Spring Semester 2023

AIRCRAFT AERODYNAMICS & FLIGHT MECHANICS

20.04.2023

Dr. Marc Immer ALR Aerospace

This lecture is adapted with permission from the lecture "Ausgewählte Kapitel der Flugtechnik" by Dr. Jürg Wildi

Know the difference between longitudinal stability, control and trim

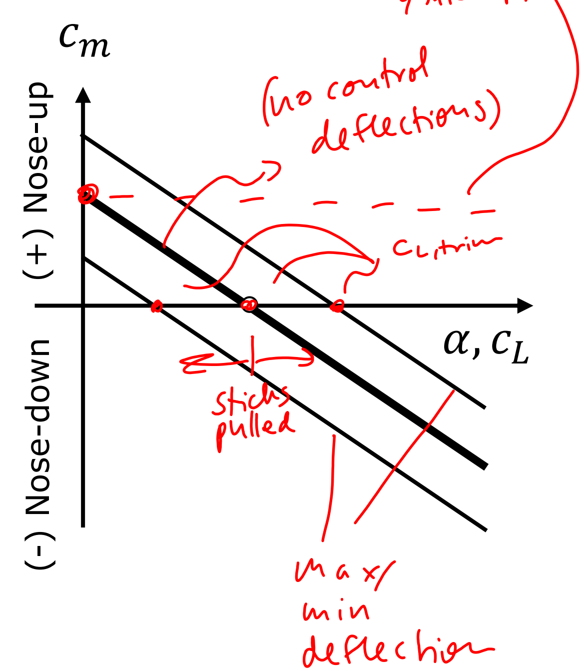
CG shifting rotates curve ~ about y intercept

short form

$$c_{M_{CG}} = c_L\left(\frac{\tilde{x}_{CG} - \tilde{x}_{\mathrm{AC},W}}{l_{ref}}\right) + c_{M_{\mathrm{AC},W}} + c_{M_F} - c_{L_\alpha,H}\eta_H V_H(\alpha_H)$$

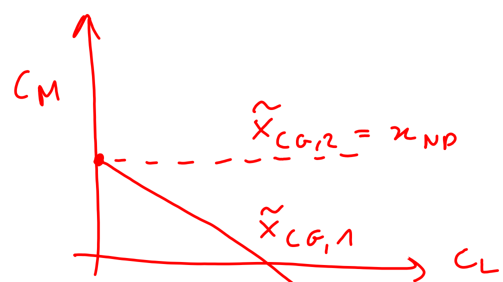
expanded in long form

$$\frac{dc_{M_{CG}}}{dc_L} = \frac{\tilde{x}_{CG} - \tilde{x}_{\mathrm{AC},W}}{l_{ref}} + \frac{dc_{M_F}}{dc_L} - \frac{c_{L_\alpha,H}}{c_{L_\alpha,W}}\eta_H V_H\left(1 - \frac{d\varepsilon}{d\alpha}\right)$$



NP: Neutral point – aerodynamic center of the aircraft

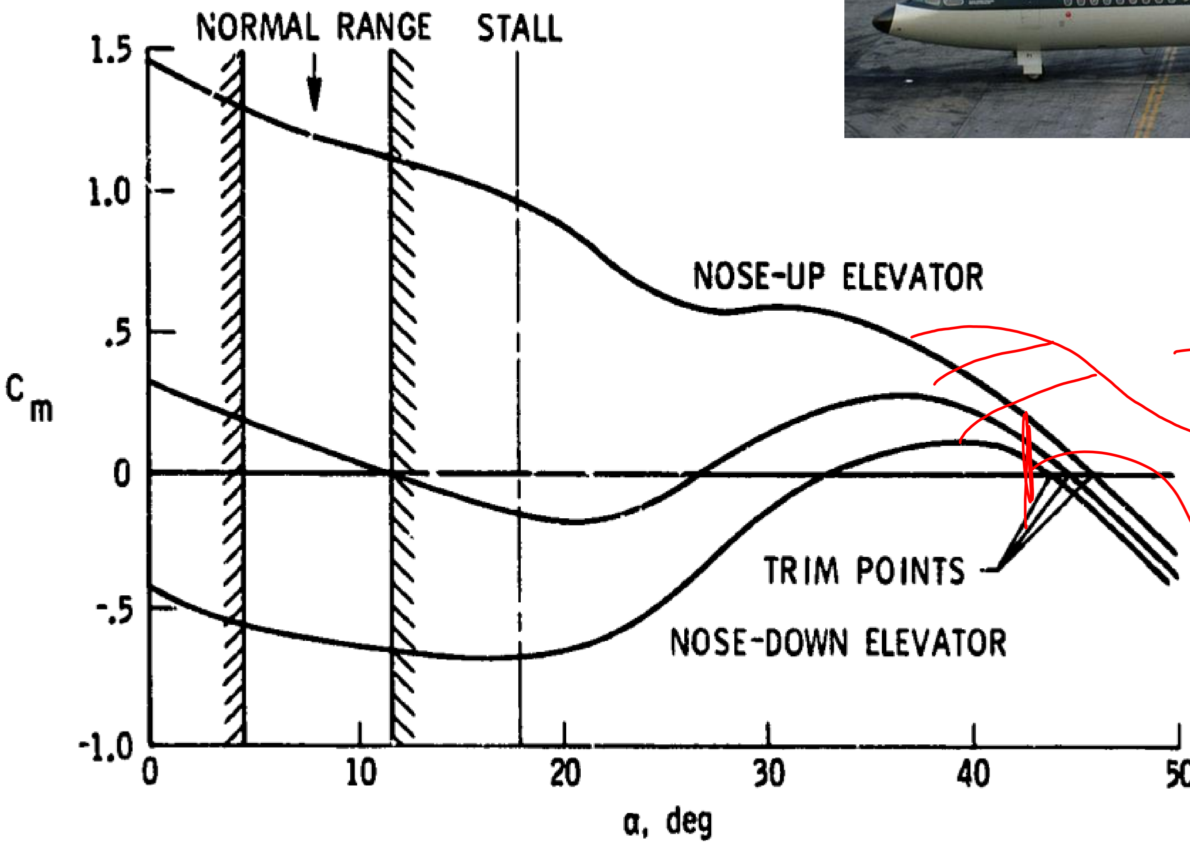
$$\frac{dc_M}{dc_L} = \frac{\tilde{x}_{CG} - \tilde{x}_{\mathrm{NP}}}{l_{ref}}$$



