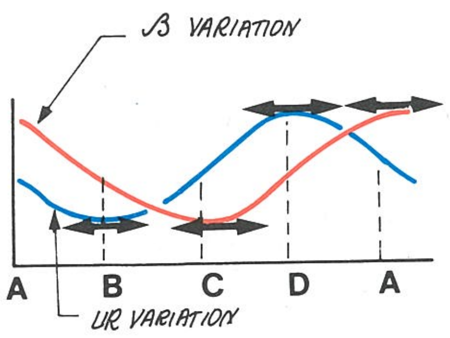


It is the same for a rotor blade which "reacts" 90° after the cause tending to change the lift. For example, if the relative spped (or pitch) is at the maximum value at "D" (this is the cause), the lift F_n (which is the effect) is not maximum at "D", but at "A", i. e. 90° beyond the point of maximum speed (or pitch). The blade being articulated in the flapping plane, the point of maximum lift "A" corresponds to the maximum blade rise (maximum flapping angle β). From D to A, the blade follows a rising trajectory.

If you have understood this simple principle : -an offset of 90° between cause and effect — the helicopter rotor has no longer any secret for you (well ! almost none). Finished the brain racking, and while it is warm.....let us continue.

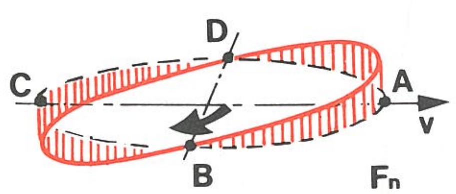
TRAJECTORY OF BLADES SUBJECTED TO LATERAL LIFT VARIATION



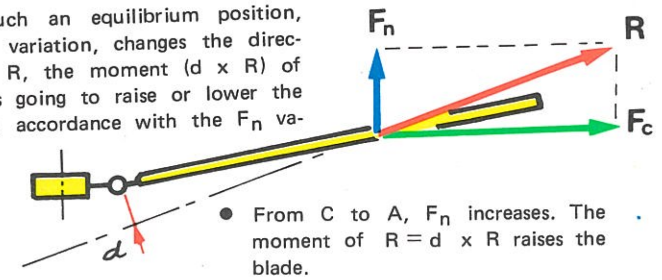


We have seen that from D to B, the velocity goes from a maximum to a minimum value and from B to D, it varies from minimum to maximum value. Effect of velocity variation : the blade rise (delayed over 90° in relation to the cause : velocity) goes through a maximum at A and through a minimum at C – From C to A, the blades rises – from A to C, it descends.

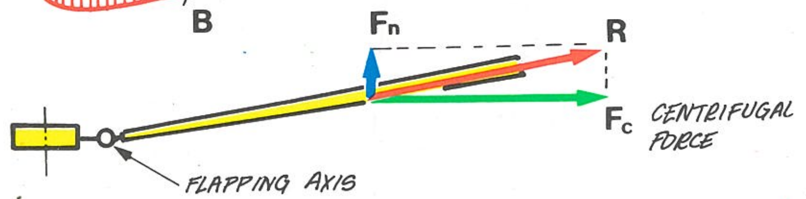
ANALYSIS OF BLADE FLAPPING



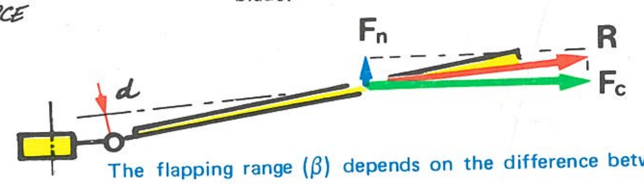
From such an equilibrium position, any F_n variation, changes the direction of R, the moment (d x R) of which is going to raise or lower the blade in accordance with the F_n variation.



- From C to A, F_n increases. The moment of R = d x R raises the blade.



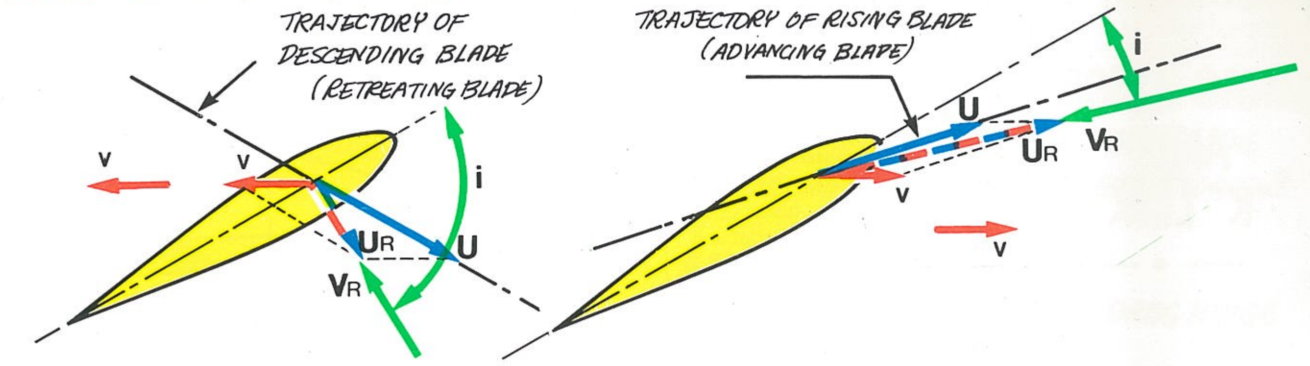
- From A to C, F_n decreases. The moment of R = d x R lowers the blade.



Do you remember the blade equilibrium conditions ? For a given value of F_n, the flapping motion stops when R (resultant of F_n and centrifugal force F_c) passes through the flapping axis. The moment of R is then equal to zero.

The flapping range (β) depends on the difference between F_n max. and F_n min.

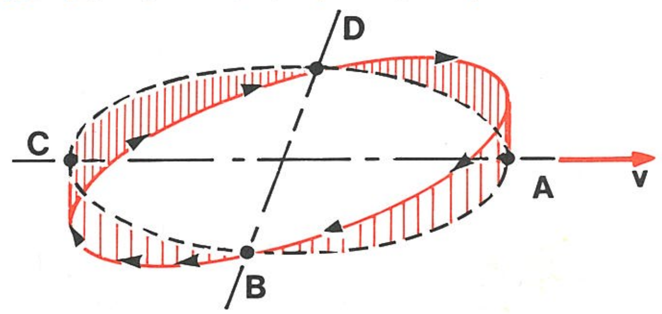
EFFECT OF FLAPPING ON BLADE PITCH



When the blade FLAPS, its tangential speed "U" (of course, aligned with the rising or descending trajectory) forms an angle with the forward speed "V", which is always horizontal.

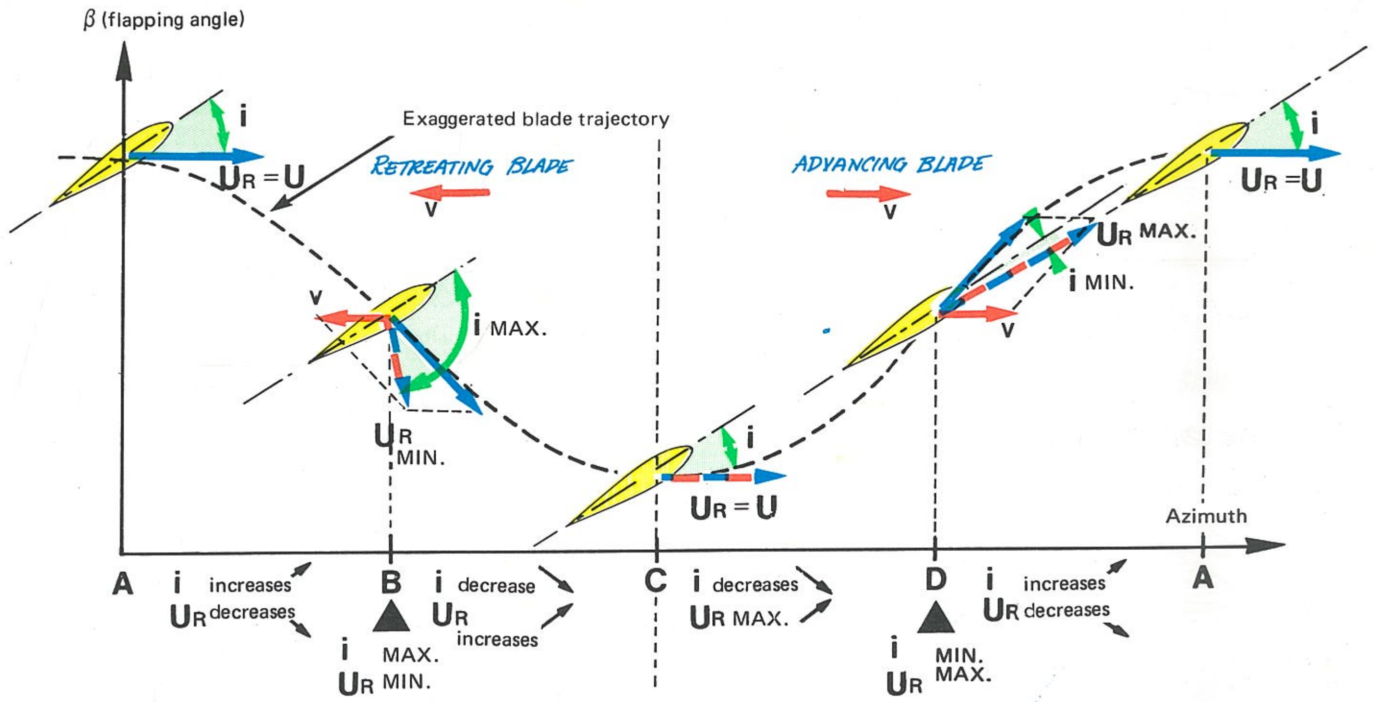
The resultant relative speed U_R definies in direction and magnitude the relative wind speed V_R which is of equal value but opposite. The direction of U_R (or V_R) determines the blade angle of attack (i). It may be seen already that the angle of attack of the descending blade (retreating blade) is greater than that of the rising blade (advancing blade).

PITCH VARIATION ACCORDING TO FLAPPING



If we follow a blade over a complete revolution, we note that the angle of attack "i".

- is MAXIMUM at point "B", where velocity U_R is at the MINIMUM value.
- is MINIMUM at point "D", where velocity U_R is at the MAXIMUM value.
- increases progressively from D to B.
- decreases progressively from B to D.



It is noted that "i" and U_R always vary in opposite direction : if "i" increases, U_R decreases (and inversely). The blade lift (F_n) varying in the same direction as "i" and U_R, the effect of the "i" and U_R variations is cancelled : EFFECT OF "I" + EFFECT OF U_R = ZERO. BLADE LIFT IS CONSTANT IN AZIMUTH. The flapping hinges cancel the lateral lift dissymmetry.

DRAG HINGE AND "K" LINK

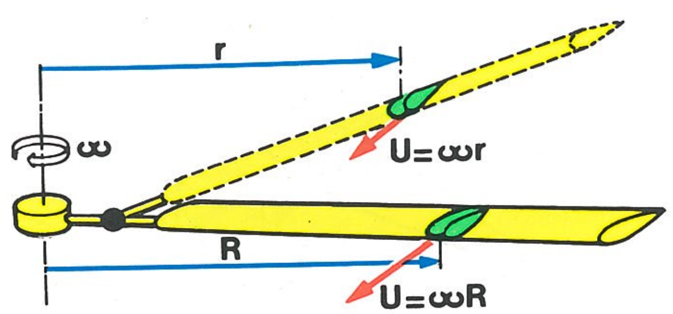
or the harmful effects of blade flapping.

Blade flapping is a necessary evil :

- necessary because as we have seen, we cannot do without it. Without flapping : excessive vertical bending stresses at blade root end and a lateral lift dissymmetry making the helicopter uncontrollable.
- an evil, since blade flapping creates, at the blade root end, in the rotation plane, alternating horizontal stresses leading to FATIGUE.

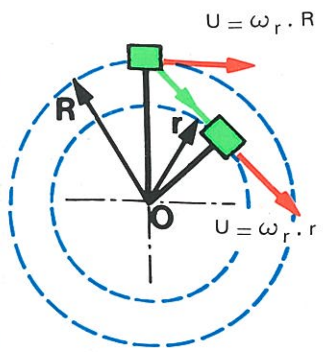
We are going to review these stresses and their remedy : The DRAG HINGE. We will also talk of a way to allow some reduction in flapping : the "K" LINK

EFFECT OF FLAPPING ON A BLADE ELEMENT TANGENTIAL VELOCITY "U"



When a blade FLAPS, the circular trajectory of any blade element is modified. Its radius decreases when the blade rises (it changes from R to r) or increases when the blade descends (it changes from r to R). The tangential velocity "U" varies as the radius. It changes from $U = \omega R$ to $U = \omega r$ when the blade rises and from $U = \omega r$ to $U = \omega R$ when the blade descends.

EFFECT OF VARIATION OF VELOCITY "U" WHEN THE BLADE RISES.



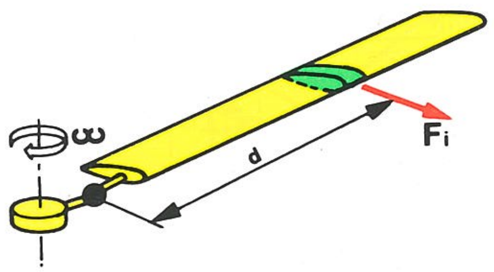
DUE TO INERTIA, THE BLADE ELEMENT TENDS TO MAINTAIN ITS INITIAL VELOCITY "U" DURING THE TRAJECTORY CHANGE

- When the blade rises, the blade element changes from the trajectory having a radius R to that of radius "r". It tends to maintain its initial velocity $U = \omega_R.R$, that is to assume a higher angular velocity ω_r so that

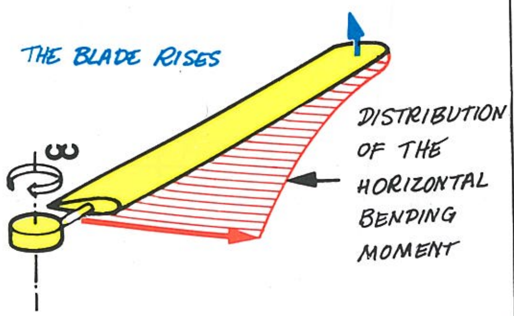
$$\omega_R . R = \omega_r . r$$

$$\omega_r > \omega_R$$

BUT...



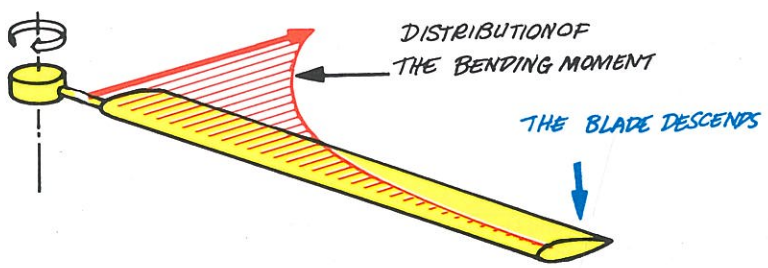
.....The blade element is LINKED rigidily to the blade and rotor both having a constant velocity "ω". Therefore, its angular velocity cannot vary and the inertia force "F_i" (tending to increase the angular velocity), which cannot act as a dynamic force becomes a static load generating a maximum bending moment at the blade root (M = d. Fi).

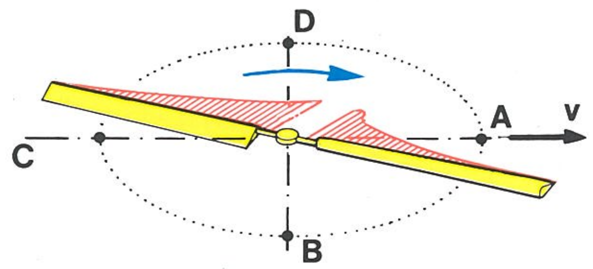


Thus, there is an inertia force F_i acting on each blade element. These forces create a resultant bending moment tending to twist the blade in the direction of rotation.

EFFECT OF VARIATION OF VELOCITY "U" WHEN BLADE DESCENDS

The same reasoning shows that when a blade descends, the trajectory radius of the blade element increases (it changes from "r" to "R") and the angular velocity tends to decrease. Therefore, there is an inertia force "F_i" and a bending moment tending to twist the blade in a direction opposite to the direction of rotation.





Thus a blade making a complete revolution is subjected :

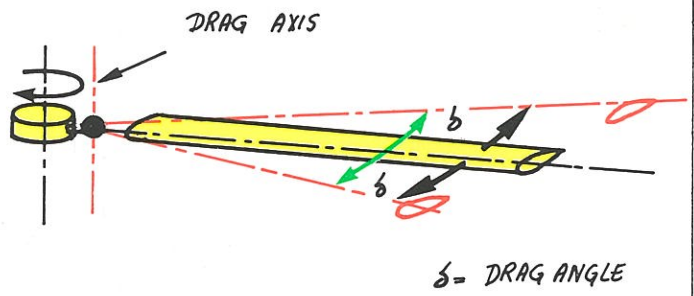
- from C to A, when it is rising (advancing blade), to a bending moment directed forward.
- from A to C, when it is descending (retreating blade) to a bending moment directed rearward.

This result is ALTERNATING bending loads which generate fatigue, particularly at the blade root end where stresses are maximum .

THE ALTERNATING INERTIA FORCES CAUSED BY THE BLADE'S VERTICAL FLAPPING, AND WHICH ACT ON THE BLADES IN THE PLANE OF ROTATION, ARE CALLED **CORIOLIS FORCES**

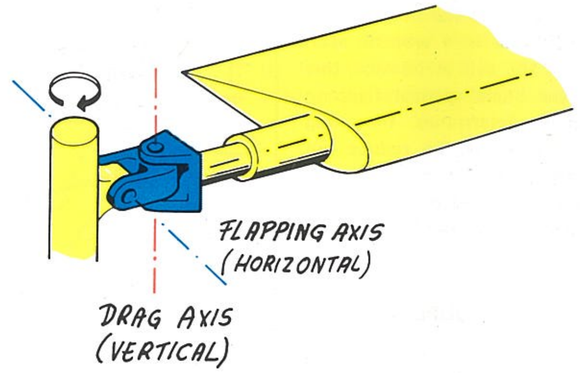
HOW CAN WE CANCEL THE EFFECT OF THE CORIOLIS FORCES?

THE DRAG HINGE

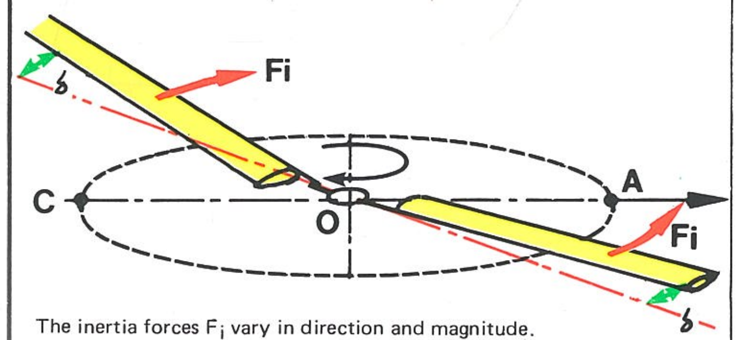


The drag hinge allows the blade, on which CORIOLIS forces are acting, to oscillate horizontally about a mean position. This degree of freedom cancels the bending moment at the blade root end.

This is a combined drag and flapping hinge.



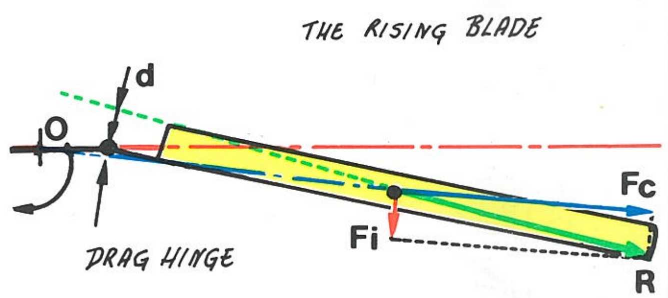
MECHANICS OF DRAG OSCILLATIONS



The inertia forces F_i vary in direction and magnitude.

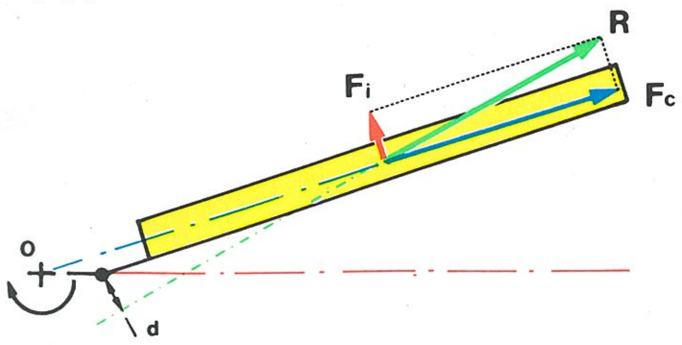
- From C to A, the blade rises. Inertia force "F_i" acting in the direction of rotation, causes the blade to oscillate in the forward direction.
- From A to C, the blade descends. Inertia force "F_i", acting in the opposite direction to the direction of rotation, causes the blade to oscillate towards the rear.
- At A and C, the blade is in a mean position ($F_i = 0$; $\delta = 0$)

RANGE OF DRAG OSCILLATIONS



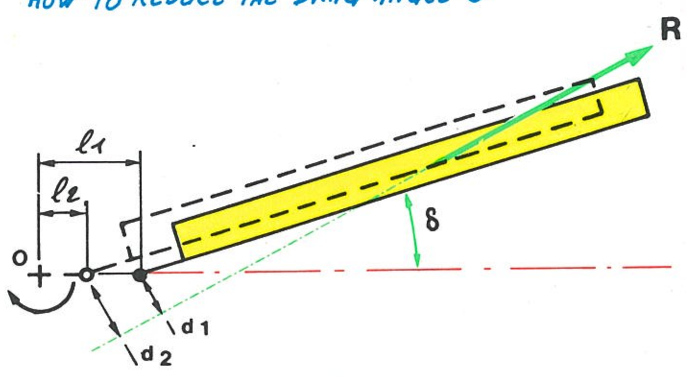
In the plane of rotation, the blade is subjected to centrifugal force (F_c), of constant magnitude and inertia force (F_i) varying in direction and magnitude. The resultant "R" of these forces generates a moment d x R which causes the blade to oscillate in the forward direction. The oscillation stops when 'R' passes through the drag hinge. The moment of R is then equal to zero.

THE DESCENDING BLADE



Likewise, when the blade is descending, the oscillation stops when the moment of R is equal to zero (d = 0).

HOW TO REDUCE THE DRAG ANGLE δ

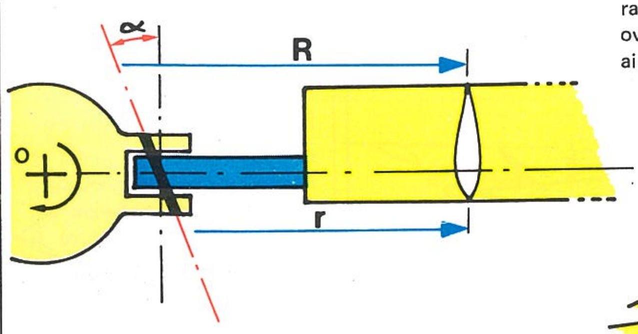


The drag hinge position relative to the centre of rotation "O" (offset "ℓ") determines the value of δ. In fact, the smaller "ℓ" the greater is δ, since the lever arm (d) of resultant R varies in the opposite direction to "ℓ". It is a way of reducing the magnitude of the alternating drag oscillations which, by disturbing the rotor equilibrium, generate large horizontal vibrations.