Deep Stall

British European Airways Flight 548

attached flow



different T-Tail deflections

deep stall (max deflections cannot change α (pitch) anymore)

(tail is in turbulent wake of main wing)

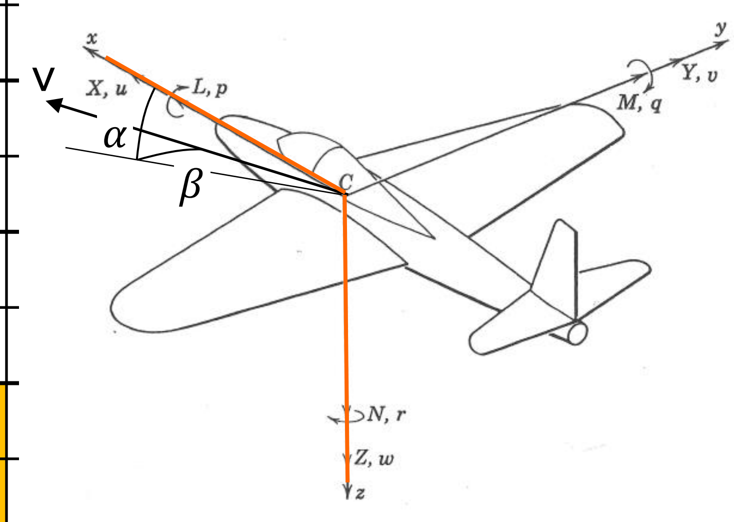
Static Stability

Disturbance		Velocity			Incidence Angles		Angular Velocity		
Forces/Moments		u	v	w	β = v / V	α = w / V	p	q	r
X-Force	$F_{A_x} + F_{T_x}$	$\frac{\partial}{\partial u}(F_{A_x} + F_{T_x}) < 0$							
		$c_{T_{x_u}} - c_{D_u} < 0$							
Y-Force	$F_{A_y} + F_{T_y}$		$\frac{\partial}{\partial v}\left(F_{A_y} + F_{T_y}\right) < 0$						
			$c_{y_\beta} < 0$						
Z-Force	$F_{A_z} + F_{T_z}$			$\frac{\partial}{\partial w}(F_{A_z} + F_{T_z}) < 0$					
				$c_{L_\alpha} > 0$					
Roll-Moment	$L_A + L_T$				$\frac{\partial}{\partial \beta}(L_A + L_T) < 0$		$\frac{\partial}{\partial p}(L_A + L_T) < 0$		
					$c_{l_\beta} < 0$		$c_{l_p} < 0$		
Pitch-Moment	$M_A + M_T$	$\frac{\partial}{\partial u}(M_A + M_T) > 0$				$\frac{\partial}{\partial \alpha}(M_A + M_T) < 0$		$\frac{\partial}{\partial q}(M_A + M_T) < 0$	
		$c_{m_u} > 0$				$c_{m_\alpha} < 0$		$c_{m_q} < 0$	
Yaw-Moment	$N_A + N_T$				$\frac{\partial}{\partial \beta}(N_A + N_T) > 0$				$\frac{\partial}{\partial r}(N_A + N_T) < 0$
					$c_{n_\beta} > 0$				$c_{n_r} < 0$

what we looked at

Directional and Lateral Static Stability

Disturbance		Velocity			Incidence Angles		Angular Velocity		
Forces/Moments		u	v	w	β = v / V	α = w / V	p	q	r
X-Force	$F_{A_x} + F_{T_x}$	$\frac{\partial}{\partial u}(F_{A_x} + F_{T_x}) < 0$							
		$c_{T_{x_u}} - c_{D_u} < 0$							
Y-Force	$F_{A_y} + F_{T_y}$		$\frac{\partial}{\partial v}\left(F_{A_y} + F_{T_y}\right) < 0$						
			$c_{y_\beta} < 0$						
Z-Force	$F_{A_z} + F_{T_z}$			$\frac{\partial}{\partial w}(F_{A_z} + F_{T_z}) < 0$					
				$c_{L_\alpha} > 0$					
Roll-Moment	$L_A + L_T$				$\frac{\partial}{\partial \beta}(L_A + L_T) < 0$				
					$c_{l_\beta} < 0$				
Pitch-Moment	$M_A + M_T$	$\frac{\partial}{\partial u}(M_A + M_T) > 0$				$\frac{\partial}{\partial \alpha}(M_A + M_T) < 0$		$\frac{\partial}{\partial q}(M_A + M_T) < 0$	
		$c_{m_u} > 0$				$c_{m_\alpha} < 0$		$c_{m_q} < 0$	
Yaw-Moment	$N_A + N_T$				$\frac{\partial}{\partial \beta}(N_A + N_T) > 0$				$\frac{\partial}{\partial r}(N_A + N_T) < 0$
					$c_{n_\beta} > 0$				$c_{n_r} < 0$

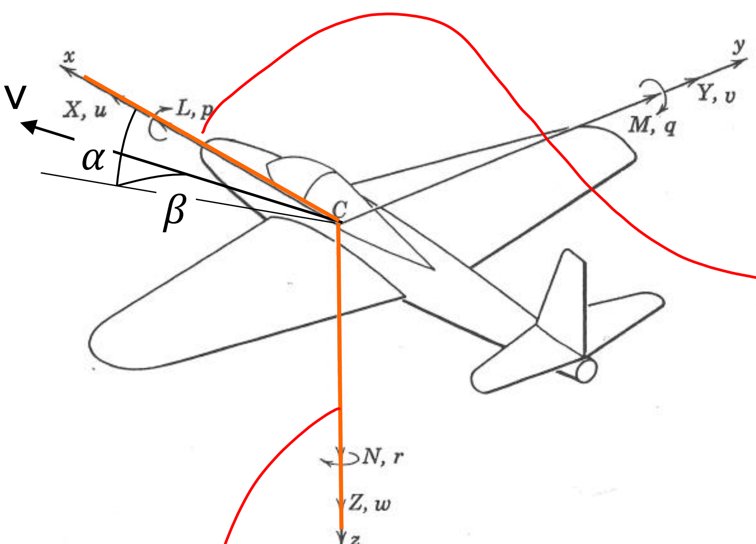


Certification Specifications CS-23

CS 23.177 Static directional and lateral stability

(a) The static directional stability, as shown by the tendency to recover from a wings level sideslip with the rudder free, must be positive for any landing gear and flap position appropriate to the take-off, climb, cruise, approach and landing configurations. This must be shown with symmetrical power up to maximum continuous power and at speeds from 1·2 VS1 up to maximum allowable speed for t
investigated. The angle of
must be appropriate to the
larger angles of sideslip u
rudder is used or a c
CS 23.143 is reached, whic
at speeds from 1·2 VS1 to
force must not reverse.

(b) The static lateral stability, as shown by the tendency to raise the low wing in a sideslip, must be positive for all landing gear and flap positions. This must be shown with symmetrical power up to 75% of maximum continuous power at speeds above 1·2 VS1 in the take-off configuration(s) and at speeds above 1·3 VS1 in other configurations, up to the maximum
the configuration being
ce-off, climb, cruise and
is. For the landing



lateral stability (roll)

$\frac{dc_n}{d\beta}$

$c_{n_\beta} > 0$

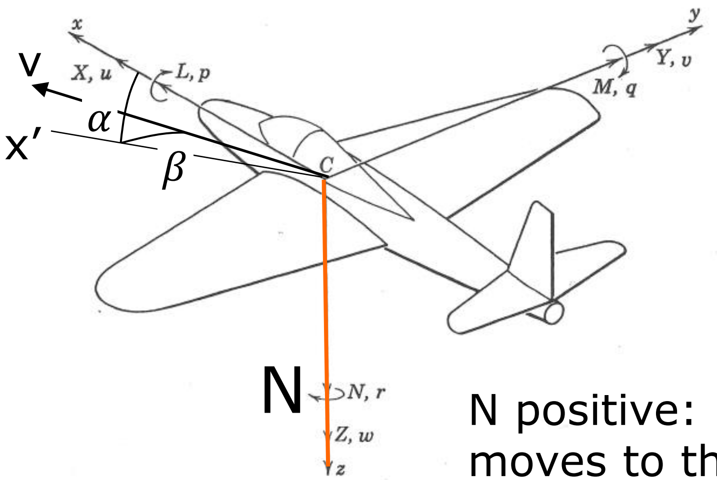
directional stability (yaw)

$c_{l_\beta} < 0$

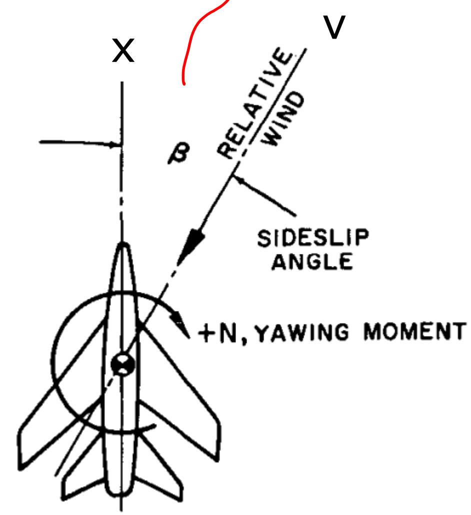
Directional Static Stability

A disturbance causes a sideslip angle β.
The airplane reacts with a yawing moment $\Rightarrow \dfrac{dc_n}{d\beta}$

positive angle β : wind comes from right



N positive: nose moves to the right



Positive directional static stability:
A positive sideslip angle results in a positive yawing moment

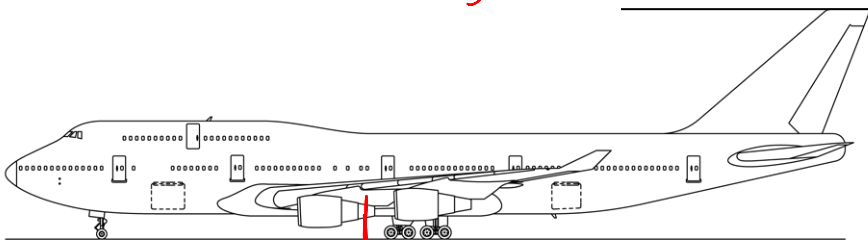
$$c_{n_\beta} = \frac{dc_n}{d\beta} > 0$$