To attenuate the drag oscillation there is a way of attacking the evil at its root, this is the blade vertical flapping which determines the drag inertia forces. To reduce the drag inertra forces, it is sufficient to reduce the flapping range β This is achieved with the

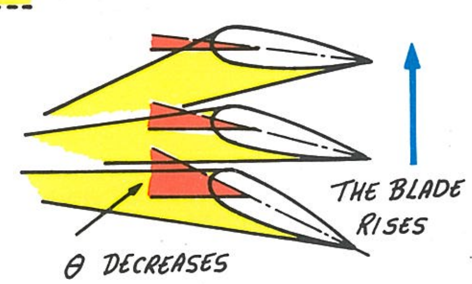
"K" COUPLING

THE "K" COUPLING



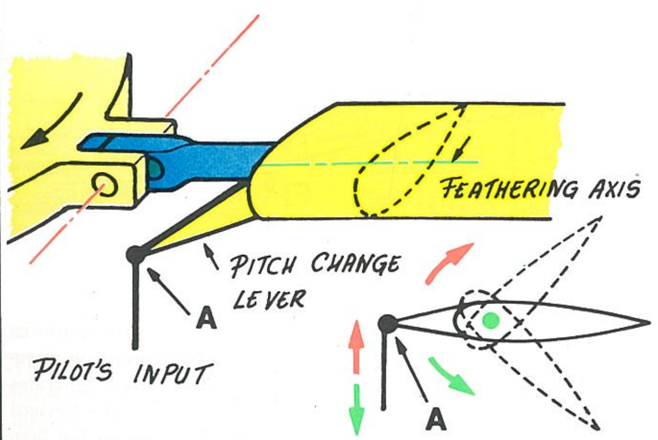
It is said that there is a "K" coupling when the flapping axis is not perpendicular to the blade longitudinal axis but is set at an angle α to the perpendicular so that when the blade rises, the pitch angle (hence, the angle of attack) decreases, reducing the blade lift (F_n), and hence the blade rise β.

When the blade rises, the trailing edge of a blade section describes an arc, having a radius R, while the leading edge moves over a smaller arc (of radius "r"). The airfoil tilts forward, θ decreases.



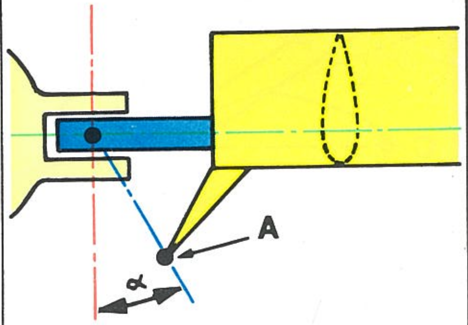
An other form of "K" coupling.

The same result is achieved by pitch control.



The blade, activated by a pitch change lever controlled by the pilot, can rotate around its longitudinal axis (feathering axis).

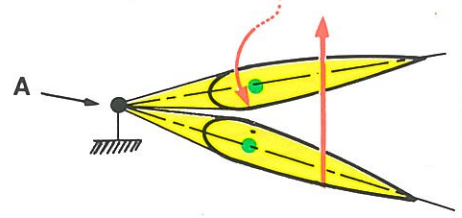
Actuation of the pitch change lever modifies the pitch angle value. Point A is fixed, unless there is pilot input.



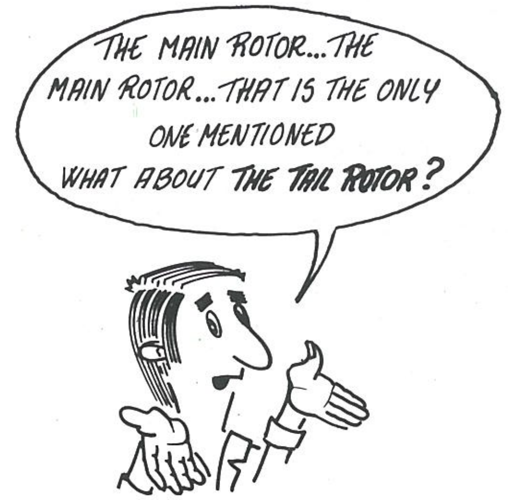
If point A is offset relative to the flapping axis (making an angle α with this axis) there is a pitch/flapping coupling ("K" coupling).

WHEN THE BLADE RISES ...

... THE PITCH DECREASES



In fact, point A being fixed, the rising blade is going to rotate about its feathering hinge in the pitch decrease direction.



My dear AERODYNAMIX, for the tail rotor it is the same thing, except :
— It operates in a vertical plane,
— the forces involved (and the stresses) are much smaller.
— it has flapping hinges (the "K" coupling is sufficient to limit the stresses, drag wise, to an acceptable level),
— it has a collective pitch control only (no cyclic pitch variation)

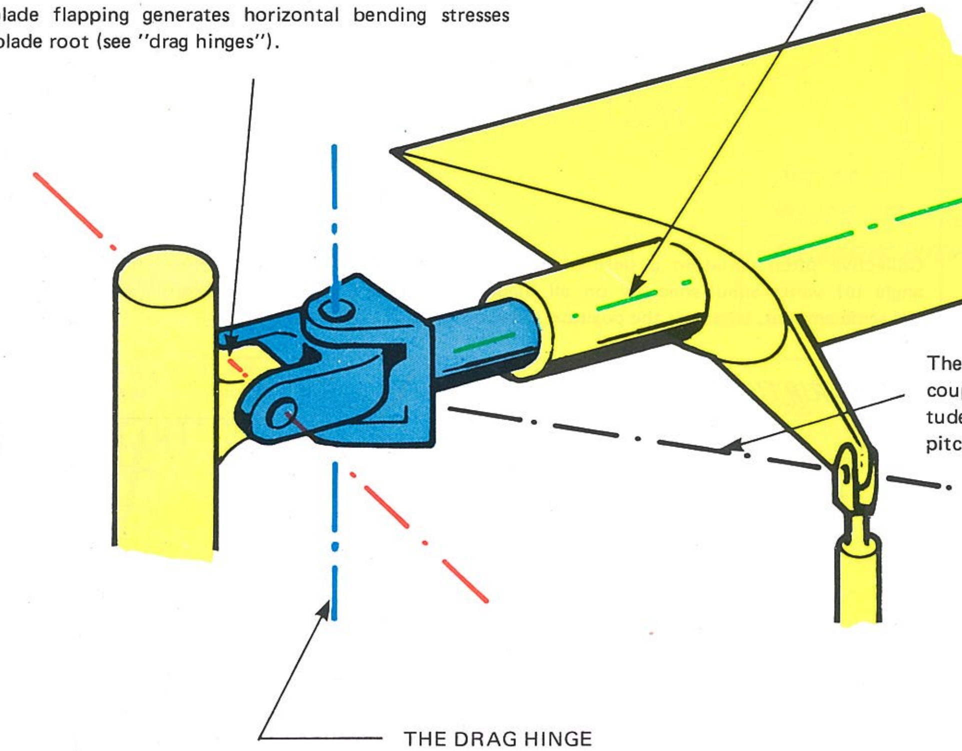
But, do not be sorry, AERODYNAMIX, we will come back to the role of the tail rotor.

TO CONCLUDE:

THE FLAPPING HINGE :
— cancels the vertical bending stresses at the blade root.
— in forward flight, compensates the lift dissymetry between advancing and retreating blades.

But, blade flapping generates horizontal bending stresses at the blade root (see "drag hinges").

Using the FEATHERING HINGE, it is possible to change the pitch angle by rotating the blade around its longitudinal axis (or feathering axis). This is under the pilot's control.



The "K" COUPLING (pitch/flapping coupling) reduces the flapping amplitude (β). When the blade rises, the pitch angle (β) decreases.

THE DRAG HINGE
— cancels the horizontal stresses resulting from blade flapping.

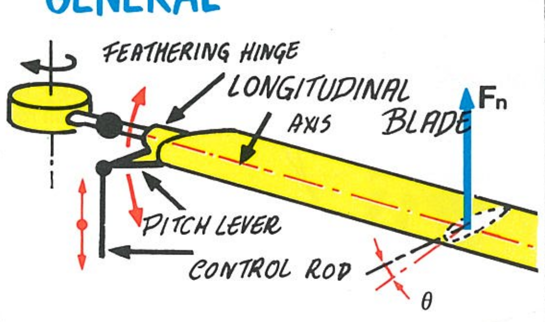
But, the alternating blade oscillations, about the drag axis, upset rotor equilibrium (hence, vibrations). To reduce the blade drag angle (δ), one solution is to reduce the flapping angle (β) which is the cause (see "K" COUPLING).

4. ROTOR LIFT CONTROL

OR THE CONTROLLED VARIATION OF BLADE PITCH ANGLE

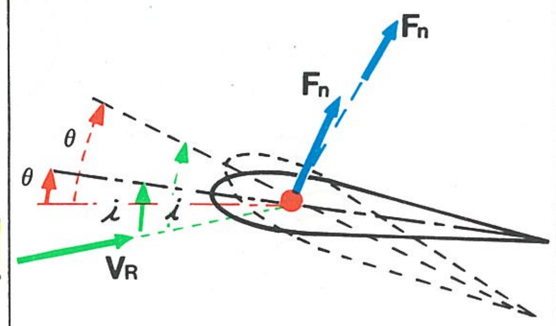
Whether Aerodynamix likes it or not, we will again talk of the main rotor.

GENERAL



We have seen that the pilot has only one means of controlling rotor lift in magnitude and direction.

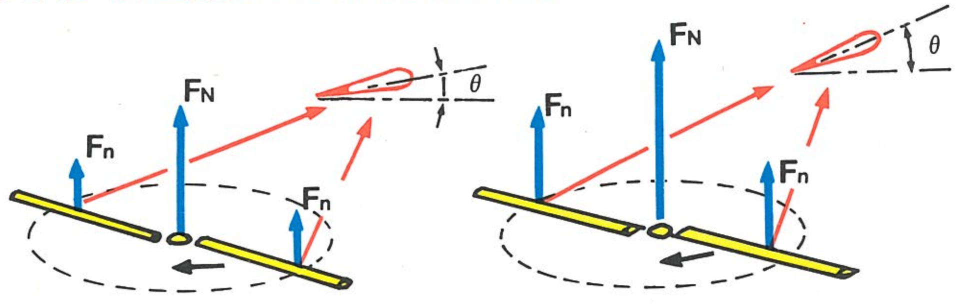
CHANGING PITCH (θ) through rotation of the blade around its longitudinal axis.



Variation of pitch θ = variation of angle of attack i = variation of lift F_n.
These three values vary together.

THE CONTROL OF ROTOR (F_N) AMPLITUDE IS OBTAINED BY THE COLLECTIVE VARIATION OF PITCH
THE DIRECTION CONTROL OF F_N IS OBTAINED THROUGH CYCLIC VARIATION OF PITCH

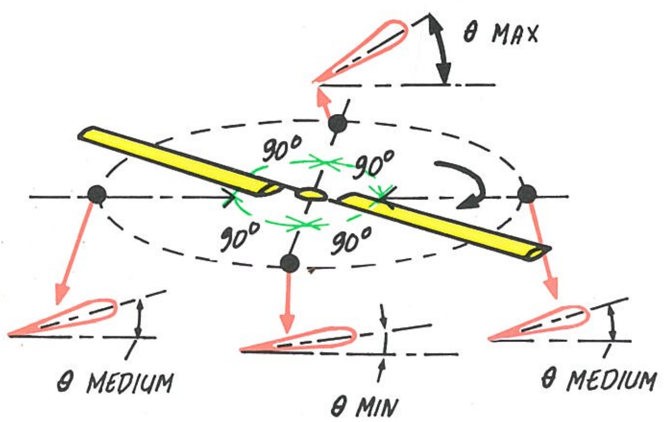
PRINCIPLE OF COLLECTIVE PITCH VARIATION



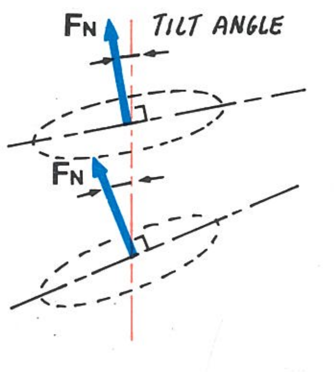
Collective pitch variation is defined when pitch angle (θ) varies simultaneously on all blades by the same amount, whatever the position in azimuth

Collective pitch variation tends to vary the magnitude of F_N but has no effect on the direction.

PRINCIPLE OF CYCLIC PITCH VARIATION

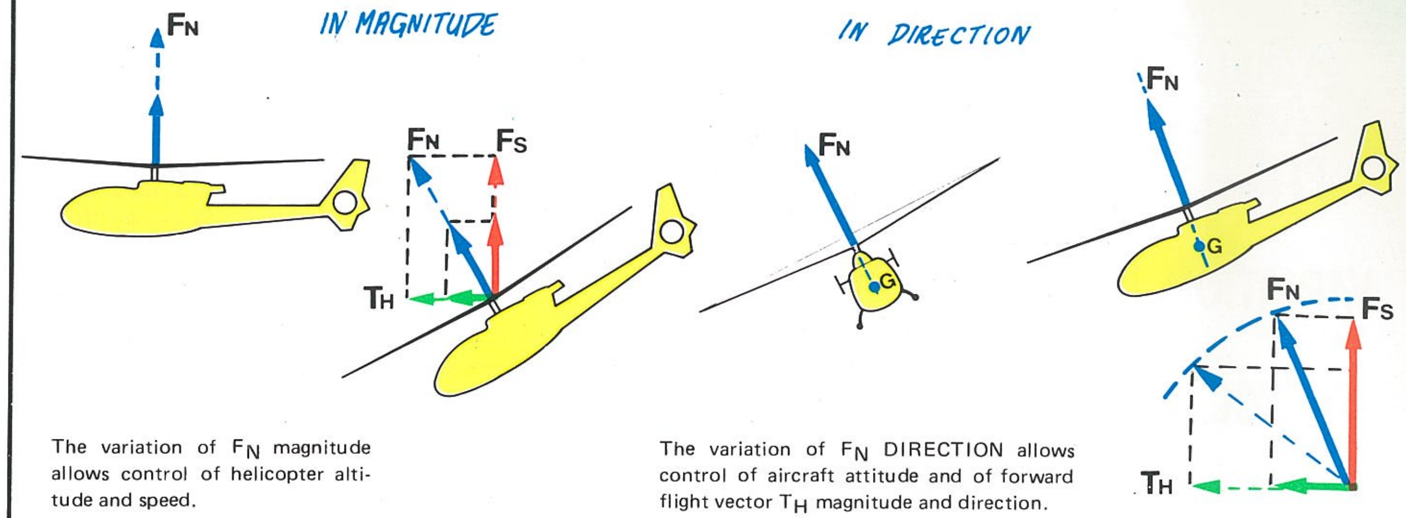


There is cyclic pitch variation when pitch angle θ varies in relation to azimuth from a maximum to a minimum value over a complete revolution of a blade (for each blade). The extreme values are obtained at opposite azimuth. The cyclic variation of pitch (controlled by the pilot) leads obviously to a cyclic variation of blade lift. The plane of rotation of the rotor becomes more inclined as the difference θ max − θ min increases.



The cyclic pitch variation changes the direction of F_N (which remains normal to the plane of rotation) but has no effect on its magnitude.

WHY MUST F_N VARY?



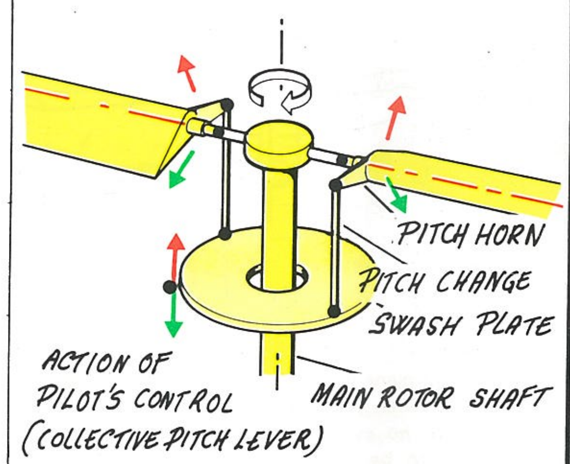
The variation of F_N magnitude allows control of helicopter altitude and speed.

The variation of F_N DIRECTION allows control of aircraft attitude and of forward flight vector T_H magnitude and direction.

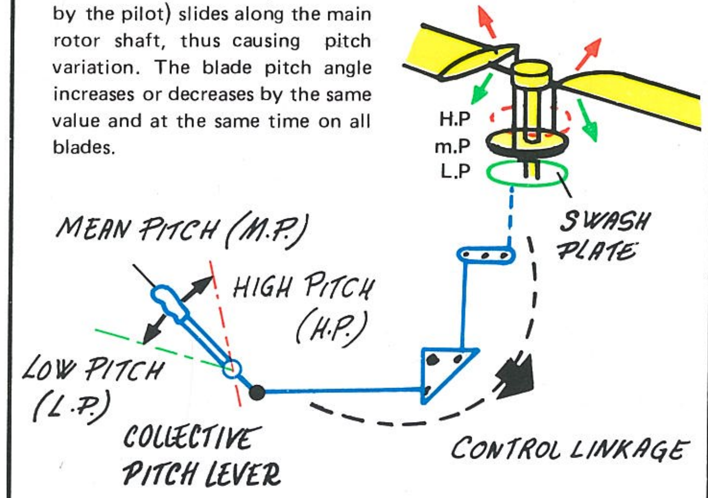
DON'T BE SO HOT HEADED AERODYNAMIX YOU ARE GOING TOO FAST... BE PATIENT... AND READ WHAT FOLLOWS!

COLLECTIVE PITCH θ VARIATION

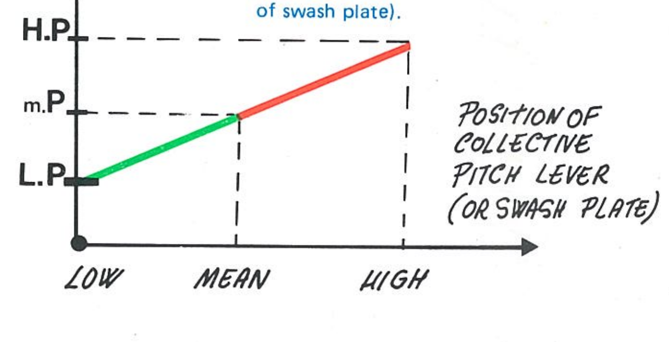
The mechanics of the collective pitch variation. The principle is very simple.



The swash plate, actuated by the collective pitch lever (controlled by the pilot) slides along the main rotor shaft, thus causing pitch variation. The blade pitch angle increases or decreases by the same value and at the same time on all blades.



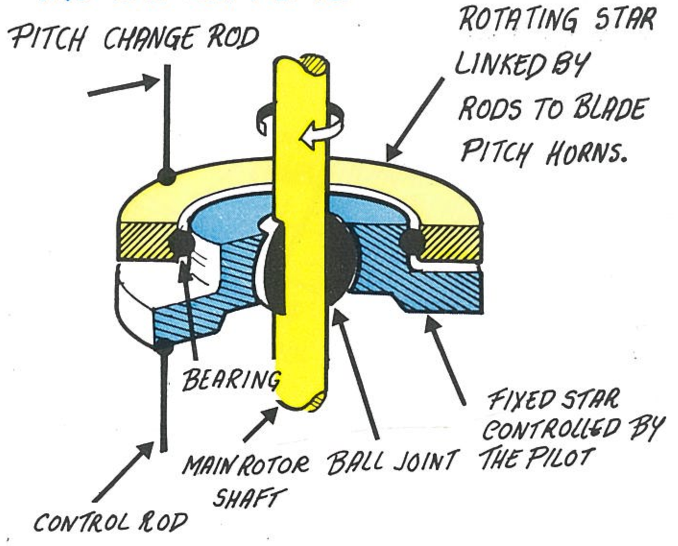
This diagram shows how the collective pitch θ varies as the control is operated. (Position of collective pitch of lever or of swash plate).



MAGNITUDE OF COLLECTIVE PITCH
L.P. = 6°
H.P. = 18°

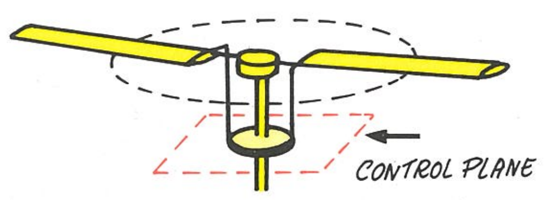
CYCLIC PITCH VARIATION (θ CYCL.)

THE SWASH PLATE



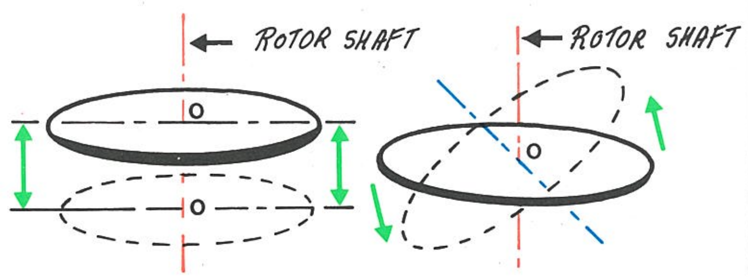
The swash plate is the essential component for cyclic pitch variation. In fact, this is a control plate which not only slides along the rotor shaft (when the collective pitch lever is operated), but may oscillate IN ALL DIRECTIONS about its sperical bearing. The oscillations of the swash plate, controlled by the pilot (CYCLIC STICK) are the basis of cyclic pitch variation.

THE CONTROL PLANE



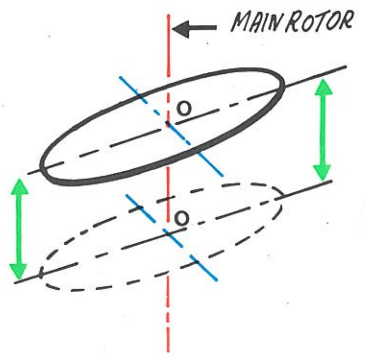
The control plane is the plane in which the swash plate is contained. When the swash plate is normal to the main rotor shaft, no cyclic variation occurs. So the control plane has to be tilted to generate a cyclic variation.

MOVEMENT OF SWASH PLATE



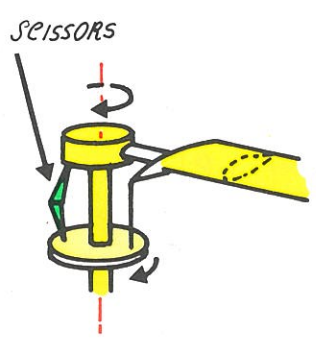
Collective pitch variation : controlled by the collective pitch lever, the swash plate slides along its own axis. No cyclic variation occurs; the control plane remains normal to the rotor shaft.

Controlled from the cyclic stick, the swash plate oscillates about its centre "O". The control plane is no longer normal to the rotor shaft : cyclic variation occurs.

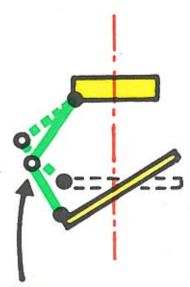


COMBINED MOVEMENTS : This is the most usual case. The collective pitch variation is added onto the cyclic variation.

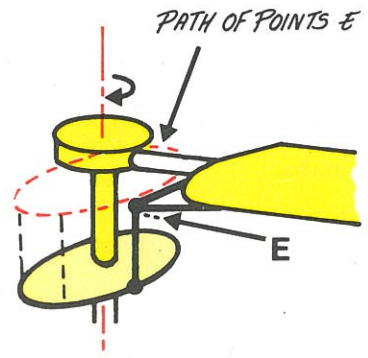
MECHANICS OF CYCLIC PITCH VARIATION



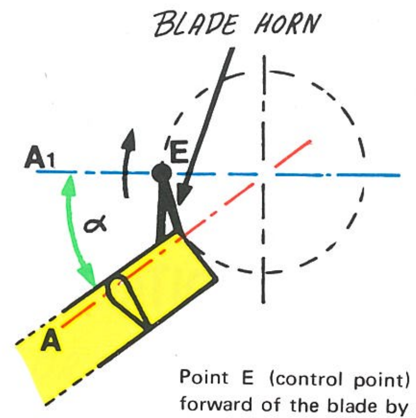
The rotating star of the swash plate is driven in rotation by the rotor hub through scissors.



The scissors center hinge allows freedom of movement to the swash plate.

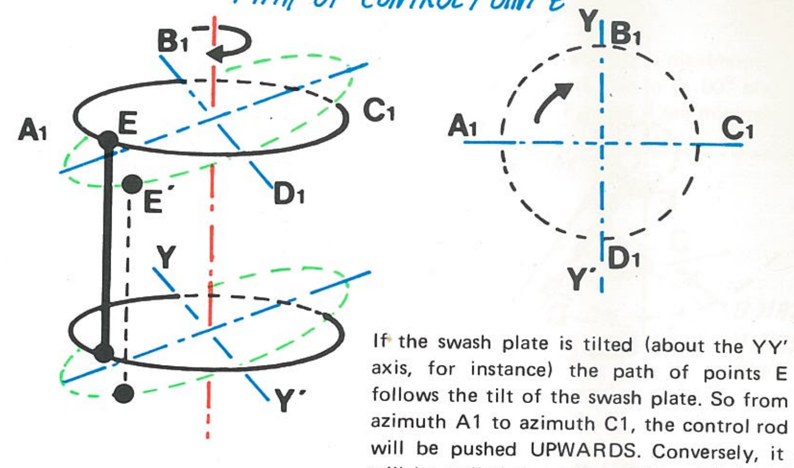


Each blade horn is connected to the swash plate by a pitch change rod. It can be seen that point E follows a path controlled by the tilting of the swash plate.



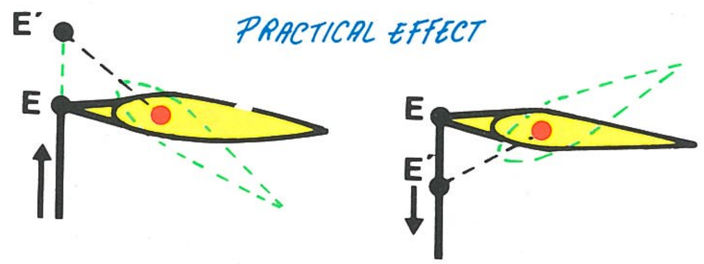
Point E (control point) is offset forward of the blade by means of the blade horn. So when the blade is said, in azimuth A, point E is in azimuth A1 - As a result, an action in A1 on blade horn produces a pitch variation in the blade located in A.

EFFECT OF SWASH PLATE TILT ON THE PATH OF CONTROL POINT "E"



If the swash plate is tilted (about the YY' axis, for instance) the path of points E follows the tilt of the swash plate. So from azimuth A1 to azimuth C1, the control rod will be pushed UPWARDS. Conversely, it will be pulled down from C1 to A1.. In B1 and D1 the control rods retain their initial position.

PRACTICAL EFFECT

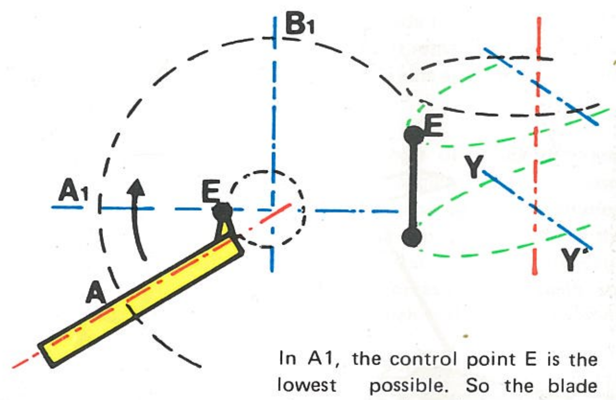


From A1 to C1 the control rods are pushed upwards :
THE PITCH INCREASES

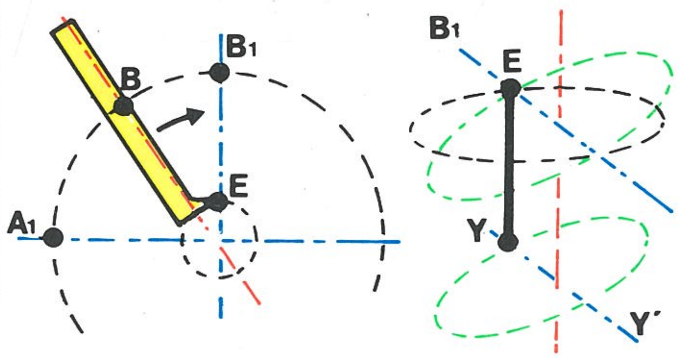
From C1 to A1 the control rods are pulled downwards :
THE PITCH DECREASES

THE TILT OF THE SWASH PLATE PRODUCES A CYCLIC PITCH VARIATION

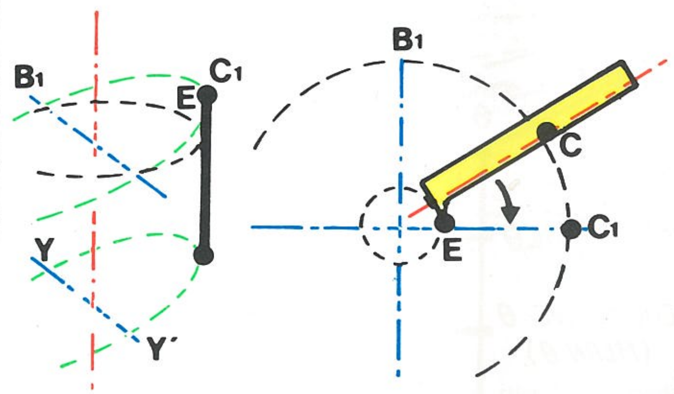
Let us examine this a bit closer, by following a blade through a complete revolution.



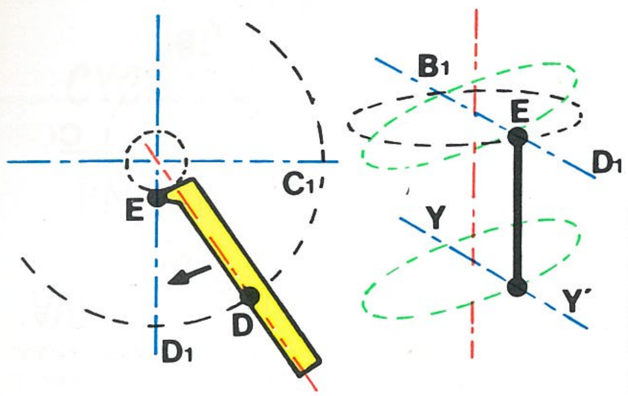
In A1, the control point E is the lowest possible. So the blade pitch angle (in A) is minimum (θ cycl. min.)



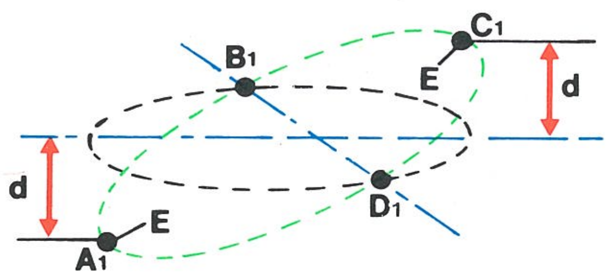
90° after A1, the control point E is over B1 corresponding to a middle position. It even be seen that in B1, the swash plate tilt has no effect, so the blade pitch (in B) will be the previous collective pitch.
In B = medium θ = collective θ



In C1, where half a revolution has been made, the control point is the highest possible. So the blade pitch angle (in C) is maximum. (MAX. Cyclic θ)

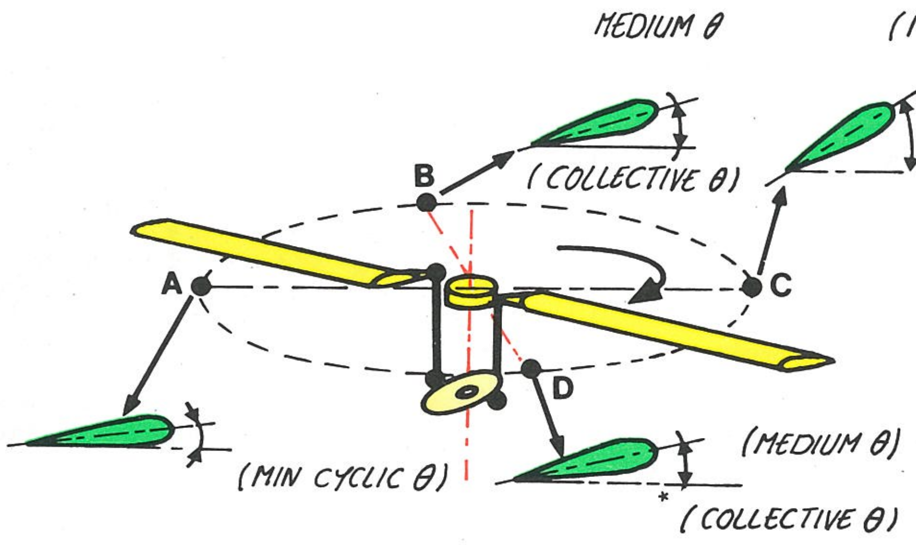


In D1 (as in B1) there is no cyclic variation effect. The blade pitch (in D) is at its medium value, that of the collective pitch.

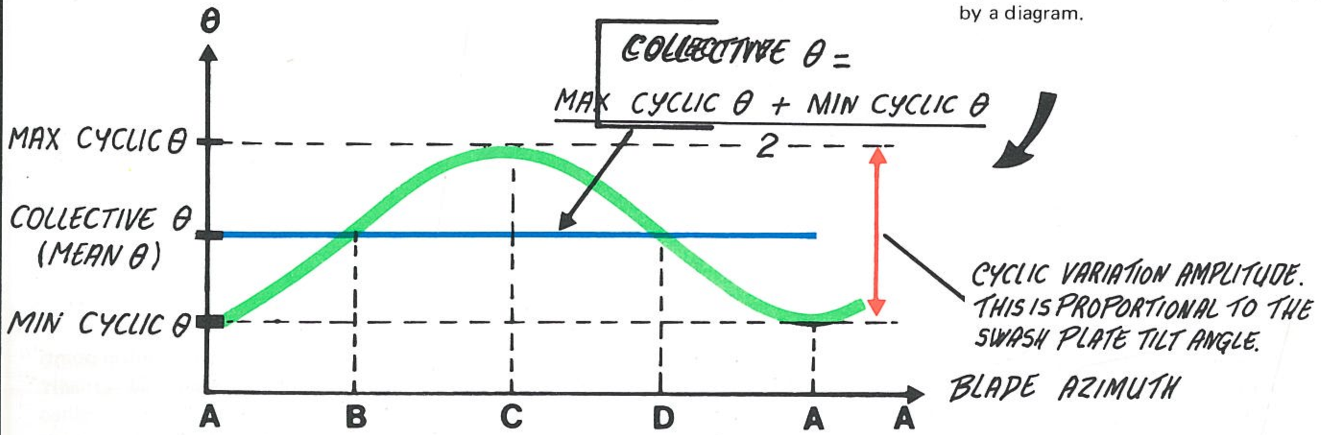


It has to be noted that the cyclic pitch variation is symmetrical in both opposite azimuth positions. In particular, if in A1, the control point E is lowered by a maximal value d, in C1 (opposite azimuth) the control point is raised by the same value d. As a result, the pitch increase in C1 is equal to the pitch decrease in A1. This is true for all opposite azimuths.

BEFORE WE STUDY THE EFFECTS OF CYCLIC VARIATION, LET US SUMMARIZE THE PRINCIPLE



In A, the pitch value is minimum (min cyclic θ). In C, the pitch value is maximum (max cyclic θ). From A to C, the pitch is progressively increased : the cyclic variation is said to be positive. From C to A, the pitch is progressively decreased : the cyclic variation is said to be negative. In B and D, where the cyclic variation is not apparent, we have the initial collective pitch value.
Cyclic pitch variation may be illustrated by a diagram.



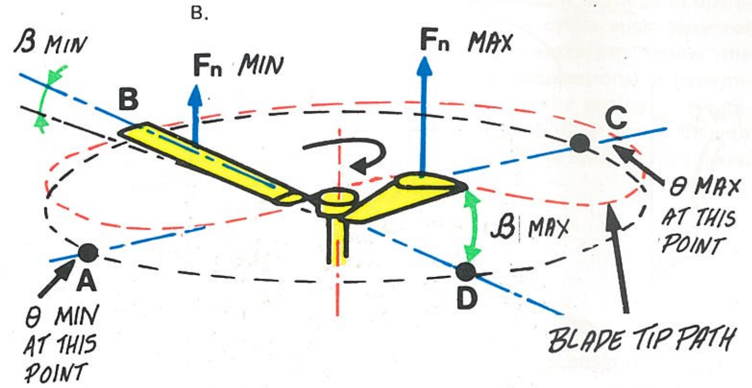
THE EFFECTS OF CYCLIC PITCH VARIATION

OR THE SAME CAUSES PRODUCE THE SAME EFFECTS

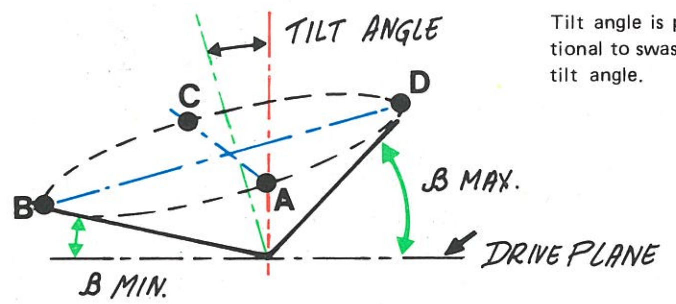
We have seen, when studying lateral lift dissymmetry, the effect of the cyclic variation of the angle of attack caused by the speed variation of the relative wind (V_R).
In the present case, it is the same effect, except that the angle of attack variation is produced by a cyclic pitch variation and not by a speed variation and that it may be applied in any direction by the controlled tilting of the swash plate.

Let us recall fundamental principle : the effect of a variation in the angle of attack (i.e. lift variation F_n and blade flapping β) is effective 90° after the angle of attack variation. Remember the gyroscope effect.

Example : If the pitch (hence the angle of attack) is maximum in C, lift F_n and blade rise (β) are maximum in D, 90° after C. If the pitch is minimum in A, F_n and β are minimum in B.



1st conclusion : cyclic pitch variation causes tilting of the rotation plane



Tilt angle is proportional to swash plate tilt angle.

The cyclic variation of lift, produced by the cyclic pitch variation, causes a variation of the blade flapping angle β. In the example above β is maximum in D (maximum lift) and minimum in B (minimum lift). So the rotation plane is tilted.

But what happens to blade lift Fn and the overall rotor lift F_N ?

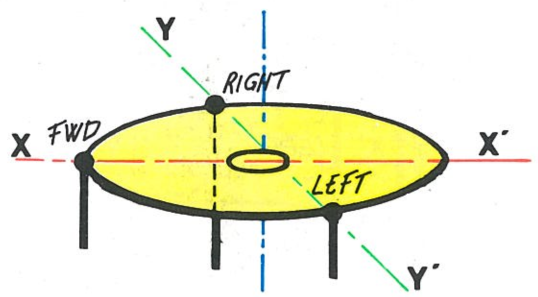
As the swash plate is inclined, cyclic variation occurs and, as a result, cyclic variation of blade lift F_n : THE ROTATION PLANE IS INCLINED. But, remember (as you have seen) : the vertical blade flapping acts as an automatic lift-regulating system.
Don't forget :
- When the blade rises, its angle of attack decreases
- When the blade descends, its angle of attack increases

so that the lift remains constant and cyclic lift variation is only present in the (very short) phase resulting in the swash plate tilt. As the blades begin to flap due to cyclic variation, the blade lift F_n becomes constant again, coming back to its initial value which is that of the existing collective pitch.

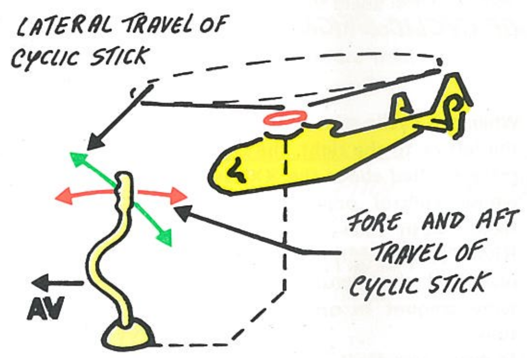
2 nd conclusion : for a given collective pitch value, the cyclic pitch variation has no effect on the magnitude of the overall rotor lift (F_N)

LATERAL AND FORE-AND-AFT CYCLIC VARIATIONS

How to control the tilt direction of the rotor rotation plane.



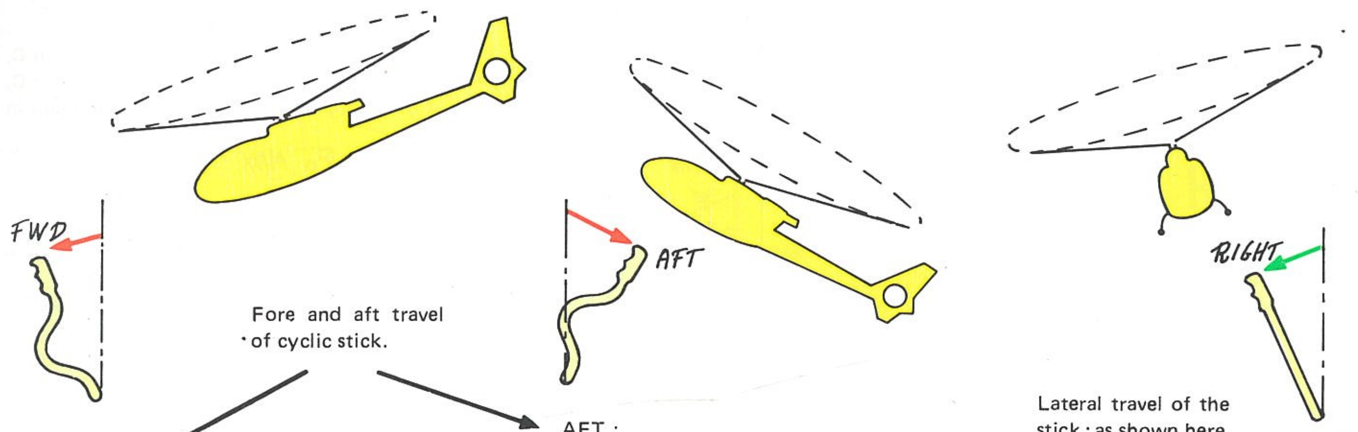
To obtain all possible tilt positions, it is possible for the swash plate to be inclined about two axes (XX' and YY') normal to each other. These pass through the input points (FWD, RIGHT LEFT) of the control rods controlled from the cyclic stick.



The cyclic stick is the control enabling the pilot to control the cyclic variation in amplitude and direction. This control can be moved in any direction. The cyclic stick when moved, causes the swash plate to tilt and with it the rotor rotation plane.

PRINCIPLE OF CYCLIC STICK ACTION:

When the pilot moves the stick in one direction, the rotor rotation plane is inclined in the same direction. Let us see how this is achieved.



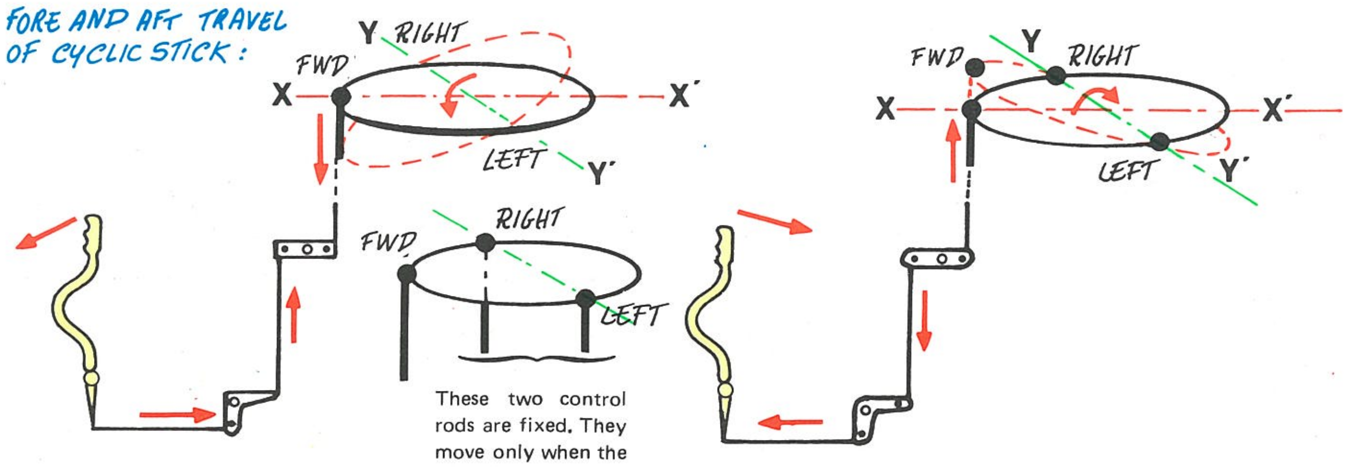
Fore and aft travel of cyclic stick.

Forward : the rotation plane is tilted forward.

AFT : The rotation plane is tilted rearward.

Lateral travel of the stick : as shown here, the stick is moved to the right.

FORE AND AFT TRAVEL OF CYCLIC STICK:



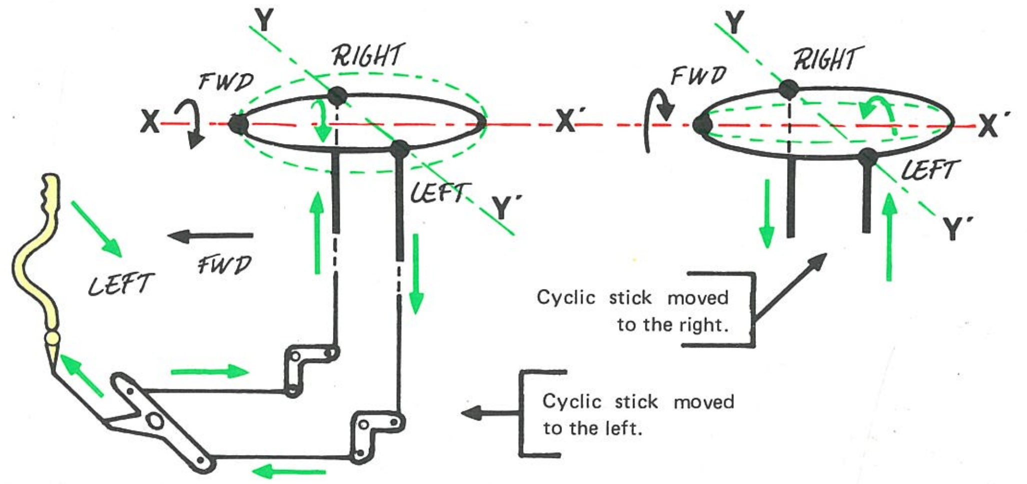
These two control rods are fixed. They move only when the stick is moved laterally.

When the cyclic stick is moved fore or aft, the swash plate is tilted about the YY' axis whose control points (LEFT and RIGHT) are fixed.

LATERAL OPERATION OF CYCLIC STICK:

When the cyclic stick is moved to the left or to the right, the swash plate is tilted about the XX' axis whose control point (FWD) is fixed. Both rods (LEFT and RIGHT), controlling the swash plate tilt are actuated by the same amount in opposite direction.

In every case (fore-and-aft and lateral position) the swash plate tilt angle is proportional to the angular travel of the cyclic stick.

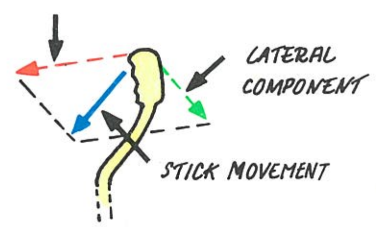


Cyclic stick moved to the right.

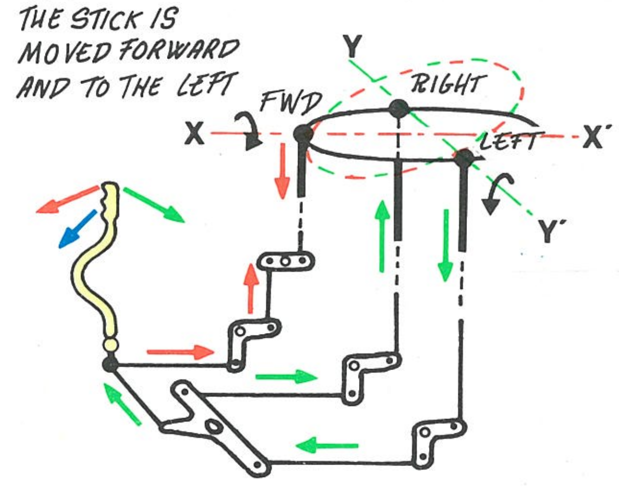
Cyclic stick moved to the left.