VTP – Vertical Tail Plane

surfaces behind CG stabilize airplane

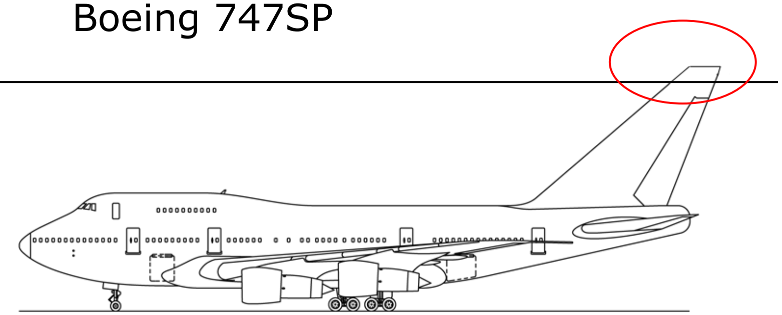
& surfaces in front of CG destabilize

Boeing 747-400



CG close to main landing gear

Boeing 747SP

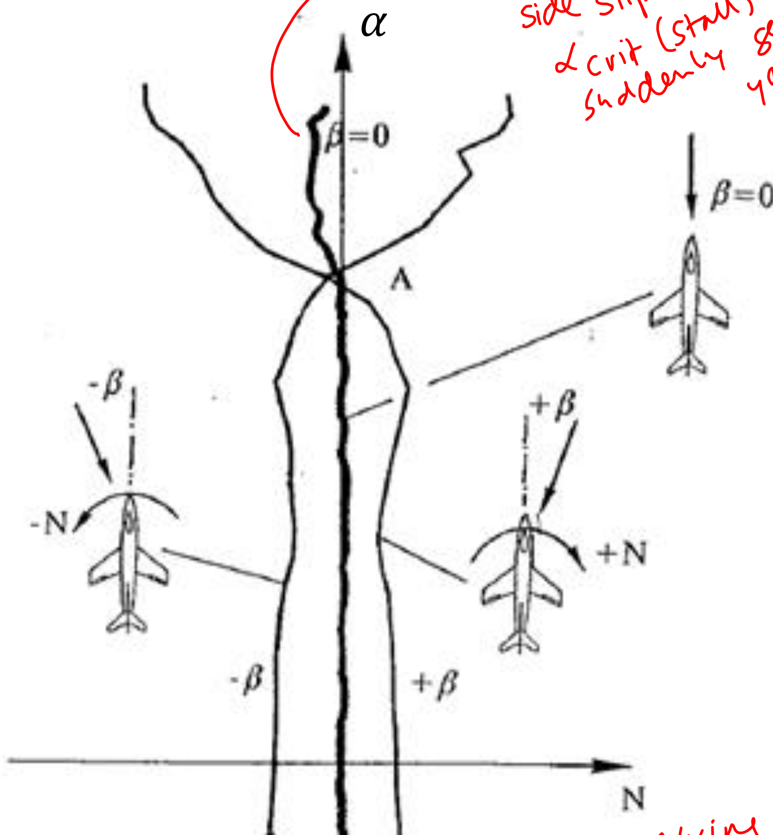


very large tail as we also need to maintain stability (control if critical (outboard) engine fails on one side (yaw disturbance)

Nose Strake

Directional Static Stability

even at zero side slip above α crit (stall) we suddenly get a yawing moment due to asymmetric flow detachment (around nose)



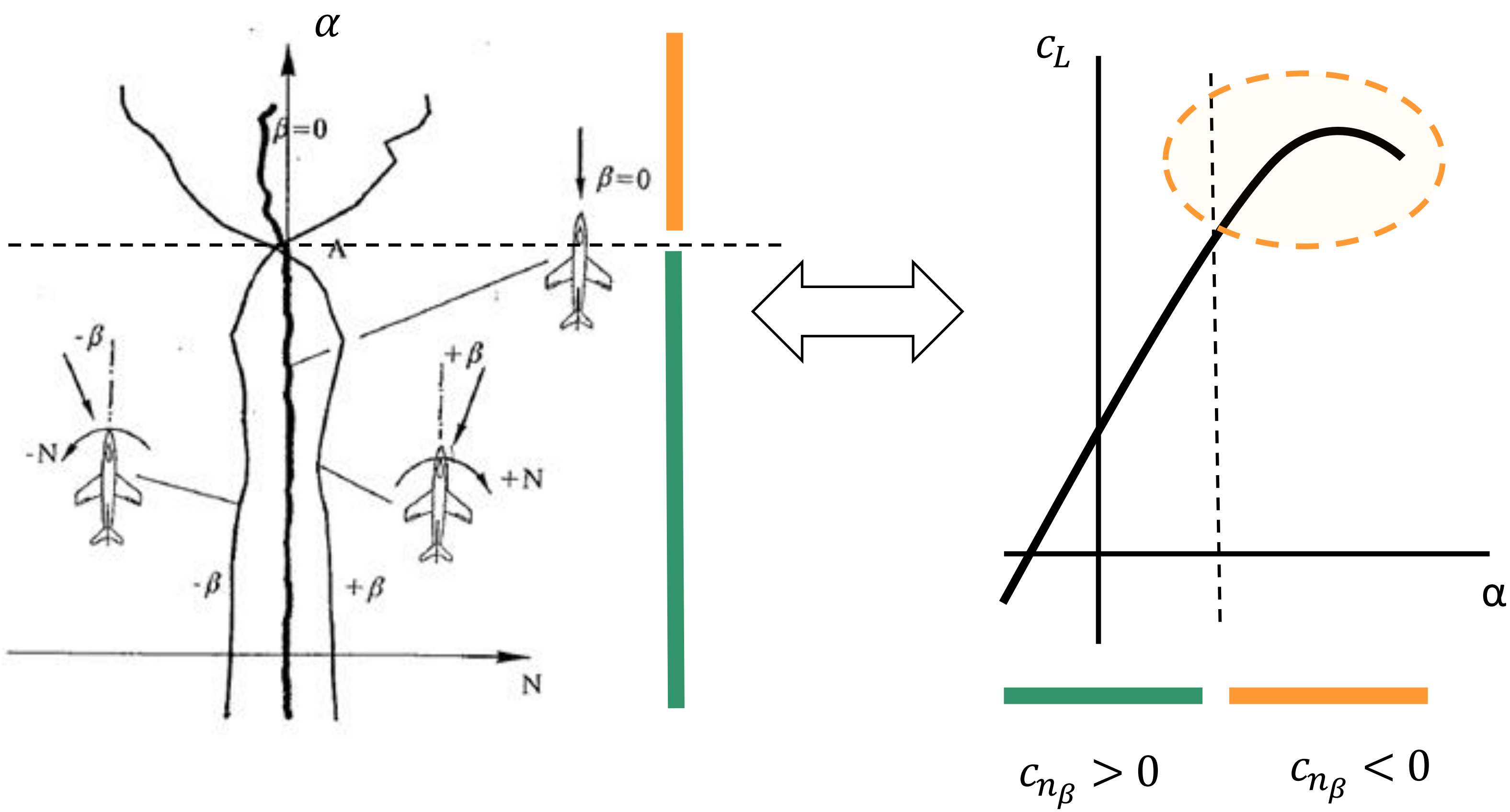
yawing moment

$$c_{n_\beta} = \frac{dc_n}{d\beta} < 0$$

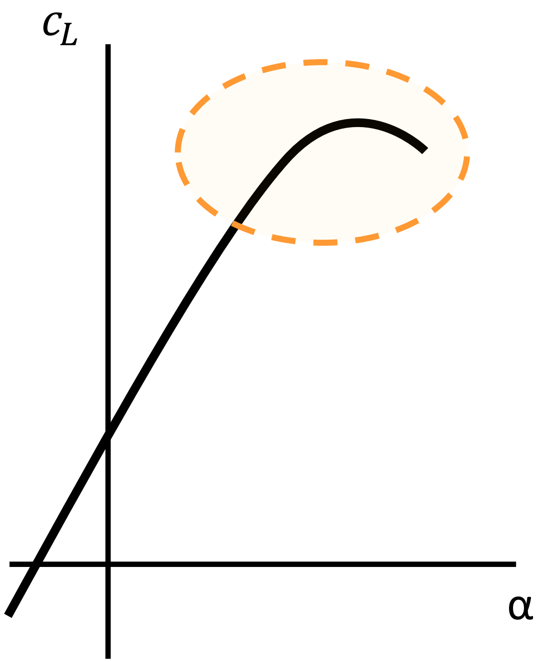
negative stability (instable)