CYCLIC STICK ACTUATION

When the stick is moved to any position, the swash plate is inclined about two tilting axes XX' and YY' by a value proportional to fore-and-aft and lateral components of the stick's travel.

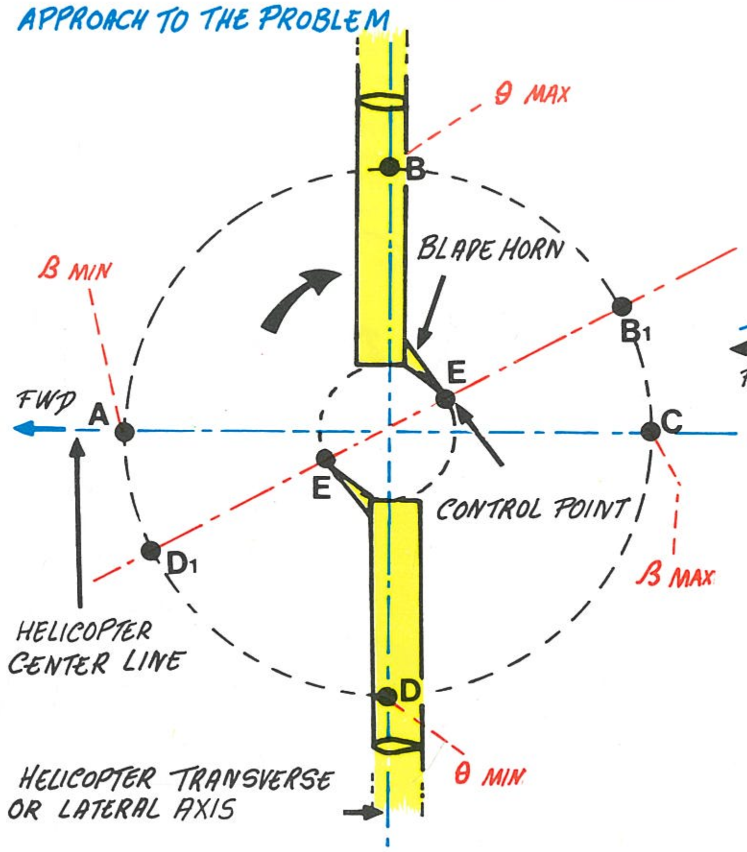


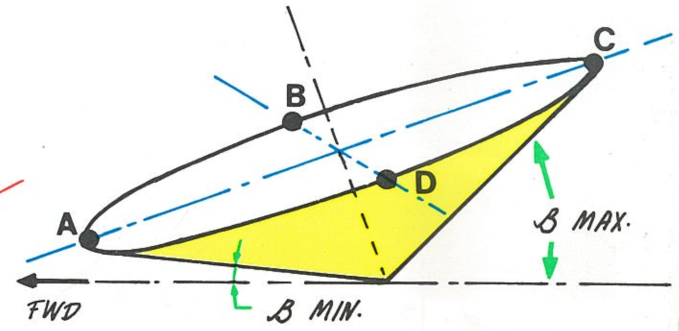
EXAMPLE : THE STICK IS MOVED FORWARD AND TO THE LEFT



The tilt of the rotor's plane of rotation when the pilot operates the cyclic stick (essential for the aircraft to "follow" the pilot's operations) is determined by the setting of the tilting axes (XX' and YY') with respect to the aircraft axes.

APPROACH TO THE PROBLEM

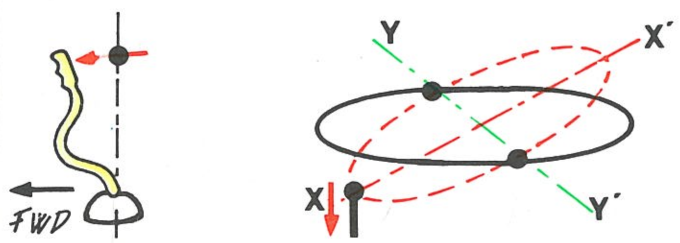




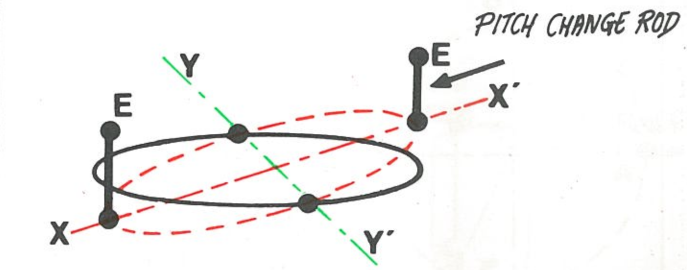
REMEMBER :

– The blade rise is maximum (β max) at 90° after the position where the blade is at its maximum pitch position (θ max). (and of course, the blade rise is minimum in the opposite azimuth).

So, if the rotor rotation plane is to be tilted forward, maximum pitch has to be applied when the blade is in azimuth B (minimum pitch is reached in azimuth D) so the blade rise (β) will be maximum in C and, therefore minimum in A.

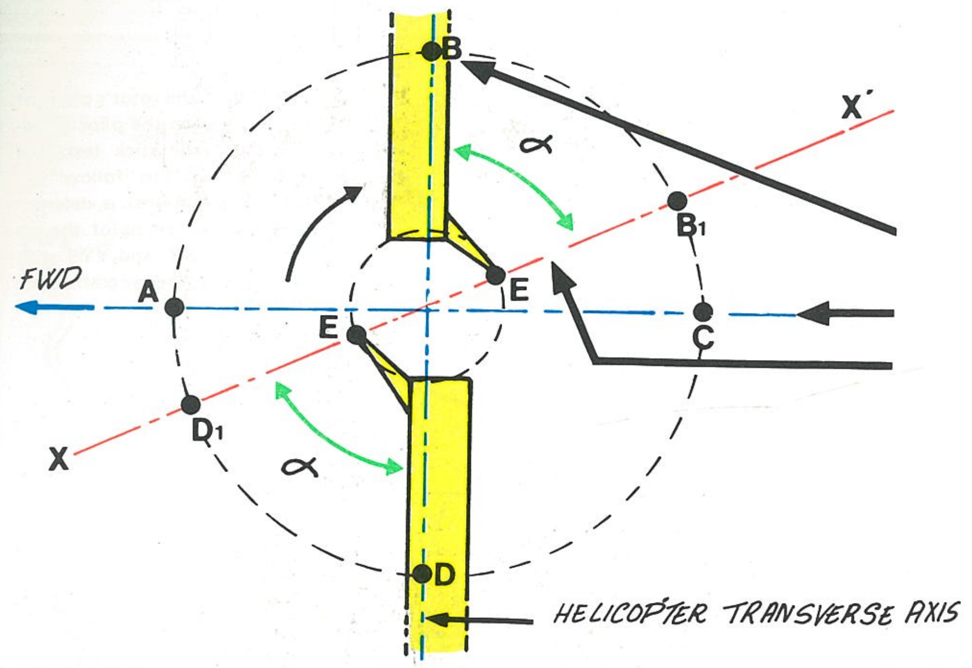


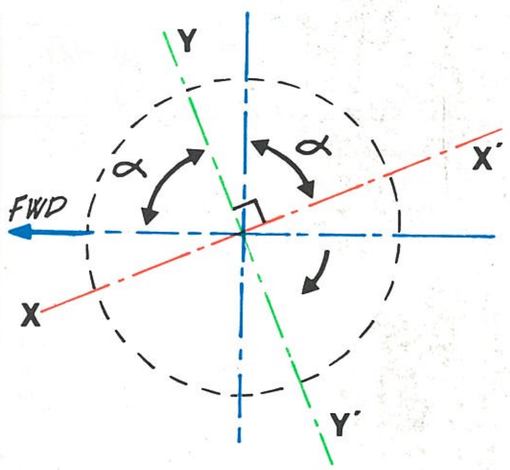
To tilt the rotor rotation plane forward, the cyclic stick is moved forward. It has been seen that the swash plate is tilted about the YY', axis, normal to the XX' axis, which tilts.



In these conditions, the highest position of control point E (and as a result the lowest position in the opposite azimuth) is obtained when E is above the tilting axis XX'.

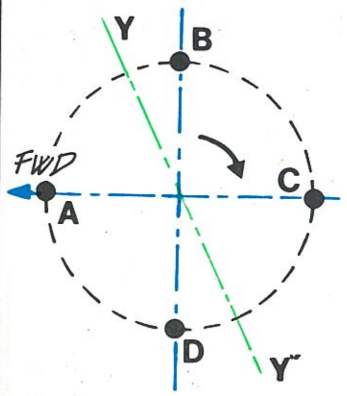
As MAX and MIN pitch values correspond to the extreme positions of control points E, it is all quite easy to understand.



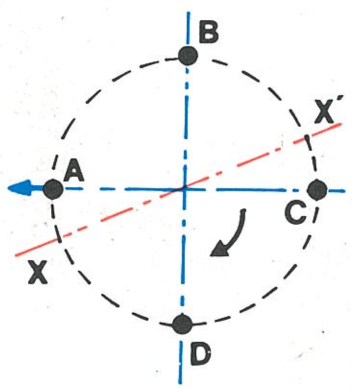


And, the position of the XX' axis being defined, that of the YY' axis is thus determined and it is possible for you to check that a swash plate tilt about the XX' axis (lateral travel of cyclic stick) produces a lateral tilt of the rotation plane either to the left or to the right according to the stick travel.

SO, NOW AERODYNAMIX IS HAPPY, LET US RUN THROUGH THAT AGAIN (TO FINISH THE PAGE)



With the cyclic stick in forward or rearward position, the swash plate is tilted about transverse axis YY' thus producing a cyclic variation of the "lateral" pitch. If the stick is forward, maximum pitch is reached in B and maximum blade rise in C. The rotation plane is tilted forward. If the stick is rearward, maximum pitch is reached in D and maximum blade rise in A. The rotation plane is tilted rearward.



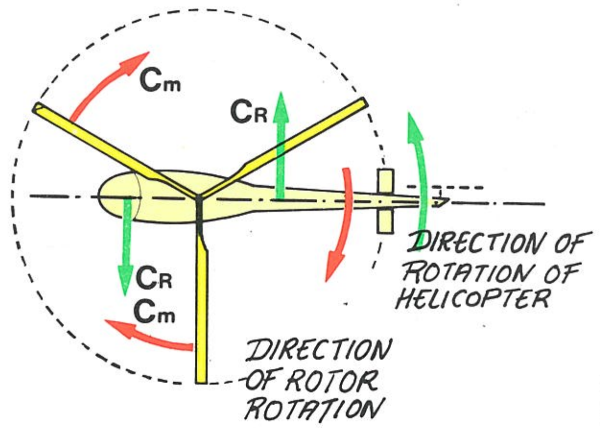
With the cyclic stick either to the right or to the left, the swash plate is tilted about fore and aft axis XX' thus producing a cyclic variation of "fore and aft" pitch.

With the stick to the right :
- Max. pitch is in C
- Max. blade rise in D
- Rotation plane is tilted to the right.

With the stick to the left :
- Max. pitch in A
- Max. blade rise in B
- Rotation plane of the rotor is tilted to the left.

5. THE MAIN ROTOR REACTION TORQUE

...AND THE TAIL ROTOR



Any force, to manifest itself, must bear on a support. If this support is free to move, it will go in the opposite direction to the force acting on it. The action of the force is said to be equal and opposite to the reaction (of the support).
The situation is the same for the helicopter rotor. To rotate, the rotor shaft to which the engine torque (Cm) is applied, rests on the helicopter structure which is pulled in the direction opposite that of the rotor by a reaction torque (C_R) equal and opposite to the engine torque (Cm). Obviously, if it was not compensated, the reaction torque would prevent the helicopter from flyng.

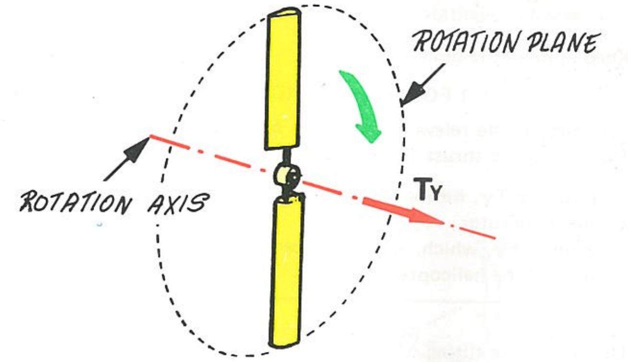
HOW CAN THE REACTION TORQUE OF THE MAIN ROTOR BE COMPENSATED?

The tail rotor (or anti-torque rotor) prevents the helicopter from rotating on its axis by the action of the main rotor reaction torque.

The tail rotor is fitted at the rear of the fuselage where, driven by the same engine as the main rotor, it rotates in the VERTICAL plane. The resultant aerodynamic force of the tail rotor, called THRUST (Thrust and lift are equivalent terms), is applied in a HORIZONTAL plane and opposed to the reaction torque of the main rotor.

CONVENTIONAL TAIL ROTOR (NOT SHROUDED)

SHROUDED TAIL ROTOR

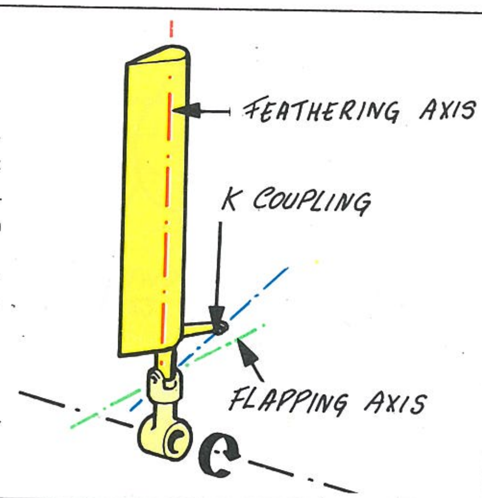


Thrust TY of the tail rotor is normal to the plane of rotation.

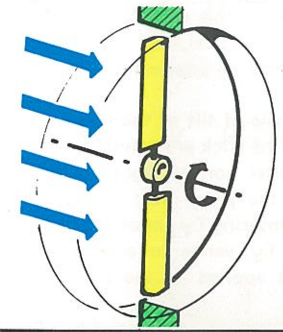
TAIL ROTOR MECHANISM

The tail rotor includes the following components, found also on the main rotor :
- Pitch hinges for controlling the magnitude of thrust Ty by collective variation of blade pitch.
- Flapping hinges compensating the asymmetrical relative speed effects between advancing and retreating blades.
- Pitch - flapping coupling (K-coupling) reducing the effect of blade flapping.

Note that there are no drag hinges.



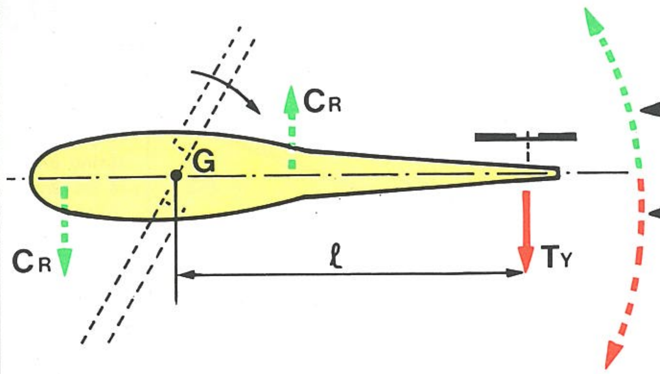
Note also that, in the case of a shrouded rotor, the flapping hinge is unnecessary and, therefore, omitted. As a matter of fact, the air flow, ducted by the rotor shroud, is normal to the plane of rotation and the relative speed of air is identical for all blades



LET US COME BACK TO THE REACTION TORQUE OF THE MAIN ROTOR

•

EFFECT OF TAIL ROTOR THRUST T_Y



The reaction torque (C_R) of the main rotor tends to rotate the helicopter in this direction.

Thrust T_Y of the tail rotor tends to rotate it in the opposite direction.

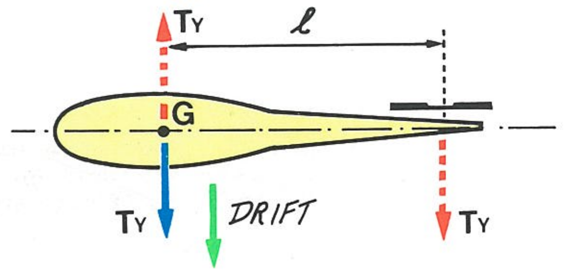
These effects cancel each other out when the moment of T_Y, with respect to the center of graivty G, is equal to the reaction torque.

$$\ell \times T_Y = C_R$$

The pitch angle of the tail rotor blades is selected so that rotor thrust T_Y which applies at the end of the fuselage, is opposed to the reaction torque of the main rotor.

This is the reason why helicopters have such a long tail. As a matter of fact, lenght ℓ of the lever arm must be increased as much as possible to reduce in the same ratio the value of thrust T_Y which consumes power.

BALANCING A TORQUE BY A FORCE OR THE EVILS OF TAIL ROTOR THRUST Ty.

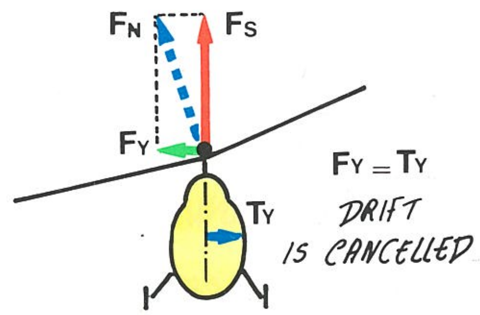


Keep in mind the basic notions :

1 FORCE = 1 FORCE + 1 TORQUE.

(or refer to the relevant page : 7). A torque cannot be balanced by a force. Thus, to thrust T_Y correspond :

- a torque T_Y, having a lever arm ℓ cancelling the reaction torque of the main rotor.
- a force T_Y, which, applied to center of gravity G, will cause a side drift of the helicopter.



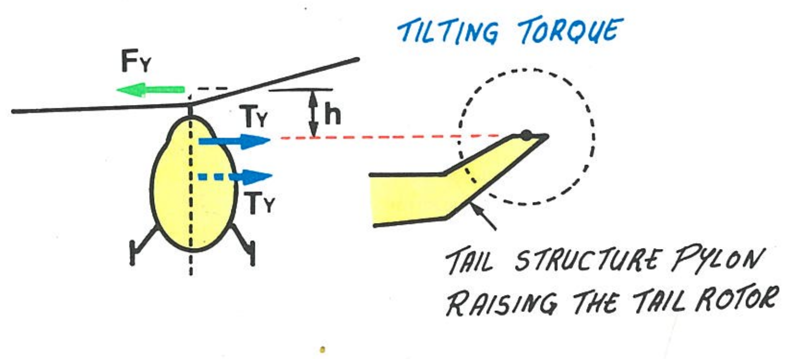
How is this drift cancelled ?

To cancel the drift an equal force directed in the opposite direction must be opposed to T_Y. This result is obtained by tilting the main rotor disc in the opposite direction to T_Y and at an angle such that horizontal component F_Y of lift F_N is equal to T_Y.

Of course, the tilting of the rotational plane of the main rotor is obtained by a cyclic lateral pitch variation (cyclic stick to the right if T_Y is directed to the left and vice versa. To avoid having to fly with the STICK permanently OFFSET, two means are used.

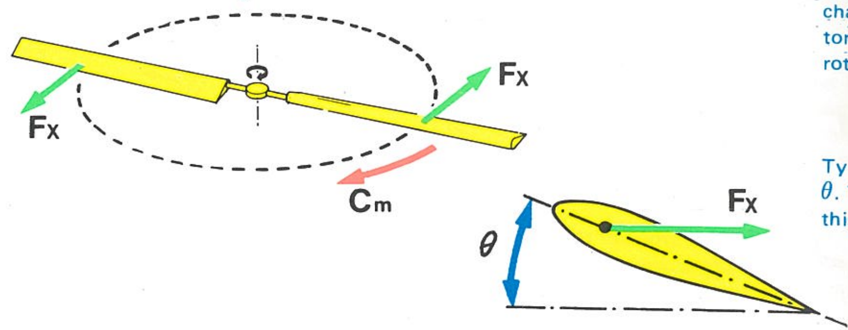
- The main rotor shaft is slightly tilted in the direction opposite to T_Y.
- The cyclic stick is OFFSET by appropriate setting of the control linkage so that, with the stick vertical, the swashplate is slightly tilted, producing a lateral inclination of the rotor disc.

The angle of tilt of the rotor shaft and the offseting of the stick are determined so as to compensate T_Y under normal flight conditions. Beyond these limits the pilot must act on the cyclic stick for compensating T_Y variations because, as we shall see later, T_Y varies in accordance with the engine torque applied to the main rotor.



However, it is not easy to get rid of the effects of the tail rotor thrust T_Y. While the main rotor tilt compensates the drift motion, there are still two equal and opposed forces (F_Y and T_Y) producing a torque having a moment h x F_Y tending to tilt the helicopter. To reduce the tilting torque, the designer acts on length h of the lever arm by raising the rotational axis of the tail rotor so that h is as small as possible.

VARIATION OF THE MAIN ROTOR REACTION TORQUE AND MEANS OF VARYING Ty AND Fy WHICH BALANCE THIS TORQUE



KEEP IN MIND :

If collective pitch θ changes, the reaction torque of the main rotor changes likewise.

Therefore :

Ty and Fy must vary as θ. The method used for this is described below.

The reaction torque of the main rotor is equal and opposite to the engine torque (C_m) balancing blade drag F_X. As seen previously, F_X depends on collective pitch θ. Accordingly, if θ varies, the engine torque varies likewise to balance the blade drag.

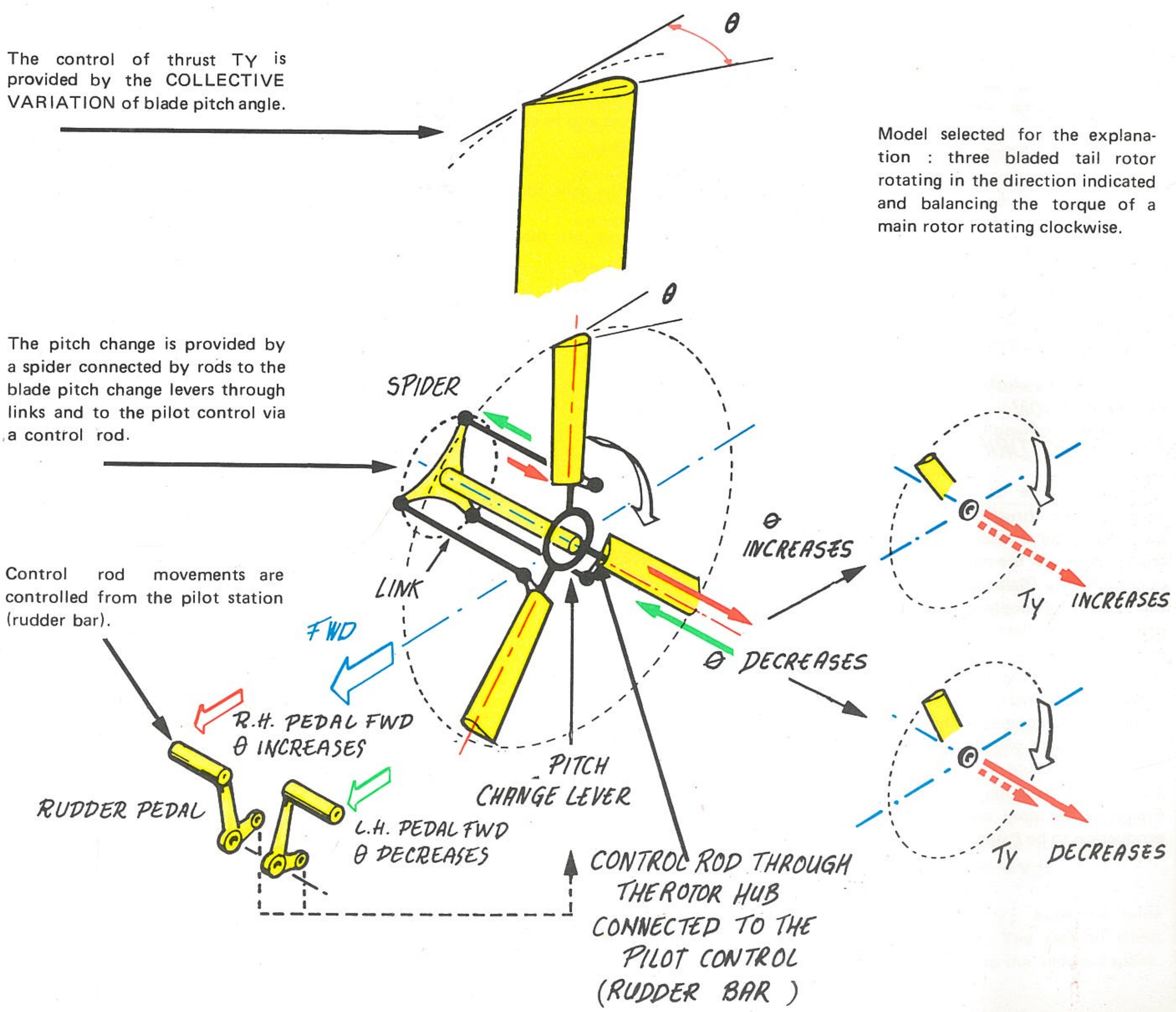
VARIATION OF TAIL ROTOR THRUST T_Y

The control of thrust T_Y is provided by the COLLECTIVE VARIATION of blade pitch angle.