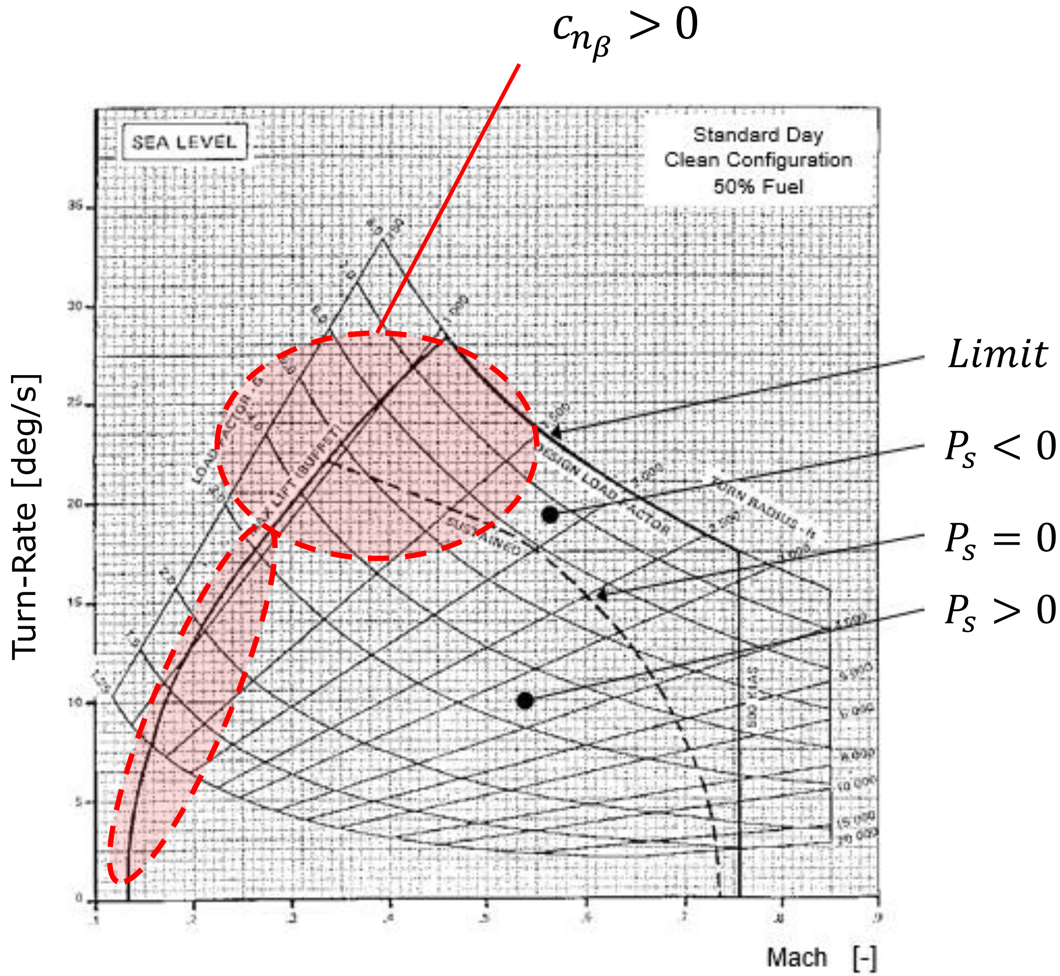
$$c_{n_\beta} = \frac{dc_n}{d\beta} > 0$$

Directional Static Stability

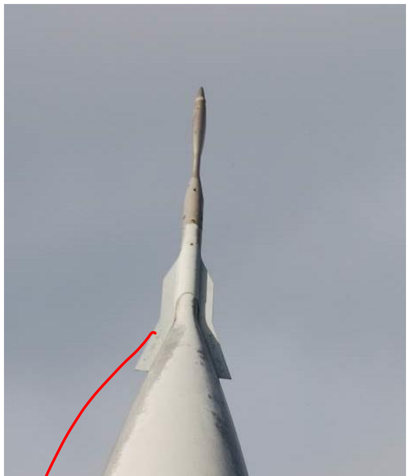


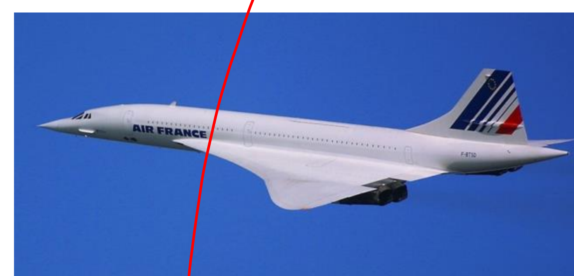
Directional Static Stability





Directional Static Stability – Nose Strakes





nose strakes
force symmetric
flow detachment

fuselage
is destabilizing

nose strakes
allows higher AoA / C_L
until we get asymm. flow
detachment (yaw disturbance)

Directional Static Stability – Nose Shape

Northrop F-5A

very small disturbances at front of aircraft have big effect, especially directional static stability (yaw)