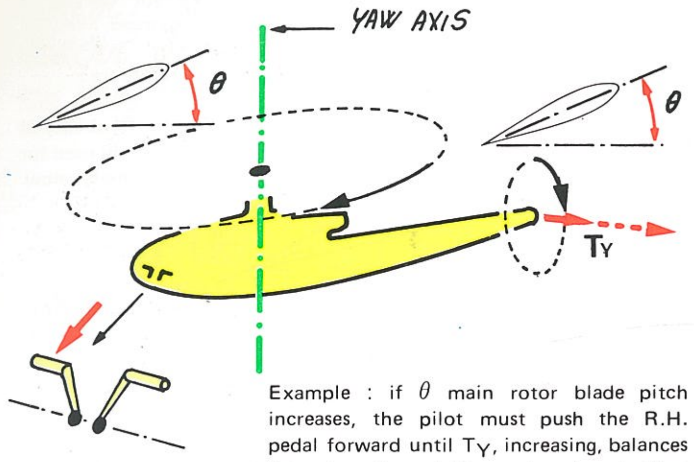
Model selected for the explanation : three bladed tail rotor rotating in the direction indicated and balancing the torque of a main rotor rotating clockwise.

The pitch change is provided by a spider connected by rods to the blade pitch change levers through links and to the pilot control via a control rod.

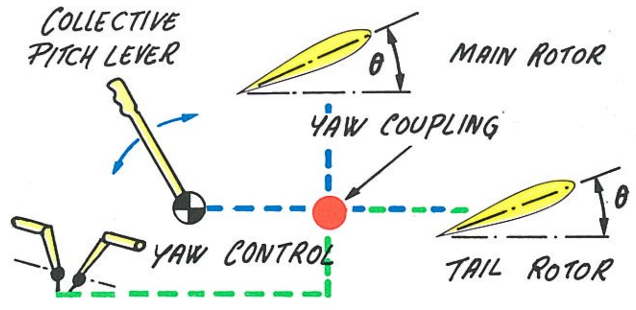
Control rod movements are controlled from the pilot station (rudder bar).



To maintain the helicopter balance around its yaw axis, the pilot must apply a thrust T_Y of a value in accordance with the engine torque ; i.e. in accordance with the collective pitch θ of the main rotor blades.



Example : if θ main rotor blade pitch increases, the pilot must push the R.H. pedal forward until T_Y, increasing, balances the new value of the main rotor reaction torque.



A simple mechanism relieves the pilot of this burden : this mechanism is the main rotor collective/tail rotor pitch "coupling". For a given pedal position any pilot action on the collective pitch lever simultaneously produces a like variation in main rotor and tail rotor pitch, so that thrust T_Y automatically balances the reaction torque of the main rotor for whatever value of main rotor pitch. It is to be noted that this "coupling" is installed only on helicopters fitted with an auto pilot.

It's an ill wind that blows nobody any good !

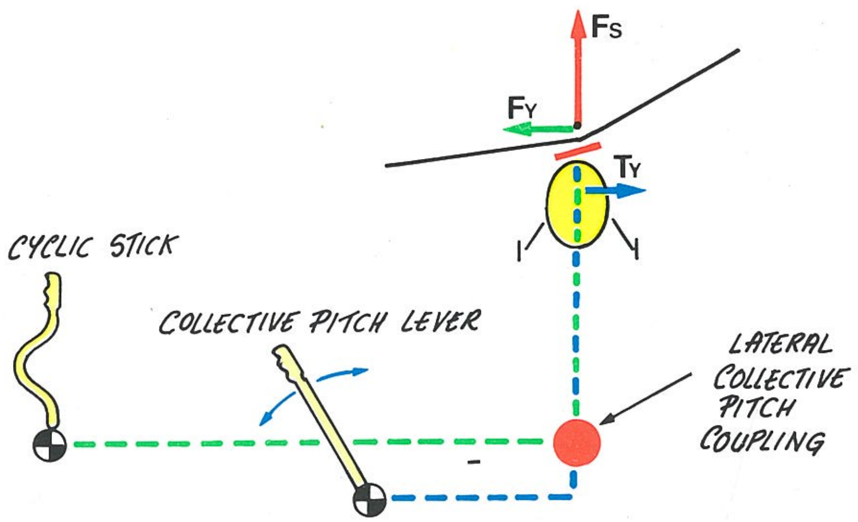
As a matter of fact, the tail rotor, intended to compensate the reaction torque of the main rotor is used also to control the aircraft about its yaw axis.

- To turn to the right, the pilot pushes the R.H. pedal.
- To turn to the left, the pilot pushes the L.H. pedal.

temporarily destroying the yaw balance of the helicopter.

FY VARIATION
AUTOMATIC DRIFT COMPENSATION

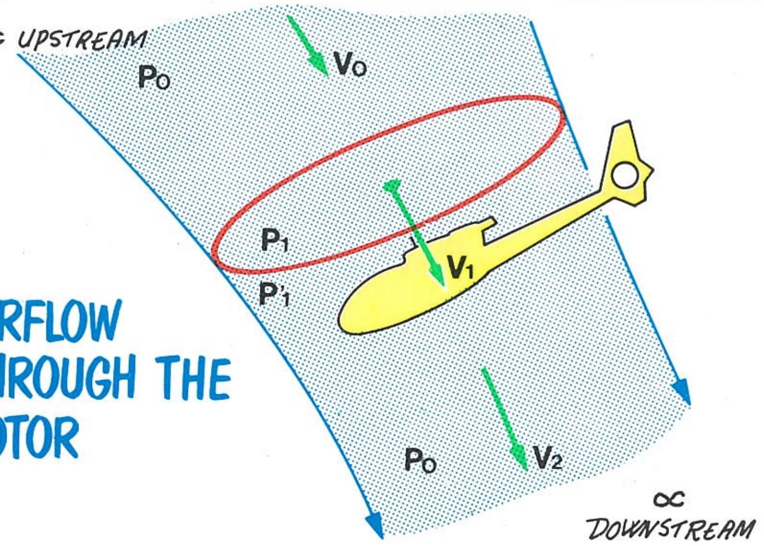
For the purpose of compensating the drift resulting from thrust T_Y of the tail rotor the pilot must, by a lateral action of the cyclic control stick, tilt the main rotor in the direction opposite to T_Y (Balance condition).
Here there is a simple way to avoid such a burden with the "lateral cyclic/collective pitch coupling". For a given action of the cyclic stick, any collective pitch lever action changes the swashplate inclination (and, therefore, that of the rotation plane) so that balance $F_Y = T_Y$ is obtained. Here, when collective pitch increases, the rotation plane tilt to the right increases. This type of coupling is rarely used. The Super Frelon is the only one among Aerospatiale's production to be fitted with it.



6. AERODYNAMIC FUNCTIONING OF ROTOR

... AND ITS NOTEWORTHY ASPECTS: GROUND-EFFECT - AUTOROTATION_VORTEX - LIMIT SPEEDS

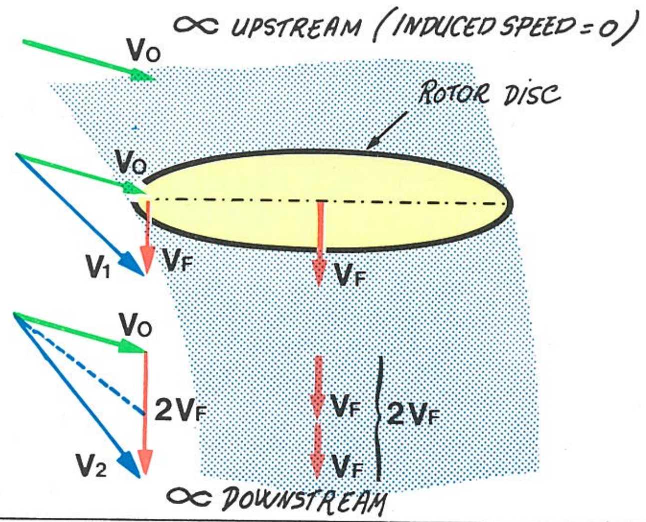
AIRFLOW THROUGH THE ROTOR



In operation, the rotor draws air through its upper area and discharges it downwards. Thus, it ACCELERATES the mass of air within its influence. The air pressure and speed vary along the flow of air in motion.

- At the upstream infinite (∞). The air pressure is Po (atmospheric pressure). The relative airspeed is Vo. It is equal and opposite to the helicopter's velocity of travel.
- In the rotor disc area, the airspeed has increased and is equal to V1. On the upper face of the disc, the pressure is P1 (P1 <Po) : negative pressure area. On the lower face, the pressure is P'1 (P'1 <Po) : positive pressure area.
- At the downstream infinite (∞) : the airspeed has still increased and is equal to V2. The air pressure is Po (atmospheric pressure).

ROTOR INDUCED SPEED OR FROUDE SPEED



The increase of air flow velocity (from Vo to V2) is steady between the upstream infinite and the downstream infinite. Therefore, it is equal on both sides of the rotor disc. This increase of velocity is called "Froude speed" V_F (or induced speed as it is induced by the rotor). Accordingly, between the upstream infinite speed and the rotor, the induced speed increases steadily. At the disc level, its value is V_F. Between the rotor and the downstream infinite, its value increases to 2 V_F. The resultant relative air velocity is expressed in terms of V_F. Thus

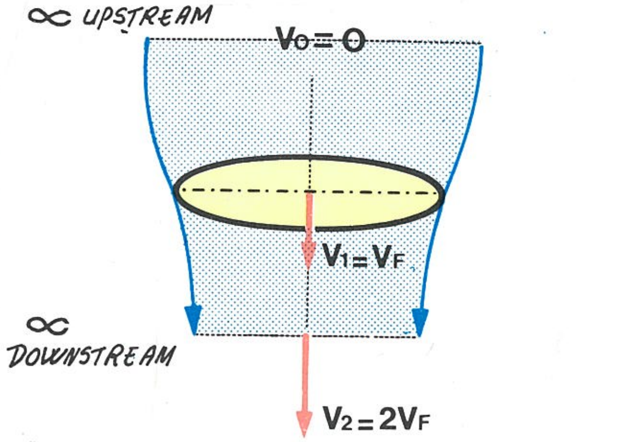
$$\vec{V1} = \vec{Vo} + \vec{V_F}$$

$$\vec{V2} = \vec{Vo} + 2\,\vec{V_F} = \vec{V1} + \vec{V_F}.$$

From this very general discussion, we shall detail the various air flow conditions in :

- Hovering
- Vertical flight upwards
- Vertical flight downwards
- Fast descent
- Slow descent
- Moderate descent
- Forward flight

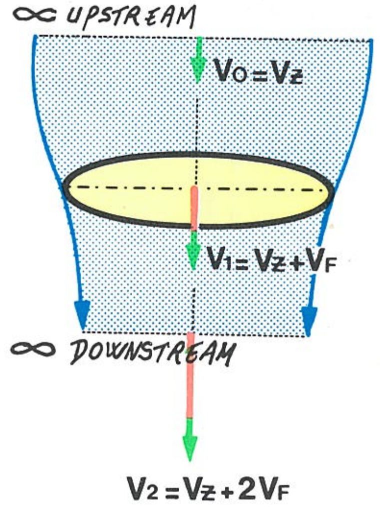
HOVERING



The helicopter is immobile relative to the air :

Vo = O In the rotor disc plane, the air flows at the induced speed (V1 = V_F).

VERTICAL FLIGHT UPWARDS

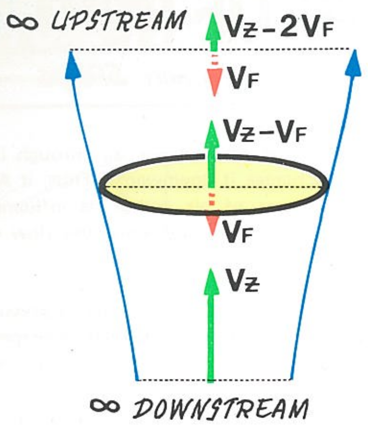


The helicopter climbs vertically at rate V_Z.

At upstream infinite, the speed Vo of air flow is equal and opposite to the rate of climb (Vo = V_Z).

V_Z and V_F have the same direction. The rate of climb is added to the induced speed.

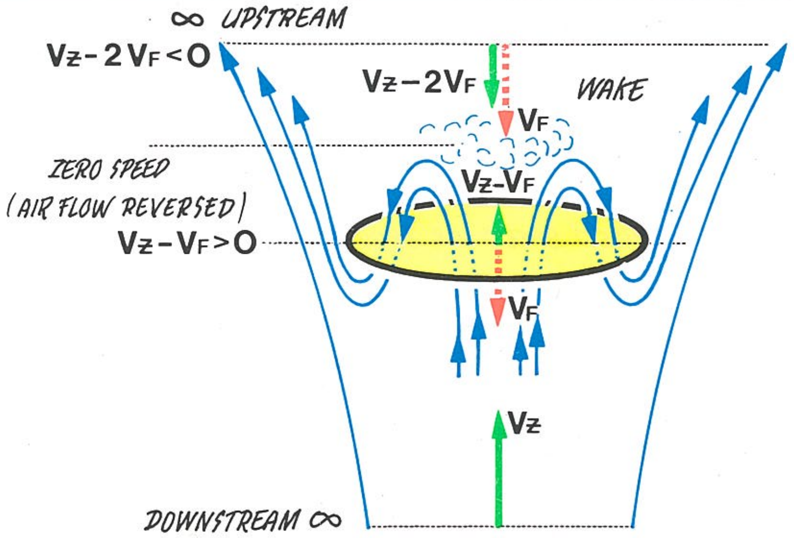
DOWNWARD VERTICAL FLIGHT - FAST DESCENT : $V_Z > 2\ V_F$ (THEORETICAL CONDITIONS)



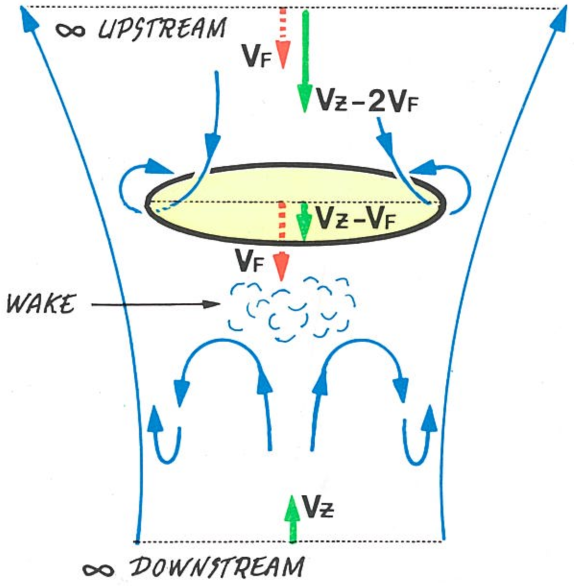
The helicopter descends : the flow is inverted and passes upwards through the rotor. At the downstream infinite, velocity V_Z of air flow is equal and opposite to the downward velocity of the helicopter. The rotor-induced speed (V_F) is still directed downwards and opposite to V_Z.
Consequence : The resultant speed decreases. At the rotor level, it is equal to $V_Z - V_F$ and reaches $V_Z - 2\ V_F$ at the upstream infinite. As $V_Z > 2\ V_F$, this speed remains positive i.e. it is always directed in the same direction.
NOTE that in these flow conditions, the rotor is WINDMILLING.

DOWNWARD VERTICAL FLIGHT - MODERATE DESCENT : $V_F < V_Z < 2 V_F$

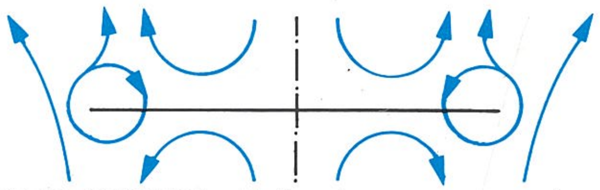
The rate of descent is considered as moderate when speed V_Z at the downstream infinite is included between V_F and 2 V_F. As in fast descent, induced speed V_F is deducted from speed V_Z. However, as V_Z is smaller than 2 V_F, the difference $V_Z - 2\ V_F$ is negative and therefore, directed in the opposite direction to V_Z which means that an inversion of the air flow above the rotor occurs. The meeting of opposite air flows produces a wake. The air flow passing through the central area of the rotor is turned down on the periphery by the descending flow ($V_Z - 2\ V_F$). The aerodynamic flow is perturbed. In this case also, as in fast descent, the rotor is driven by the air flow ; this is called AUTOROTATIVE DESCENT, which will be covered later.



DOWNWARD VERTICAL FLIGHT - SLOW DESCENT ($V_Z < V_F$) AND VORTEX CONDITION

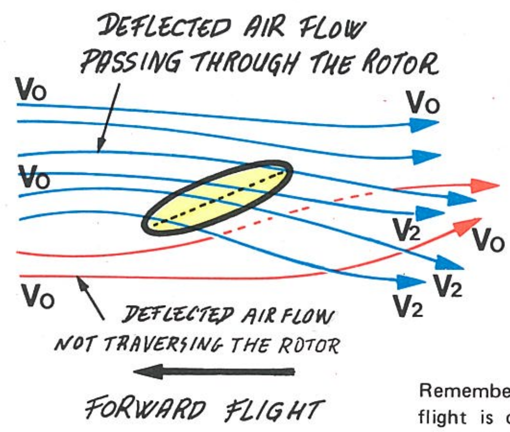


While fast and moderate rates of descent correspond to unpowered flight conditions (the power is supplied by the air flow and a free wheel inserted in the transmission system allows the rotor to rotate freely), the slow descent is a powered flight condition as the pilot controls the helicopter descent by reducing the collective pitch.
Look at the flow figure : as the vertical speed of air flow at the downstream infinite (V_Z) is lower than the induced speed (V_F), the inversion of the air flow velocity occurs under the rotor. (As at the rotor level $V_Z - V_F < 0$). A wake occurs under the rotor and the air flow is turned down. The upper air flow forms a vortex near the blade tips. For a downward rate of about 2 m/s, the upward and downward air flows concur on the rotor disc. THE BLADES ROTATE IN THEIR OWN WASH while the air forms a vortex ring insulating the rotor which is no longer traversed by the air flow. This phenomenon is called VORTEX CONDITION. Such a configuration is dangerous as the rotor, in stall area, cannot be controlled anymore. It is easy for the pilot to come out of this situation, either by flying forward or by reducing the collective pitch to initiate autorotation (V_Z increase).



VORTEX CONDITION : Air flow does not traverse any longer the rotor which is insulated by the vortex ring.

FORWARD FLIGHT



Just remember

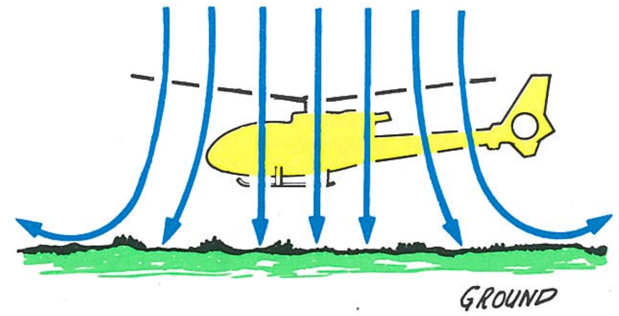
- In forward flight, the rotor operates both as a propeller and as a wing :
  - As a propeller, it accelerates the mass of air flowing through it (air flow normal to the rotor disc).
  - As a wing, it causes deflection of the air flow.

Remember also that passing from vertical to forward flight is called "transition". When initiating forward flight, the concurrence of both air flows causes a turbulence in the flow resulting in vibrations and high stresses in the blades.

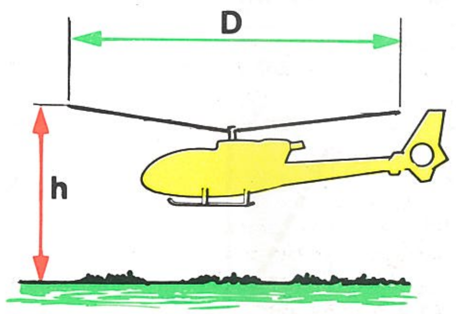
* SEE ON PAGE 51 AERODYNAMIX'S ACCIDENT

GROUND EFFECT

AND ITS BENEFITS

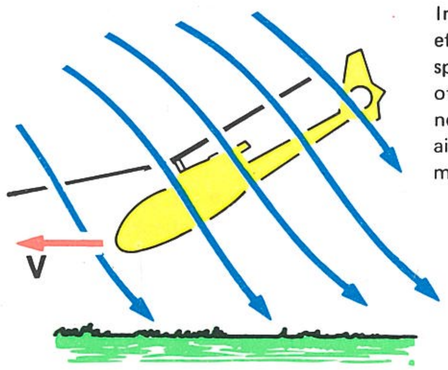


When the helicopter is hovering in the immediate vicinity of the ground the kinetic energy communicated to the air by the rotor (induced speed) is cancelled on contact with the ground and converted into pressure energy, with the exception of the peripheric area where air flow is deflected. The pressure increase is felt on the lower surface of the blades resulting, of course, in an increase in rotor lift F_N. The aircraft is said to be IN GROUND EFFECT (I.G.E.).



The lift increase depends on distance "h" between the rotor disc and the ground. If h = 1/3 D (D is the rotor diameter) ; the increase of F_N is 20 per cent approximately. It decreases to 10 percent for h = 1/2 D and becomes negligible from h = D. The aircraft is then said to be out of ground effect (O.G.E.).

THE GROUND EFFECT IN FORWARD FLIGHT



In forward flight, the ground effect is less as the forward speed is greater. This decrease of the ground effect is explained by the deflection of the air flow and by the aircraft's movement.

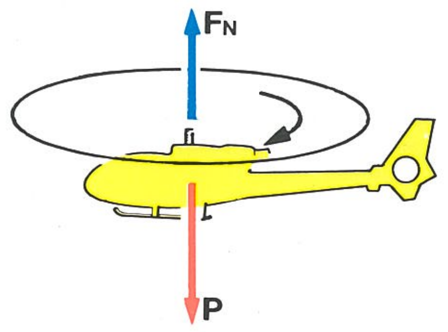
For instance, for h = 1/2 D, a forward speed of 30 km/hr reduces the ground effect to 2 percent.

CONSEQUENCES OF THE GROUND EFFECT IN HOVERING

For a given power level (i.e., with the rotor operating at constant speed and a given collective pitch), in ground effect, the lift is increased by 10 percent approximately. Accordingly, for hovering in ground effect (I.G.E.) the power required is less than for hovering out of ground effect (O.G.E.). This is the explanation of the I.G.E. and O.G.E. hovering performance curves in the flight manuals. In this connection, the helicopter hover ceiling is higher in ground effect than out of ground effect.