Northrop F-5E

Lateral Static Stability

most important

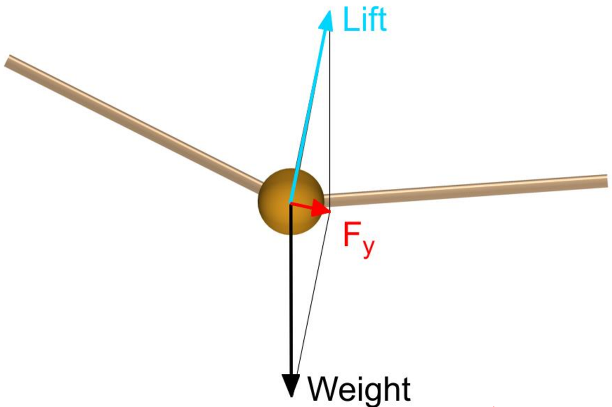
Disturbance		Velocity			Incidence Angles		Angular Velocity		
Forces/Moments		u	v	w	β = v / V	α = w / V	p	q	r
X-Force	$F_{A_x} + F_{T_x}$	$\frac{\partial}{\partial u}(F_{A_x} + F_{T_x}) < 0$							
		$c_{T_{x_u}} - c_{D_u} < 0$							
Y-Force	$F_{A_y} + F_{T_y}$		$\frac{\partial}{\partial v}(F_{A_y} + F_{T_y}) < 0$						
			$c_{y_\beta} < 0$						
Z-Force	$F_{A_z} + F_{T_z}$			$\frac{\partial}{\partial w}(F_{A_z} + F_{T_z}) < 0$					
				$c_{L_\alpha} > 0$					
Roll-Moment	$L_A + L_T$				$\frac{\partial}{\partial \beta}(L_A + L_T) < 0$		$\frac{\partial}{\partial p}(L_A + L_T) < 0$		
					$c_{l_\beta} < 0$		$c_{l_p} < 0$		
Pitch-Moment	$M_A + M_T$	$\frac{\partial}{\partial u}(M_A + M_T) > 0$				$\frac{\partial}{\partial \alpha}(M_A + M_T) < 0$		$\frac{\partial}{\partial q}(M_A + M_T) < 0$	
		$c_{m_u} > 0$				$c_{m_\alpha} < 0$		$c_{m_q} < 0$	
Yaw-Moment	$N_A + N_T$				$\frac{\partial}{\partial \beta}(N_A + N_T) > 0$				$\frac{\partial}{\partial r}(N_A + N_T) < 0$
					$c_{n_\beta} > 0$				$c_{n_r} < 0$

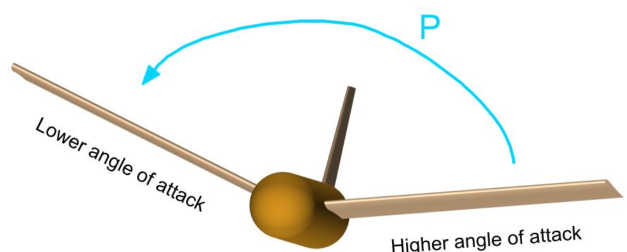
Lateral Stability - Dihedral Effect

$\frac{\partial}{\partial \beta}(L_A + L_T) < 0$
$c_{l_\beta} < 0$

There is no “pure” lateral (rolling) static stability derivative.

A disturbance in the roll angle results in side-force and therefore in a sideslip angle β





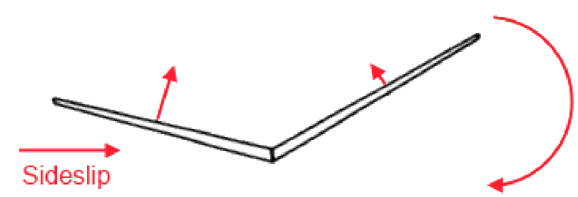
as we can see more of the underside => more lift.

bank angle (roll) -> side slip angle -> restoring moment (counteracts roll)

A sideslip angle β should result in a restoring rolling moment

$c_{l_\beta} < 0$

wing dihedral : geometry
dihedral effect : lateral stability derivative



This stability can be provided by having a dihedral angle (V-shape of the wing) and/or wing sweep.

neg. dihedral angle : anhedral (inverted V)

Speed Stability

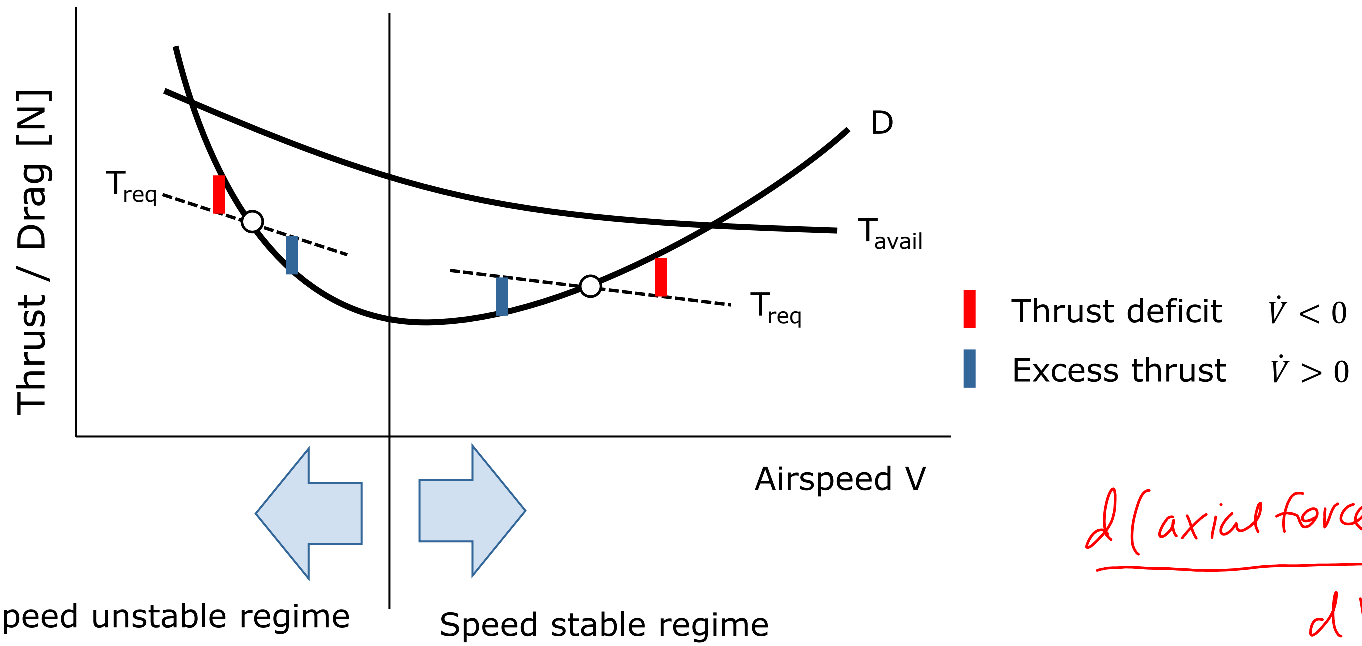
Disturbance		Velocity			Incidence Angles		Angular Velocity		
Forces/Moments		u	v	w	β = v / V	α = w / V	p	q	r
X-Force	$F_{A_x} + F_{T_x}$	$\frac{\partial}{\partial u}(F_{A_x} + F_{T_x}) < 0$							
		$c_{T_{x_u}} - c_{D_u} < 0$							
Y-Force	$F_{A_y} + F_{T_y}$		$\frac{\partial}{\partial v}\left(F_{A_y} + F_{T_y}\right) < 0$						
			$c_{y_\beta} < 0$						
Z-Force	$F_{A_z} + F_{T_z}$			$\frac{\partial}{\partial w}(F_{A_z} + F_{T_z}) < 0$					
				$c_{L_\alpha} > 0$					
Roll-Moment	$L_A + L_T$				$\frac{\partial}{\partial \beta}(L_A + L_T) < 0$		$\frac{\partial}{\partial p}(L_A + L_T) < 0$		
					$c_{l_\beta} < 0$		$c_{l_p} < 0$		
Pitch-Moment	$M_A + M_T$	$\frac{\partial}{\partial u}(M_A + M_T) > 0$				$\frac{\partial}{\partial \alpha}(M_A + M_T) < 0$		$\frac{\partial}{\partial q}(M_A + M_T) < 0$	
		$c_{m_u} > 0$				$c_{m_\alpha} < 0$		$c_{m_q} < 0$	
Yaw-Moment	$N_A + N_T$				$\frac{\partial}{\partial \beta}(N_A + N_T) > 0$				$\frac{\partial}{\partial r}(N_A + N_T) < 0$
					$c_{n_\beta} > 0$				$c_{n_r} < 0$

Speed Stability - u

An increase in forward velocity u should result in a deceleration

$$\frac{\partial}{\partial u}\left(F_{A_x} + F_{T_x}\right) < 0$$

$$c_{T_{x_u}} - c_{D_u} < 0$$



$$\frac{d\,(\text{axial force (drag, thrust)})}{dV}$$

we cannot neglect thrust !

Speed stability (u) is not required. An instability is manageable by the pilot

Speed Stability - v

A sidewise velocity disturbance should result in an opposing sidewise aerodynamic force

$$\frac{\partial}{\partial v}\left(F_{A_y} + F_{T_y}\right) < 0$$

$$c_{y_\beta} < 0$$

$$v = \beta \mathbf{V}$$

$$c_{y_\beta} < 0$$

Can be of importance in uncoordinated turn

Speed Stability - w

$$\frac{\partial}{\partial w}\left(F_{A_z} + F_{T_z}\right) < 0$$

$$c_{L_\alpha} > 0$$

A vertical velocity disturbance should result in an opposing vertical aerodynamic force.
Note: positive z-direction is downwards

$$w = \alpha \mathbf{V}$$

$$c_{L_\alpha} = \frac{dc_L}{d\alpha} > 0$$

Note: positive lift is upwards (in negative z direction)

c_{L_α} is usually positive within the normal flight regime ($c_L < c_{L_{max}}$)

Relates to the gust load factor and the damping of the short period mode

Speed Stability – Pitching Moment

An increase in forward velocity u should result in a pitch-up moment. This increases the angle of attack (lift coefficient), causing a higher drag, resulting in a deceleration

$$\frac{\partial}{\partial u}(M_A + M_T) > 0$$

$$c_{m_u} > 0$$

$$c_{m_u} > 0$$

This stability condition relates to longitudinal static stability and becomes important in the transonic flight regime (around Mach 1)

→ "Mach-tuck / tuck under"
center of pressure moves aft
@ around Mach 1 (transsonic)

Static Stability – Angular Motion

Disturbance		Velocity			Incidence Angles		Angular Velocity		
Forces/Moments		u	v	w	β = v / V	α = w / V	p	q	r
X-Force	$F_{A_x} + F_{T_x}$	$\frac{\partial}{\partial u}(F_{A_x} + F_{T_x}) < 0$							
		$c_{T_{x_u}} - c_{D_u} < 0$							
Y-Force	$F_{A_y} + F_{T_y}$		$\frac{\partial}{\partial v}(F_{A_y} + F_{T_y}) < 0$						
			$c_{y_\beta} < 0$						
Z-Force	$F_{A_z} + F_{T_z}$			$\frac{\partial}{\partial w}(F_{A_z} + F_{T_z}) < 0$					
				$c_{L_\alpha} > 0$					
Roll-Moment	$L_A + L_T$				$\frac{\partial}{\partial \beta}(L_A + L_T) < 0$		$\frac{\partial}{\partial p}(L_A + L_T) < 0$		
					$c_{l_\beta} < 0$		$c_{l_p} < 0$		
Pitch-Moment	$M_A + M_T$	$\frac{\partial}{\partial u}(M_A + M_T) > 0$				$\frac{\partial}{\partial \alpha}(M_A + M_T) < 0$		$\frac{\partial}{\partial q}(M_A + M_T) < 0$	
		$c_{m_u} > 0$				$c_{m_\alpha} < 0$		$c_{m_q} < 0$	
Yaw-Moment	$N_A + N_T$				$\frac{\partial}{\partial \beta}(N_A + N_T) > 0$				$\frac{\partial}{\partial r}(N_A + N_T) < 0$
					$c_{n_\beta} > 0$				$c_{n_r} < 0$

Static Stability – Rolling Motion

The increase of the roll-rate p should result in an opposing rolling moment L

$$c_{l_p} < 0$$

$$\frac{\partial}{\partial p}(L_A + L_T) < 0$$

$$c_{l_p} < 0$$

Note: rolling rate gets dampened, the roll angle itself does not $\rightarrow 0$

Important in dynamic maneuvers. For rigid airplanes and flight conditions without major regions of separated flow (stall), this stability condition is usually fulfilled.

Static Stability – Pitching Motion

The increase of the pitch-rate q should result in an opposing pitching moment M

$$\frac{\partial}{\partial q}(M_A + M_T) < 0$$

$$c_{m_q} < 0$$

$$c_{m_q} < 0$$

This is also called the pitch damping derivative.