AUTO-ROTATION

OR HELICOPTER FLIGHT IN CASE OF ENGINE FAILURE



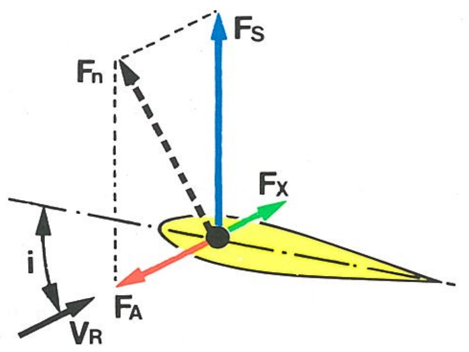
After an engine failure, the helicopter does not fall. Its rotor, driven under the action of the relative wind, benefits from a lift F_N which, while inferior to weight P of aircraft, is sufficient to slow down the descent and maintain control of the aircraft until the landing.

HOWEVER, THE SITUATION IS NOT AS SIMPLE AS IT LOOKS.

Question : why does the rotor still rotate (and, accordingly developing a lift F_N) when it is no longer driven by the engine ?

We shall now examine autorotation in vertical and inclined descent. First, let us explain the existence of autorotative and anti-autorotative forces acting simultaneously on every blade.

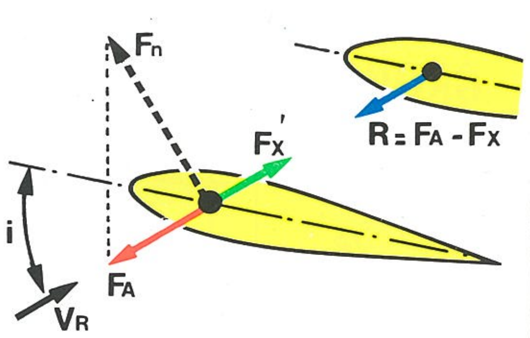
AUTOROTATIVE AND ANTI-AUTOROTATIVE FORCES



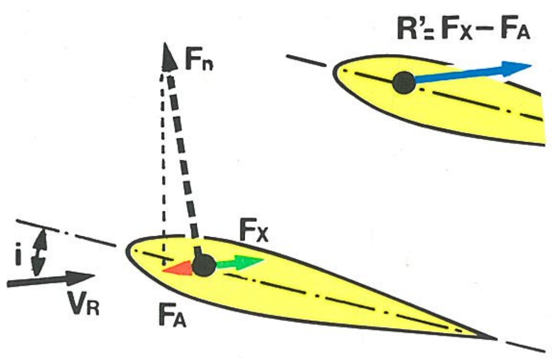
. If F_n is broken down along a vertical line and along the direction of relative wind V_R, we obtain :

- 1 force F_S, or lift force
- 1 force F_A, or propulsion force, opposed to drag F_X.

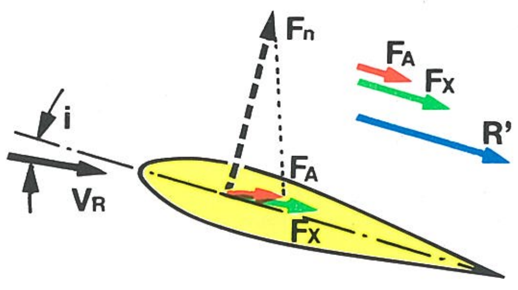
Reminder : Two forces act on a rotating blade : Lift F_n, normal to the relative wind V_R and drag F_X directed along the relative wind.



If the angle of attack i is large, F_n is directed well forward and force F_A is greater. If F_A is greater than F_X, their resultant R is directed forward = it constitutes the autorotative force driving the blade in rotation.



On the other hand, if the angle of attack "i" decreases, the lift component F_n tilts back and the propulsive component F_A decreases. When $F_A < F_X$, the resultant R' is directed rearwards. This is the anti-autorotative force which slows down the blade.



For very low values of i, F_n is tilted towards the rear of the blade. Component F_A is then directed rearward and added to the drag. The anti-autorotative force is strong.

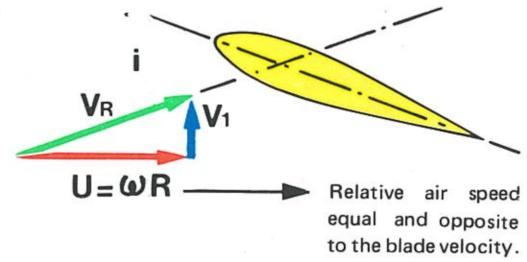
Remember : The autorotative and anti-autorotative forces depend on the blade's angle of attack :

- at a large angle of attack the force is autorotative
- at a small angle of attack, the force is anti-autorotative.

But, how are these forces distributed over each blade ?

AUTOROTATION DESCENT FROM HOVERING

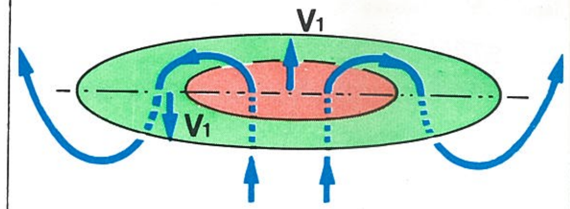
ANGLE OF ATTACK VARIATION ALONG A BLADE IN AUTOROTATION



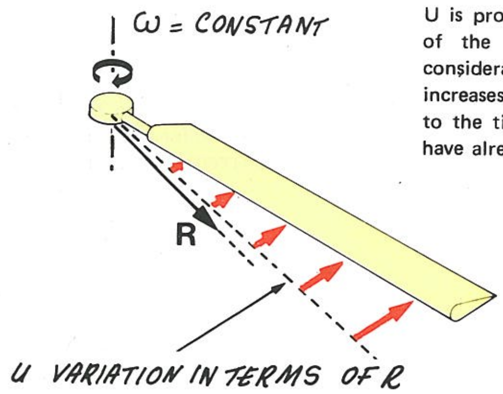
The blade angle of attack depends only on the direction of the relative wind V_R. In autorotation from hovering, where the descent is vertical, the relative wind results from the tangential velocity of the blades ($U = \omega R$) and from the vertical speed of the air passing through the rotor (V1).

VARIATION OF VERTICAL SPEED V1

The autorotation descent is performed at the moderate descent rate already described. In its central area the air flow is passing upward through the rotor. Above the rotor, the vertical speed is cancelled and air flow is deflected towards the disc periphery and passes through it in a downward direction (speed V1 is reversed).

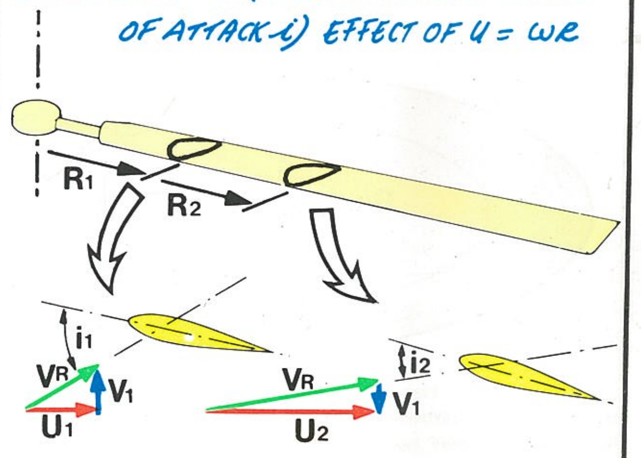


VARIATION OF TANGENTIAL VELOCITY ($U = \omega R$)



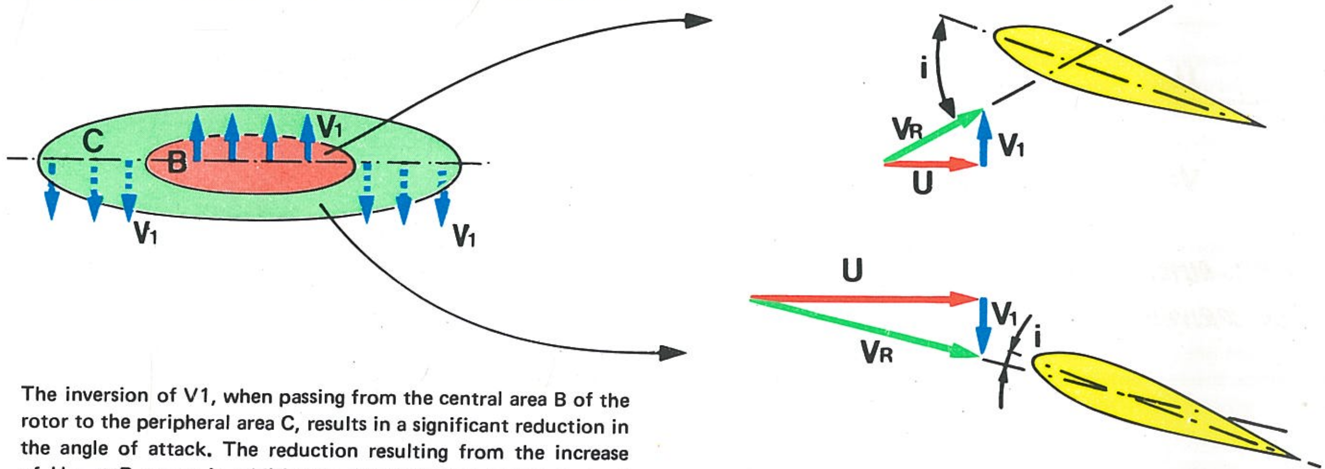
U is proportional to radius R of the blade section under consideration. The velocity increases evenly from the root to the tip of the blade (as we have already seen).

VARIATION OF VR (OR VARIATION OF ANGLE OF ATTACK-i) EFFECT OF $U = \omega R$



R2 > R1 causes U2 > U1 and i2 < i1

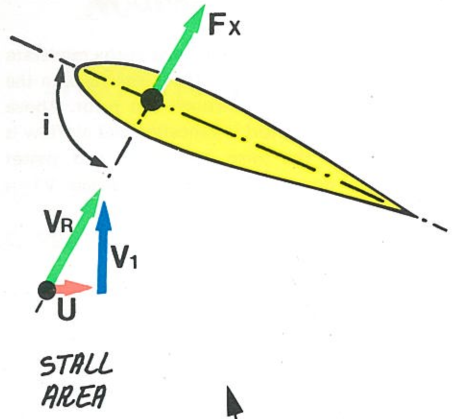
COMBINED EFFECT OF U AND V1 VARIATIONS



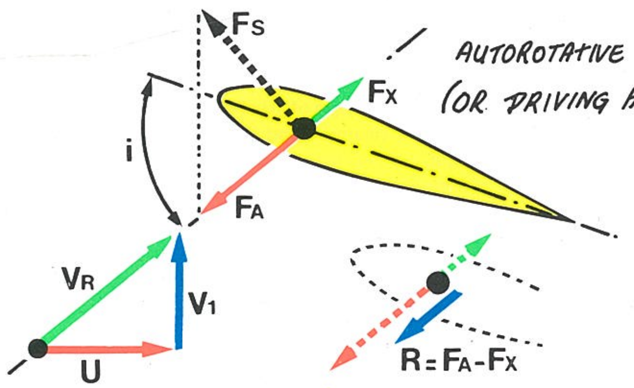
The inversion of V1, when passing from the central area B of the rotor to the peripheral area C, results in a significant reduction in the angle of attack. The reduction resulting from the increase of $U = \omega R$ comes in addition to this reduction in the angle of attack. For all these explanations, the collective pitch of blades is, of course, considered as being constant.

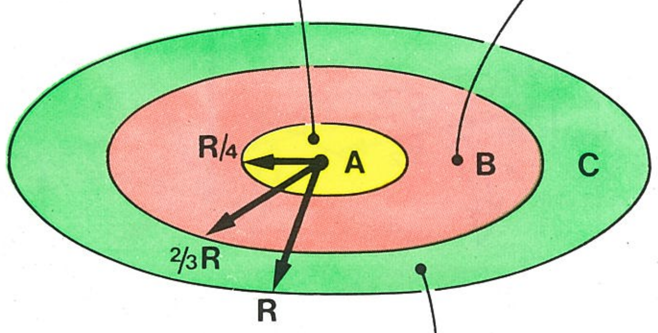
AUTOROTATIVE AND ANTI-AUTOROTATIVE AREAS OF THE ROTOR

Because of the continuous angle of attack variation from the root to the tip of the blade, the rotor is divided into 3 distinct areas, A, B and C.



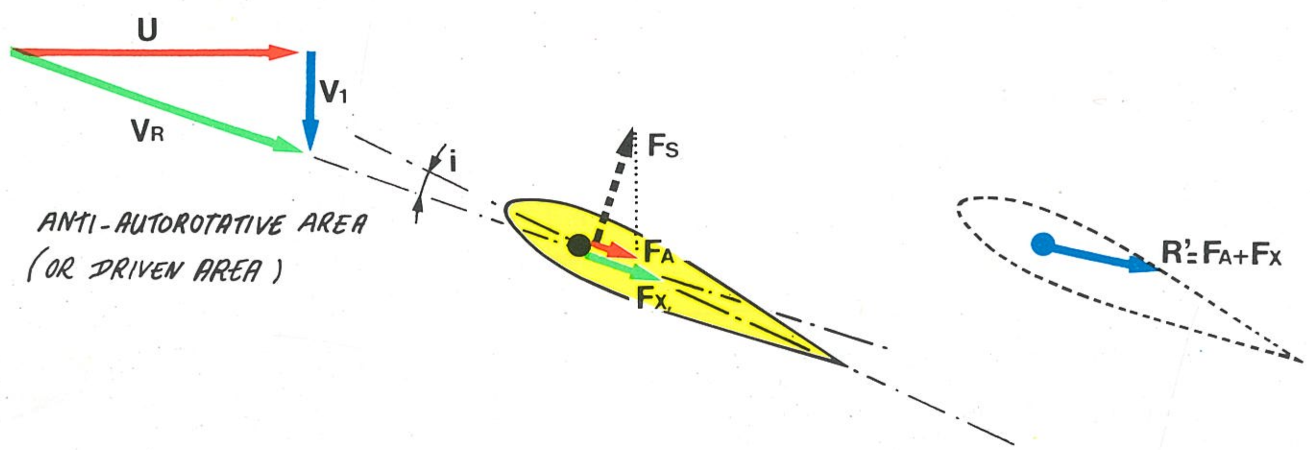
AREA A. at the blade root where V1 is predominant with respect to U, angle of attack i is very large. This is the STALL AREA, the lift is zero. Drag F_x is strong and opposed to rotation.
This area covers 1/4 of rotor radius R.



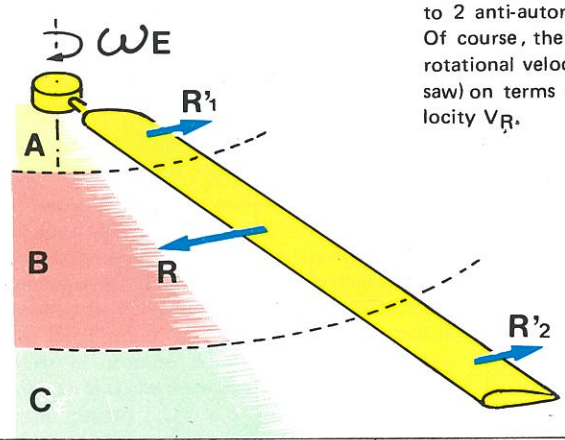


AREA B. Around the stall area, there is an area with a high angle of attack. In this area extending from R/4 to 2/3 R, the resultant R of forces along V_R is directed forward and drives the blade in rotation. This is the AUTOROTATIVE AREA.

AREA C. Finaliy, at the rotor periphery where the air flow is deflected downwards, the angle of attack is low. Resultant R' of forces along V_R is directed rearward. This is the ANTI-ROTATIVE AREA. Note in areas B and C the upward force F_S whose resultant constitutes rotor lift F_N in autorotation.



ROTOR IN EQUILIBRIUM



Thus, every rotor blade in subjected, in area B, to an autorotative resultant force "R" and, in areas A and C, to 2 anti-autorotative forces, resultants R'1 and R'2. Of course, the value of these forces depends on the rotational velocity of the rotor which depends (as we saw) on terms $U' = \omega R$ and V1 depends on the air velocity V_R.

There is an equilibrium state ω_E such that the effect of autorotative R and antirotative R' and R'2 forces is cancelled. Then, the rotor rotates at constant velocity ω_E. Helicopter manufacturers adjust the collective pitch value and blade twist to obtain ω_E very close to the normal operating r.p.m.

THE INFLUENCE OF COLLECTIVE PITCH θ ON ωE

The blade's angle of attack, which conditions autorotation, naturally depends on collective pitch θ.

- If θ is too large, the rotor is slowed down.
- If θ is two small, the rotor is accelerated.

CONCLUSION. There is an optimum pitch for autorotation.
The "low pitch" limit on the collective pitch lever protects the rotor from excessive r.p.m. (and the danger of excessive centrifugal forces).

EFFECT OF BLADE TWIST ON ωE

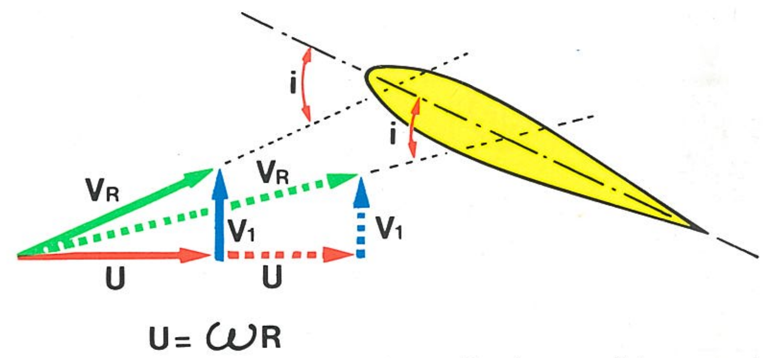
Blade twist, which increases the pitch angle at the root end and decreases it at the blade tip is a significant factor for the equilibrium speed ω_E.

If the twist is high the autorotative area (and therefore ω) increases. If the twist is low, it is the anti-autorotative area which increases and the speed decreases.

AUTOMATIC STABILIZATION OF ROTOR R.P.M. IN AUTOROTATION

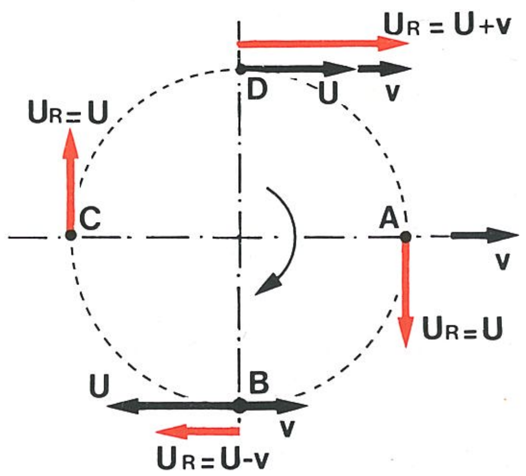
If, for some reason, velocity ω increases, $U = \omega R$ increases and the angle of attack decreases. The anti-autorotative area becomes preponderant, reducing the r.p.m.

If, on the other hand, velocity ω decreases, the angle of attack increases, the auto-rotative area becomes preponderant and restores the equilibrium speed.



If ω increases, U increases and angle of attack decreases. The anti-autorotative force increases and the rotor, restrained, returns to the equilibrium speed ω_E.

AUTOROTATION FROM FORWARD FLIGHT



In autorotation from forward flight a new component appears, the forward speed v of the helicopter. This new factor does not change the explanation as the phenomenon remains basically the same. However, the velocity of relative wind V_R is, in this case, the resultant of :

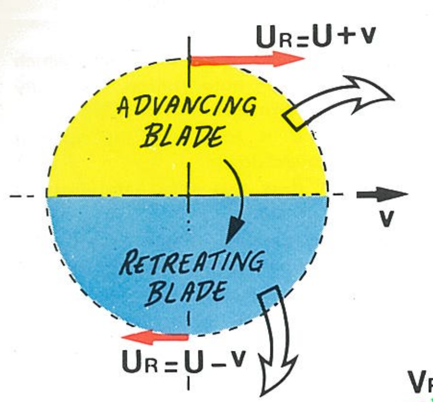
- Blade velocity U ($U = \omega R$)
- Vertical velocity of air flow $= V_1$
- Forward speed v

In the plane of rotation, the blade velocity U is combined with the forward speed v to give the relative speed U_R varying with blade azimuth :

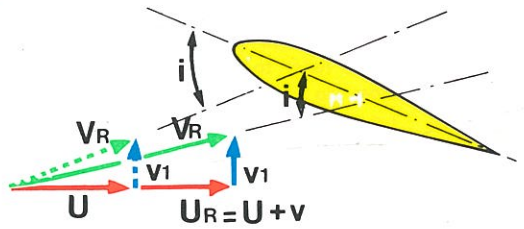
In A and C $U_R = U$

- In B, U_R is minimum $U_R = U - v$
- In D U_R is maximum $U_R = U + v$

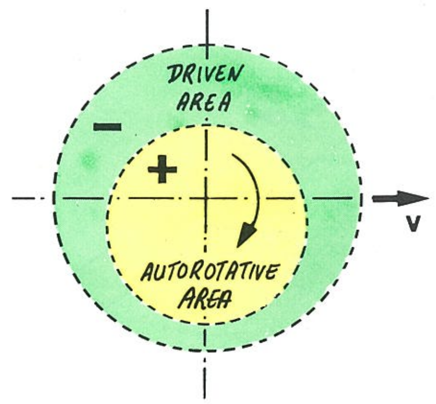
EFFECT OF v ON VR, i AND THE AUTOROTATIVE AREA



On the advancing blade side, U_R is greater than U and the blade angle of attack decreases. Hence, the autorotative area DECREASES on the advancing blade side.



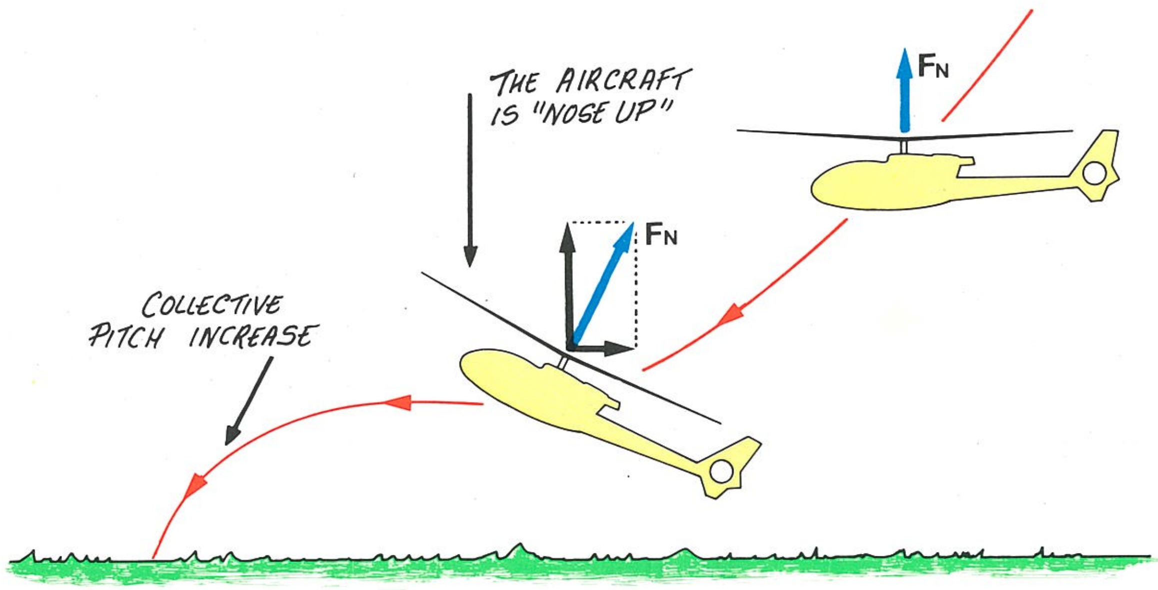
Conversely, on the retreating blade side, U_R is smaller than U. The blade angle of attack increases. Accordingly, the autorotative area INCREASES on the retreating blade side.



The angle of attack increase on the retreating blade side (and its decrease on the advancing blade side) offset the autorotative area towards the retreating blade side. Because of forward speed v :

THE AUTOROTATIVE FORCE IS PREPONDERANT ON RETREATING BLADES.

AUTOROTATIVE LANDING



The autorotative descent rate remains relatively high. However, the pilot has a means of "breaking" this rate and landing softly. At some meters above the ground, the aircraft is placed "nose up" (cyclic stick backward) so as to reduce the forward speed. This results in a sharp increase in the angle of attack on all blades which, in turn, increases during a very short time the rotor r.p.m. and hence lift F_N. The aircraft rises slightly and lands while the lift decreases.

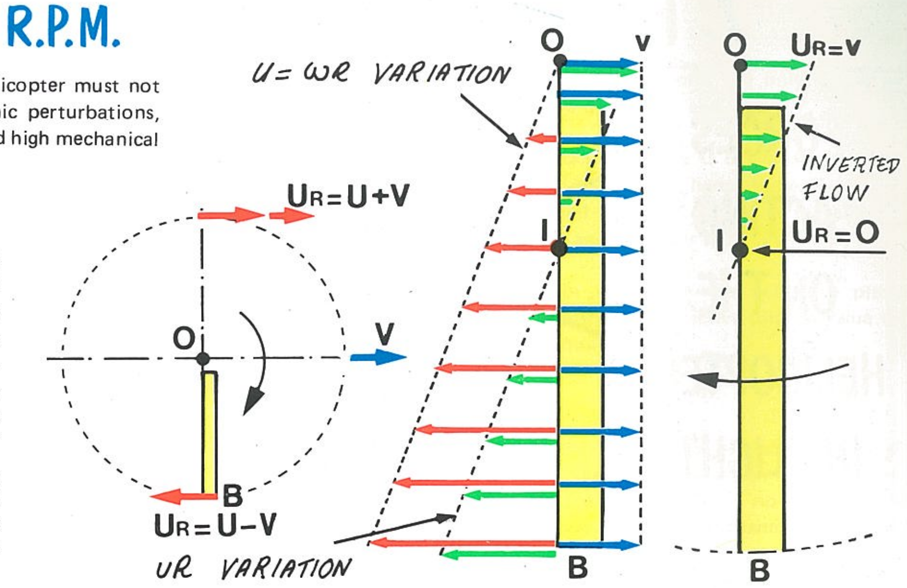
Just before landing (at 3 or 4 m. above the ground), the pilot may, by a collective pitch increase, still further increase lift. (but at the cost of rotor r.p.m.).

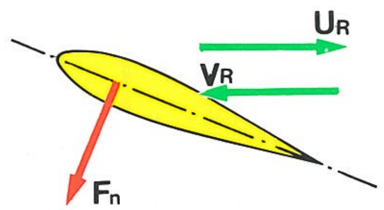
LIMITATION OF ROTOR R.P.M.

The rotor r.p.m. and forward speed of the helicopter must not exceed certain limits above which aerodynamic perturbations, develop on blades causing stall, vibrations and high mechanical stresses.

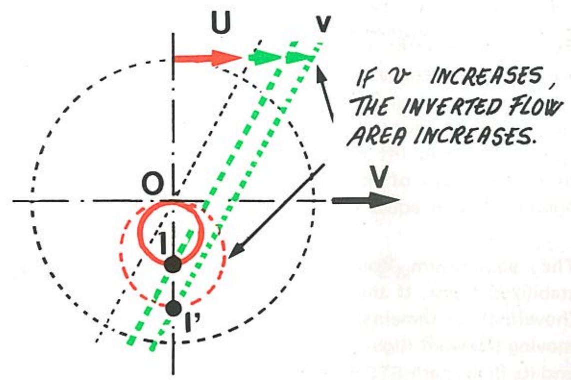
THE INVERTED FLOW AREA

In forward flight, on the retreating blade, the forward speed U is deducted from blade speed U. The resultant relative speed U_R decreases. So much so that, at the root end, the blade will be directed in the opposite direction to the relative wind. Look at the picture. The blade is taken in azimuth B, the most unfavourable position as U and v are directly opposed. In "O" (rotor center) : U_R = v. In "I" where U = v, U_R = 0. Between 0 and I, the relative speed U_R is opposed to the sense of rotation of the blade. The air flow is inverted and attacks the blade on the trailing edge side.





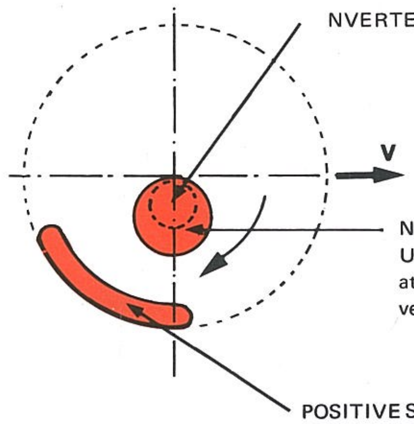
The flow inversion causes turbulence and creates NEGATIVE lift. Therefore, speeds U and v must be determined to reduce as far as possible the effect of the inverted flow.



The inverted flow area (try to construct it from the above explanation) is outlined by a circle tangential to center 0 of rotor and located on the retreating blade side. Diameter 0 I of the inverted flow area is inversely proportional to the U - v difference. It is easily understood that the forward speed "v" of the helicopter is limited, otherwise performance would rapidly decrease.

OTHER LIMITATION AREAS.

The retreating blade is also the seat of 2 stall areas :



NVERTED FLOW AREA

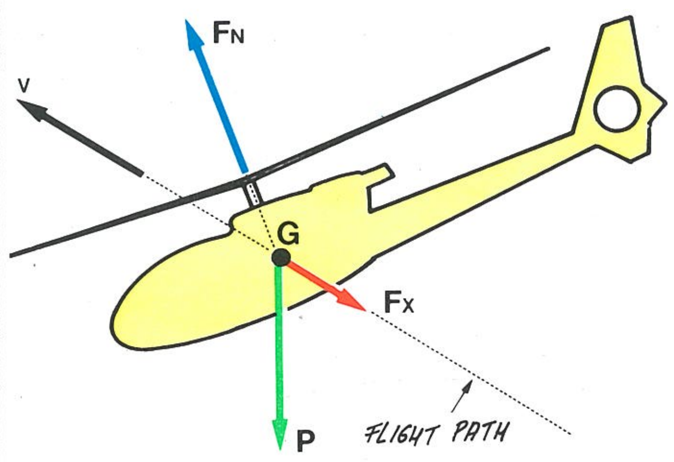
NEGATIVE STALL AREA
U is very low. Angle of attack 'i' is negative and very high = stall.

POSITIVE STALL AREA. The retreating blade rises, the angle of attack is very large and positive = stall.

Finally, velocity U of blades must not be close to the speed of sound velocity (Mach 1) as, at Mach 0.8, compressibility phenomena appear. They cause the separation of the boundary layer and, therefore, loss of lift, vibration etc ... Here it is the advancing blade which is the problem where U and v are added. Keep in mind that, for this reason the blade velocity U is limited to approximately 250 m s.).

7. HELICOPTER FLIGHT and the power required

FORCES ACTING ON THE HELICOPTER IN FLIGHT



In flight, three forces act on the helicopter :

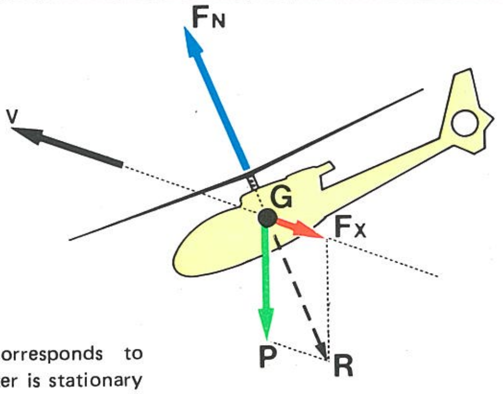
- its weight P, applied at the centre of gravity G.
- The aircraft's overall drag F_X resulting, in forward flight, from the resistance opposed by the air to the airframe. F_X is applied at the helicopter's aerodynamic centre, which to simplify the explanation is assumed to coincide with the centre of gravity G. Direction of F_X : opposite to that of forward speed 'v'.

Lift F_N, applied at the rotor centre, perpendicular to the rotation plane.

HELICOPTER EQUILIBRIUM IN FLIGHT

For the helicopter to be in equilibrium, resultant R of weight P and drag F_X should be equal and acting in opposite direction to lift F_N. The overall resultant of the forces applied is then equal to zero.

The equilibrium condition corresponds to stabilized flight. If the helicopter is stationary (hovering), it remains so. If the helicopter is moving (forward flight) its speed is CONSTANT and its flight path STRAIGHT.



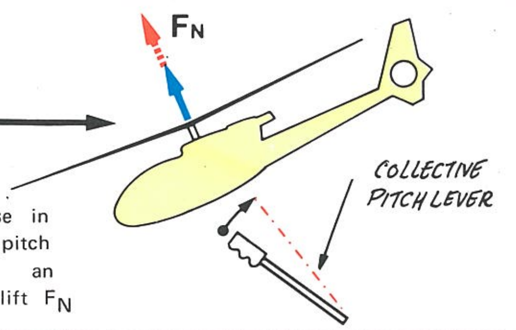
R EQUAL AND OPPOSITE TO FN THE HELICOPTER IS IN EQUILIBRIUM

BE QUIET... BE QUIET, AERODYNAMIX YOUR TRIBULATIONS ARE NEARLY OVER !

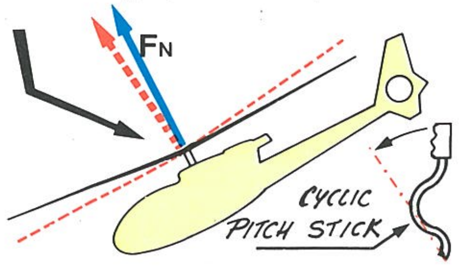
VARIATION OF THE FORCES IN ACTION

VARIATION OF LIFT FN (REMINDER)

- The magnitude of F_N depends on the collective pitch.
- The direction of F_N depends on the cyclic pitch.

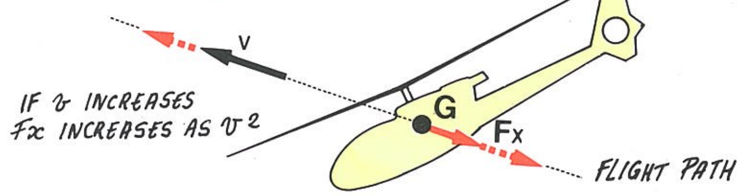


The increase in collective pitch results in an increase in lift F_N



The variation of cyclic pitch changes the tilt of F_N. It is inclined in the same direction as the cyclic stick and through an angle proportional to the cyclic stick travel.
For a given collective pitch θ, F_N decreases as the altitude (or temperature) increases and increases as the forward speed increases.
To maintain constant lift, it is necessary to increase θ as the altitude (or temperature) increases.

Variation of drag F_X.

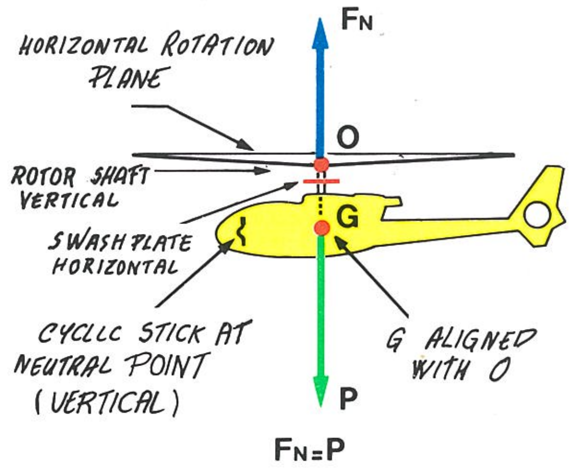


Drag F_X is expressed (as you know) by the equation $F_X = 1/2\, \rho S v^2 C_X$. where C_X is the aircraft unit drag factor and S the cross-section area. (They are constant values for a given flight path).
Remember that F_X is proportional to the square of the forward speed "v" and to the air density "ρ"

HOVERING

EQUILIBRIUM IN "THEORETICAL" HOVERING

(Zero wind and centre of gravity G aligned with the center of rotation O).



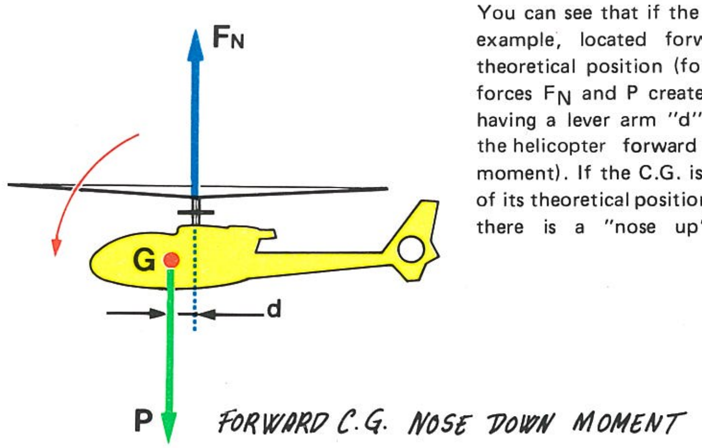
- In no wind conditions, the only forces in action are the lift F_N and weight P.
- The center of gravity G is aligned with the center of rotation O, hence forces F_N and P are aligned (without change in the aircraft attitude) and the rotor shaft is vertical.
- The pilot, acting on the collective pitch lever, adjusts the collective pitch θ value to ensure equilibrium :

$$F_N = P$$

- The cyclic pitch stick is placed in neutral position (vertical), the swash plate is horizontal, therefore there is no cyclic pitch variation and the rotation plane is horizontal.

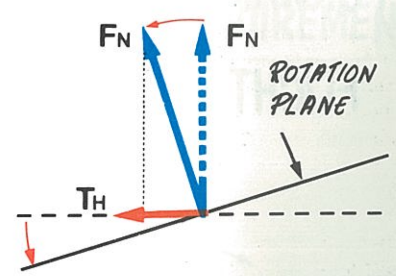
EFFECT OF CENTRE OF GRAVITY 'G' LOCATION ON HOVERING

The center of gravity is not exactly aligned with the rotor center of rotation (theoretical location). It moves between the FORWARD and REAR C.G. limits according to the load carried and the fuel consumption.

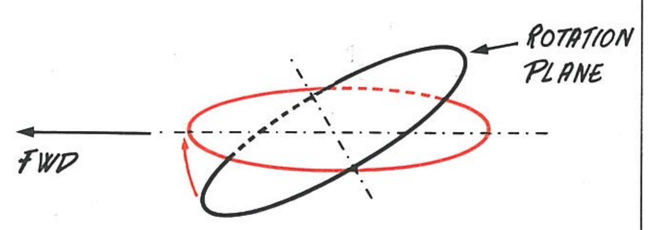


You can see that if the C.G. is, for example, located forward of its theoretical position (forward C.G.) forces F_N and P create a moment having a lever arm "d" which tilts the helicopter forward (nose down moment). If the C.G. is located aft of its theoretical position (rear C.G.) there is a "nose up" moment.

If the cyclic stick is kept in neutral (theoretical hovering), the swash plate tilts with the helicopter (it remains perpendicular to the rotor shaft) together with the rotor rotation plane and lift F_N : the lift horizontal component T_H will initiate forward flight.

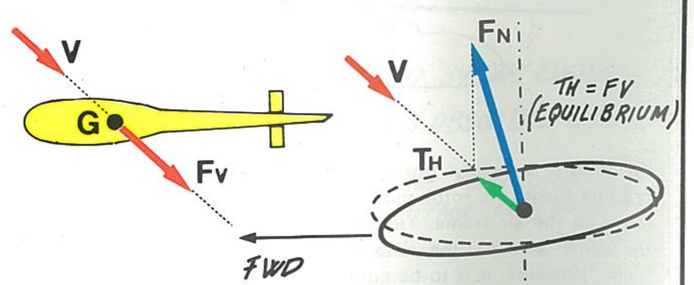


To stay in a hover, the rotation plane has to be brought back to the horizontal.



If the rotor is tilted forward (forward C.G.) the cyclic stick must be moved rearward to produce a cyclic pitch variation which will tilt back the rotation plane and cancel the horizontal component T_H. In the case of rear C.G. the stick must be moved forward.

EFFECT OF THE WIND ON HOVERING



If there is wind, the helicopter will drift at speed V (force F_V). To maintain hovering (cancel the drift), a new force is to be opposed to F_V. This new force is obtained by tilting the rotor disc in the opposite direction to that of the wind in such a way that horizontal component T_H is equal and opposite to F_V. Hence, in a hover, to cancel the wind effect, the cyclic stick is to be moved in the opposite direction to that of the wind and through a distance proportional to the speed of the wind.

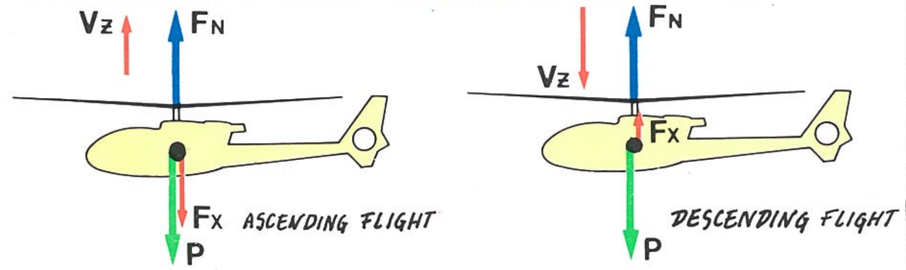
CONCLUSION :

Hovering flight requires :

- The equality $F_N = P$, obtained by action on the collective pitch lever (only one lever position for a given altitude and weight "P").
- The compensation of parasite forces (C.G. location, wind ... etc.*), obtained by action on the cyclic stick. And this is the real art of handling, as in hovering, the pilot has to anticipate these parasite forces (particularly the wind) by nearly continuous action on the cyclic stick.

* There are other parasite forces ; for example : the residual thrust of the turbine engines.

ASCENDING AND DESCENDING FLIGHT



Vertical flight from hovering is initiated by acting on the collective pitch lever.

- Increase of pitch. F_N increases and the helicopter climbs ($F_N > P$)
- Decrease of pitch. F_N decreases and the helicopter descends ($F_N < P$).

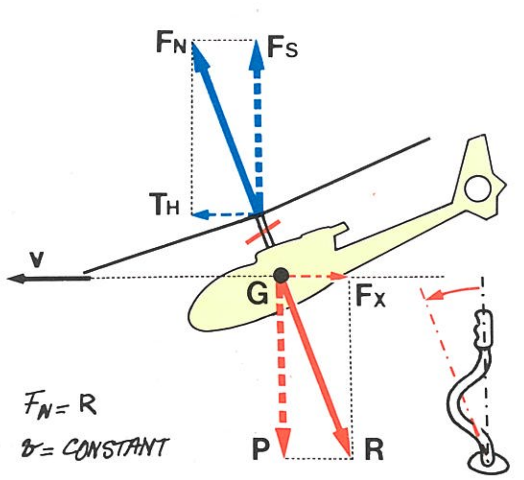
It is to be noted that drag F_x, which increases with vertical speed V_Z, gives an equilibrium position (V_Z = constant) when

$F_N = P + F_x$ (in ascending flight)

$F_N + F_x = P$ (in descending flight)

FORWARD FLIGHT

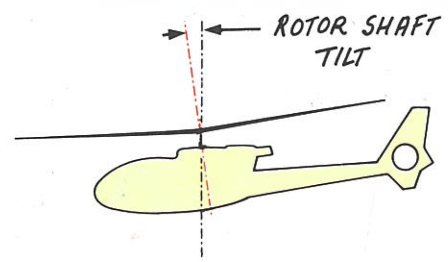
EQUILIBRIUM IN FORWARD FLIGHT



By moving the cyclic stick forward, there is a longitudinal cyclic pitch variation causing a forward tilt of the rotor disc (this tilt is proportional to the stick travel). Then, lift F_N has two components :

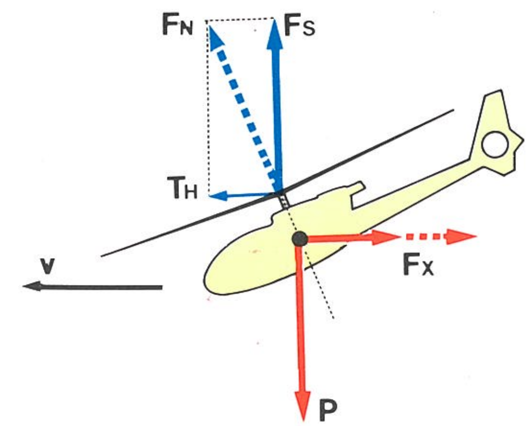
- F_S providing lift and balancing weight P
- T_H providing forward drive and balancing drag F_x.

The aircraft attitude corresponds to the rotor disc tilt, this being uncomfortable for the crew (and the passengers), particularly at high speed when rotor disc tilt is increased to have a greater T_H.



To ensure a nearly horizontal helicopter attitude in cruising flight, the rotor shaft is tilted slightly forward relative to the air frame. This tilt (about 5°) decreases, by the same amount, the nose down attitude in forward flight. However, it is to be noted that, hovering, the rotor shaft tilt has to be compensated by moving the cyclic stick rearward.

EFFECT OF DRAG Fx



For given collective and cyclic pitches (i.e.a well defined value of T_H and F_S), forward speed "v" will increase until the drag ($F_x = 1/2\, \rho S v^2 C_x$), increasing as the square of this speed, balances the forward component T_H. Then, the forward speed remains constant. After that, if a higher speed v is desired, F_N (i.e. T_H) has to be increased. The new value of T_H corresponds to a new equilibrium speed. It is to be noted that any higher of F_N results in an increase of F_S. Hence, if an altitude gain is not desired, the rotor disc has to be tilted a little more.

EFFECT OF FORWARD SPEED "V" ON LIFT "FN" (REMINDER)

For a given value of collective pitch, lift F_N increases as the forward speed increases.

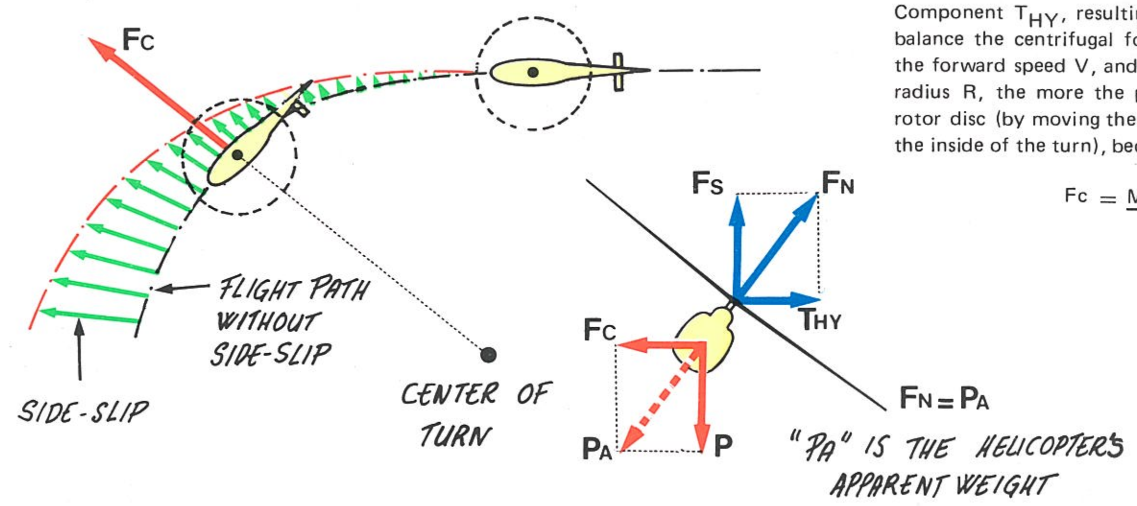
Consequence : The collective pitch required for forward flight is smaller than that required in hovering. We will review this when talking about the power required for flight.

EQUILIBRIUM IN TURNS

In turns, a new force appears, the centrifugal force F_C which, if not balanced, would cause side-slipping. To balance F_C, it is again rotor disc tilt which is used :

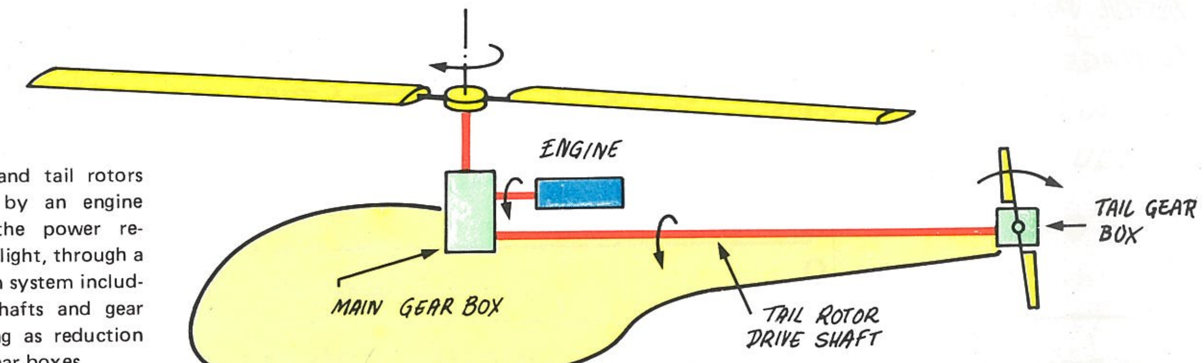
lateral tilt towards the inside of the turn. Component T_{HY}, resulting from this tilting, balance the centrifugal force F_C. The higher the forward speed V, and the tighter the turn radius R, the more the pilot has to tilt the rotor disc (by moving the cyclic stick towards the inside of the turn), because :

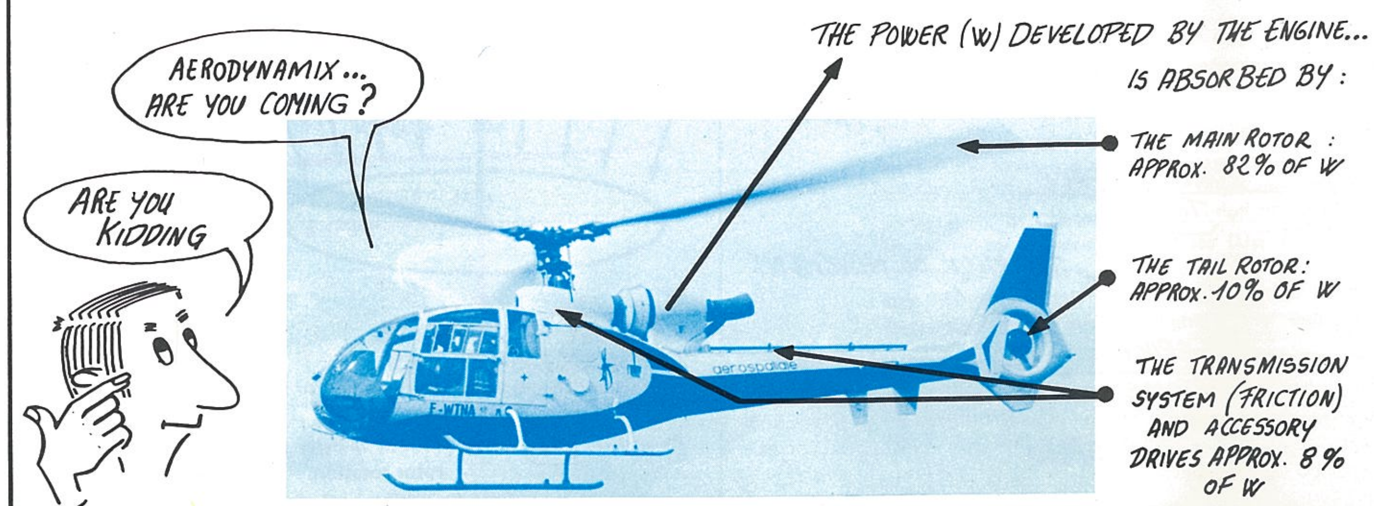
$$F_C = \frac{Mv^2}{R}$$



THE POWER REQUIRED FOR FLIGHT AND BASIC POWER REQUIREMENTS

The main and tail rotors are driven by an engine supplying the power required for flight, through a transmission system including drive shafts and gear boxes acting as reduction and angle gear boxes.

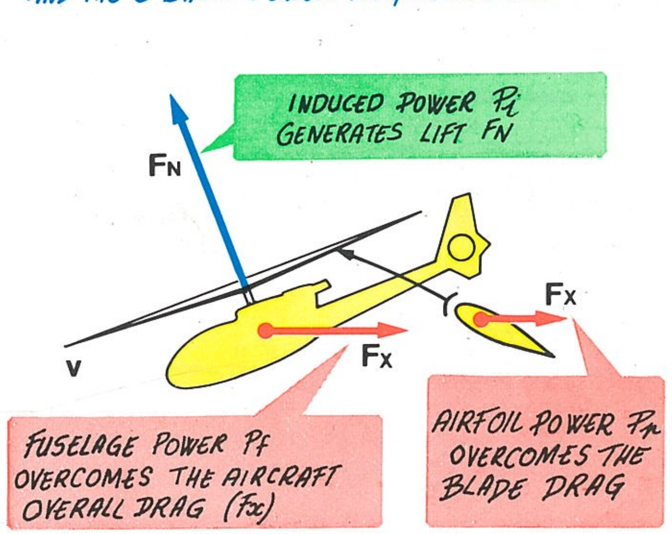




DEFINITIONS:

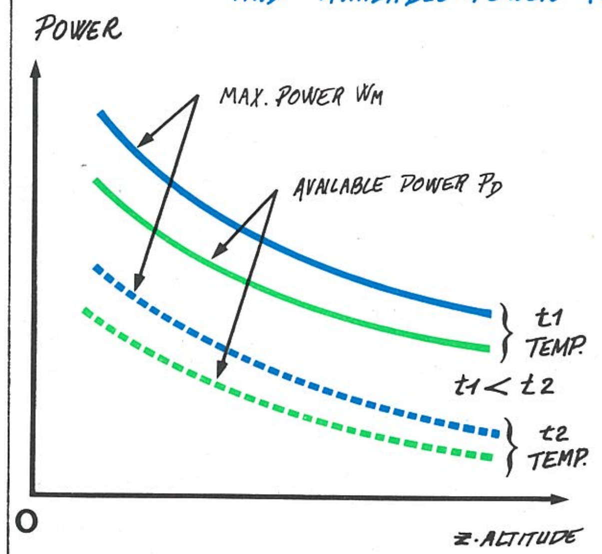
- The AVAILABLE POWER (P_D) is the power usable at the main rotor, that is power "W" developed by the engine, less the power absorbed by the tail rotor and transmission system. It amounts to 80 - 85 % of W.
- The power required for flight (P_N) is the energy absorbed by the main rotor to keep the helicopter flying. The power required depends on the flight conditions ; helicopter weight, altitude, forward speed, ambient temperature. It is limited by the available power (P_D), since the main rotor cannot absorb more energy (PN) than it receives (P_D).

THE 3 LEVELS OF THE POWER REQUIRED (P_N) AND THE 3 BASIC POWER REQUIREMENTS



POWER REQUIRED (P_N) = INDUCED POWER (P_i) + AIRFOIL POWER (P_p) + FUSELAGE POWER (P_f)

VARIATION OF MAX POWER (W_M) DEVELOPED BY THE ENGINE AND AVAILABLE POWER (P_D).



The engine power W depends on the air density ρ. W decreases as ρ decreases. ρ depends on the atmospheric pressure and the air temperature and so... power decreases as the altitude and temperature increase.

The available power (P_D), being a constant percentage of W_1 (82% approx.), varies as W_M.

GENERAL EXPRESSION OF POWER (REMINDER)

$P = \frac{\text{FORCE} \times \text{SPACE}}{\text{TIME}}$

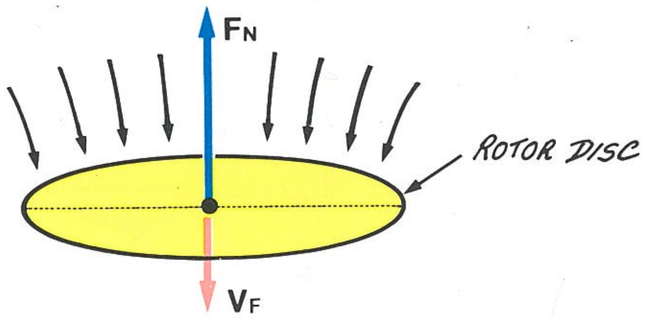
FORCE x SPACE → MOVEMENT OF FORCE APPLICATION POINT

TIME → DURATION OF MOVEMENT

SINCE $\frac{\text{SPACE}}{\text{TIME}} = \text{SPEED}$

P = FORCE x SPEED

INDUCED POWER Pi



This demonstrates that the expression for induced power is :

$P_i = F_N \cdot V_F$ → Froude velocity transmitted to the air by the rotor rotation.

VARIATION OF INDUCED POWER $P_i = F_N \cdot V_F$

- The term F_N of the induced power expression depends on the helicopter weight only :

$F_N = P = m.g$

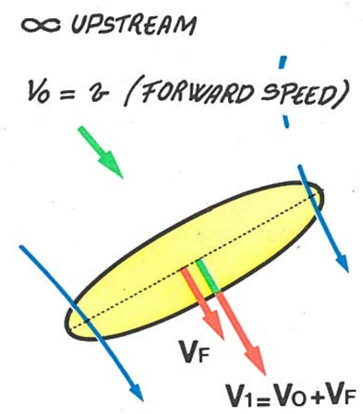
- The term V_F depends mainly on forward speed v, in fact (remember)

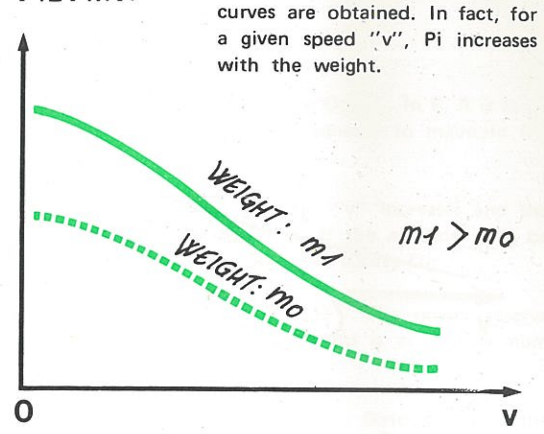
$V_1 = V_0 + V_F$. $V_F = V_1 - V_0$

Vo, velocity at the infinite upstream of the rotor disc is equal to the forward speed v. Hence, the expression :

$V_F = V_1 - v$

Remember that V_F (hence Pi) decreases as v increases.





This is the general pattern of Pi variation relative to v. It is to be noted that for different helicopter weights (mo , m1 ...), different curves are obtained. In fact, for a given speed "v", Pi increases with the weight.

AIRFOIL POWER (P_p)

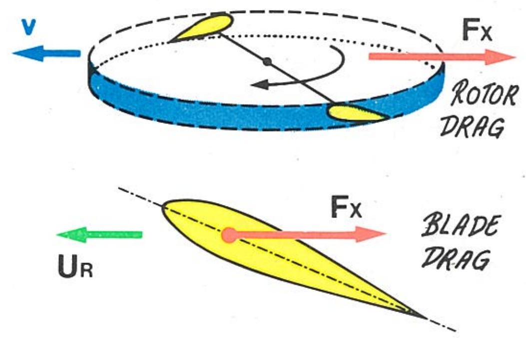
ALSO CALLED PASSIVE POWER

This is the power required to overcome blade drag. The expression for the rotor overall drag is similar to that of the blade :

$F_x = 1/2\ \rho\ S\ v^2\ C_x$.

where

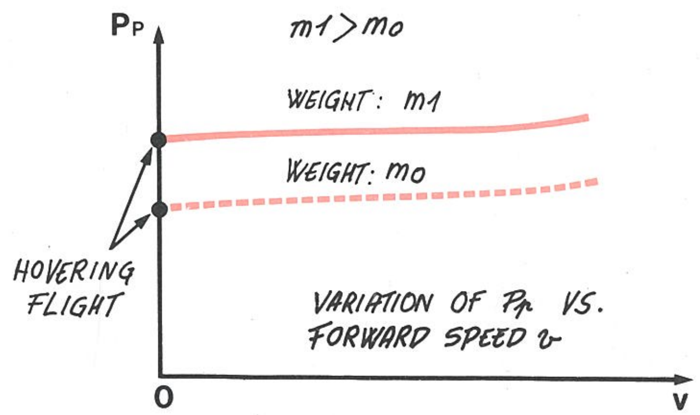
- ρ : air density
- S : airfoil cross-section area
- v : airfoil relative velocity $v = U_R$
- C_x : rotor unit drag coefficient.



AIRFOIL POWER (P_p) IS THE PRODUCT OF THE ROTOR DRAG TIMES THE RELATIVE BLADE VELOCITY (U_R)

$P_p = F_x \cdot U_R$
$= \frac{1}{2} \rho S . U_R^2 . C_x . U_R$
$= \frac{1}{2} \rho S . U_R^3 C_x$

VARIATION OF AIRFOIL POWER

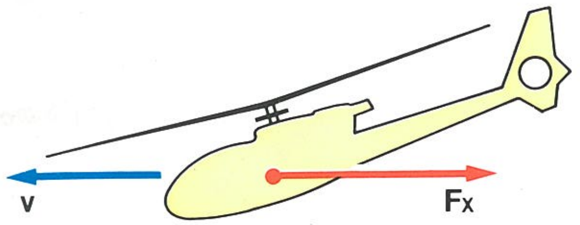


The variable terms of the Pp expression are :
ρ , U_R and C_x

Effect of these terms on P p :

- ρ : Pp increases as the altitude or temperature increases
- U_R :
  - In a hovering, where $U_R = U = \omega R$, Pp is constant. In fact, the rotor operates at constant speed.
  - In forward flight, the relative blade velocity U_R varies with the forward speed "v". But, if the advancing blade velocity increases ($U_R = U + v$) that of the retreating blade decreases ($U_R = U - v$) and "v" brings little change in the airfoil power. Remember that Pp increases slightly as "v" increases.
- C_x : C_x varies with lift (C_Z), hence Pp increases together with F_N, that is with the helicopter weight $P = m.g$.

FUSELAGE POWER (Pf)



This is the power required to overcome the helicopter drag. Therefore, like the airfoil power, it is a passive power. The expression for the helicopter drag is :

$Fx = 1/2 \rho . S . V^2 . Cx$

where :

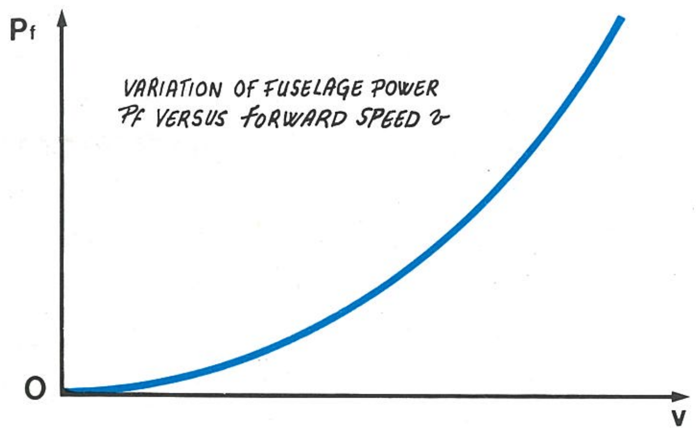
- S : max cross-section area
- v : forward speed
- C_x : drag coefficient.

$Fx = 1/2 \rho S . v^2 Cx$

The fuselage power is the product of the helicopter drag times the forward speed.

$P_f = F_x . v$
$= 1/2 \rho . S . v^2 . C_x . v$
$= 1/2 \rho . S . v^3 . C_x .$

VARIATION OF FUSELAGE POWER

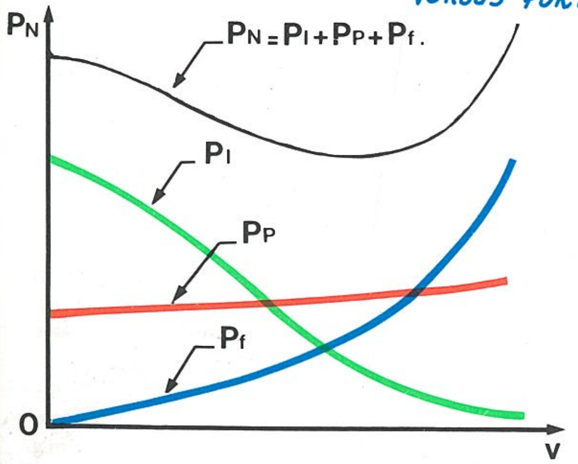


$P_f = 1/2 \rho . S . v^3 . C_x$

The terms S and C_x in the fuselage power expression have little effect and depend on the helicopter flight path.
(Variation of max. cross-section and angle of attack of helicopter surfaces.).

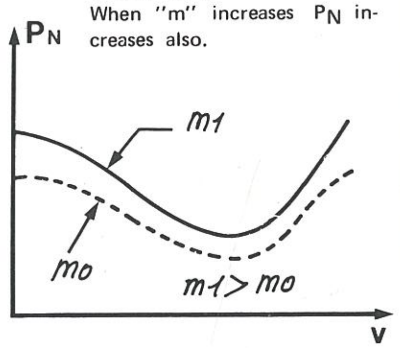
- ρ has the usual effect : P_f decreases as the altitude or temperature increases.
- But the forward speed factor "v" plays a significant role. P_f varies as the cube of this speed ; that is, the fuselage power increases very quickly as the forward speed increases.

VARIATION OF THE POWER REQUIRED P_N VERSUS FORWARD SPEED v.

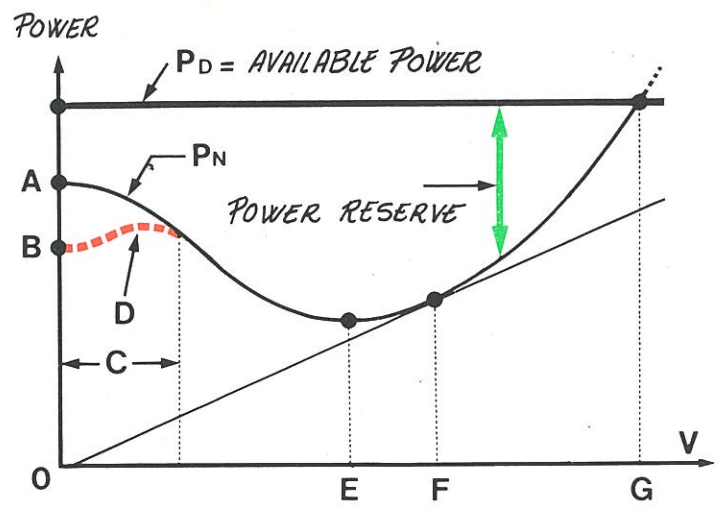


The power required P_N is the sum of the 3 basic power ratings : Pi, P_p and P_f. If, for each value of the forward speed, the corresponding values of Pi, P_p and P_f are added, the "P_N variation vs. speed "v" curve is obtained for a given altitude and weight. You may note that P_N decreases as "v" increases, falls to a minimum value then increases rapidly (effect of P_f).

EFFECT OF HELICOPTER WEIGHT "m". As for the elementary curves, there is a P_N curve for each helicopter weight "m".
When "m" increases P_N increases also.



REVIEW OF THE CURVE "POWER REQUIRED VS. SPEED" - NOTEWORTHY POINTS



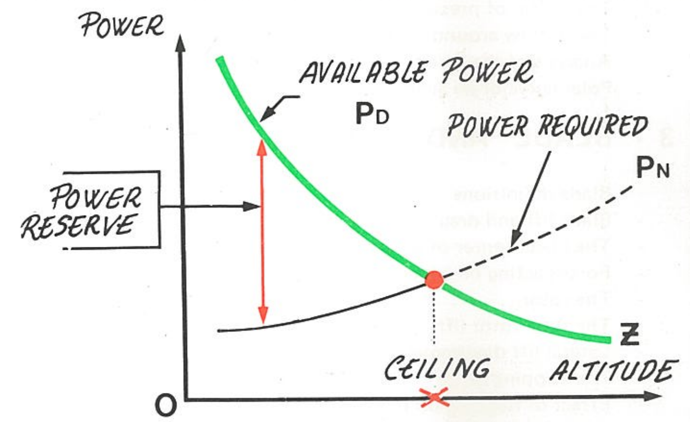
- In A, the helicopter is hovering O.G.E.. In B, it is in an I.G.E. hover. Less power is required to maintain the I.G.E. hover.
- C is called the transition zone, "v" increases and the ground effect is less effective. If the altitude is to be held, the power has to be increased (Curve D).
- E - MINIMUM POWER SPEED - The power reserve (space between P_D and P_N curves) is at its maximum value.
- F - MAX. EFFICIENCY SPEED - Determined by the tangent drawn to the curve from "0". The $\frac{P_N}{V}$ ratio is the smallest possible ; this means that at this point, the highest possible speed is obtained at the lowest possible power (best range speed).
- G - Maximum speed. Determined by the intersection of the P_N and P_D curves. There is no power reserve.

HELICOPTER CEILINGS

ALTITUDE LIMITS

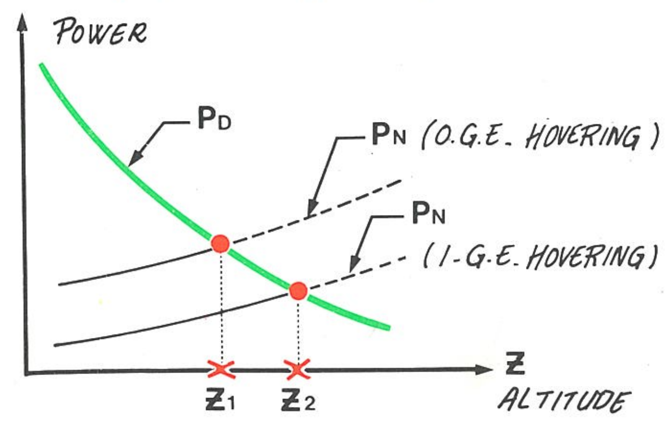
The culprit here is the air density (and solely that) which decreases progressively as the altitude, increases :

- Firstly the altitude increases, the engine suffers more and more from a lack of air and the power developed falls as does The the associated available power P_D.
- Secondly the air's carrying capacity, is progressively decreasing and more energy (pitch, increase) is required to maintain the same lift value. Therefore the result is an increase of the induced power (Pi), and hence of the power required (P_N).



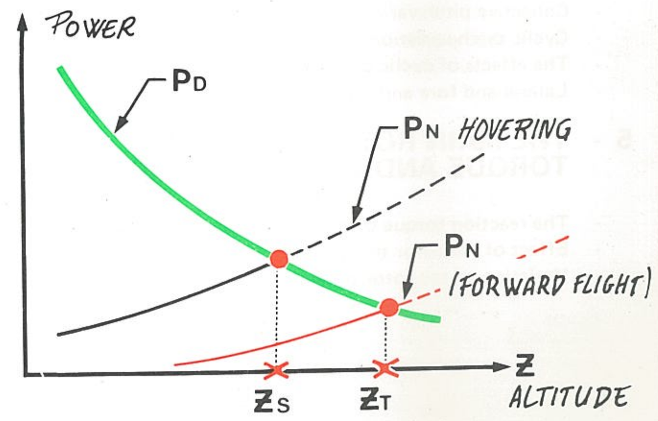
CONSEQUENCE : Obviously, the "P_N" upward curve intersects the P_D downward curve - the corresponding altitude is called "CEILING" there is no power reserve and the helicopter cannot climb any longer.

CEILING IN HOVERING FLIGHT...



In ground effect, where less power is absorbed the ceiling is higher than in O.G.E. conditions : $Z2 > Z1$

AND IN FORWARD FLIGHT



The power required P_N decreases as the forward speed increases. Therefore, the ceiling in forward flight is higher than the ceiling in hovering flight : $Z_t > Z_s$.