This stability condition is usually required and generally fulfilled by conventional aircraft configurations

→ PIO : pilot induced oscillations → e.g. F22 raptor crash

Static Stability – Yawing Motion

The increase of the yaw-rate r should result in an opposing yawing moment N

$$\frac{\partial}{\partial r}(N_A + N_T) < 0$$

$$c_{n_r} < 0$$

$$c_{n_r} < 0$$

Relates to the yaw damping and the so called "Dutch-Roll". This stability condition usually needs to be fulfilled and is provided by the vertical tail.

Stability and Controllability

more wing sweep
better for faster flip

20.03.2014: Dassault Neuron, Falcon F7X, Rafale

Example: Loss of Primary Controls

Baghdad, 22. Nov. 2003. A DHL Airbus A300F was hit by a surface-to-air missile on the left wing during climb.

https://en.wikipedia.org/wiki/2003_Baghdad_DHL_attempted_shootdown_incident

DHL Airbus A300F

Loss of all hydraulics (primary control surfaces)

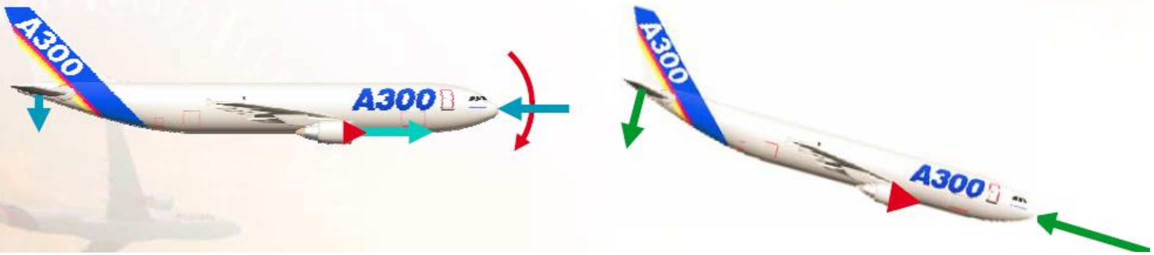
- All hydraulics lost
  - Ailerons, rudder and elevators are « floating » in the wind (zero hinge moment)
  - THS is frozen
  - Spoilers are inoperative and prevented to deflect (sucked by the airflow) by a non return valve. But one of them is slightly leaking.
  - Slats and flaps configuration are retracted and frozen
- Left wing in fire and associated fuel tank is emptying
- A significative amount of the left wing surface is missing

- **BUT**:

BOTH ENGINES ARE STILL RUNNING

DHL Airbus A300F

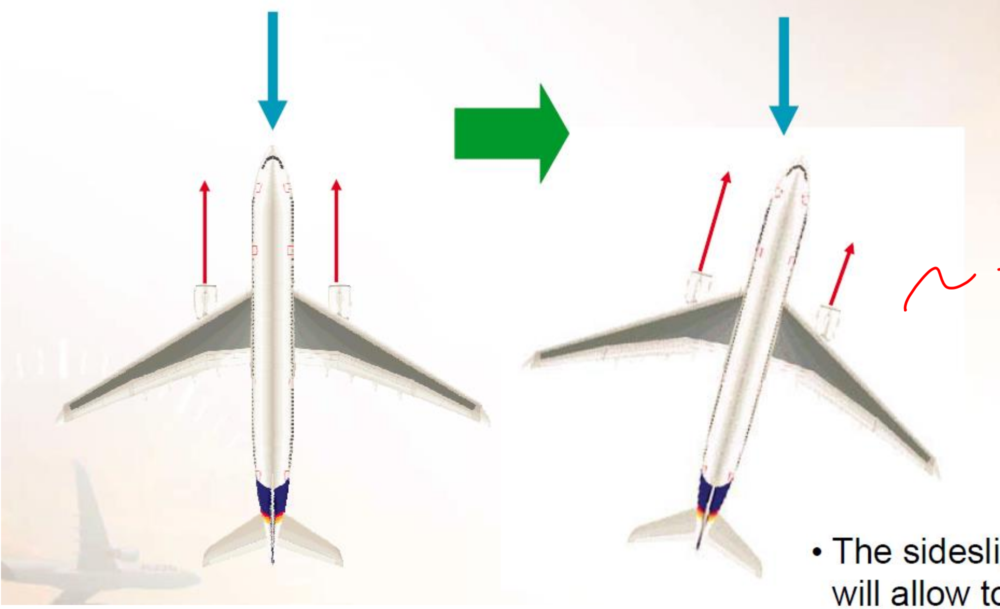
- When the controls froze, A/C was stabilized at a certain speed, with a given thrust and a given THS position
- A thrust variation (decrease) will create a pitch (down) moment
- This pitch down motion will continue until :
  - The thrust is restored at the adequate level, or
  - The speed has increased sufficiently so that the down lift of the tailplane compensates the pitch down moment created by the reduction of thrust.



- **THE THRUST BECOMES A PITCH CONTROL**
- Speed becomes a consequence of the chosen combination of pitch and thrust.
- Note that against intuition (and initial reaction), a thrust reduction will finally induce a speed increase and vice versa.

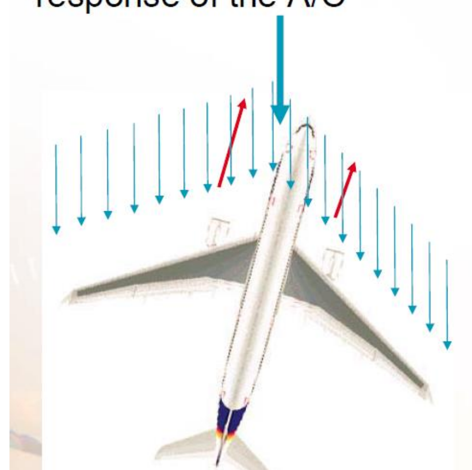
DHL Airbus A300F

• Increasing the thrust on one engine, will first generate sideslip



this wing is now "swept more"
=> less lift
=> roll right

• The sideslip will induce asymmetric lift; this asymmetric lift will allow to generate some bank, but with a delayed response of the A/C



With left sideslip (more thrust on left engine), the airplane yaws, then rolls to the right.

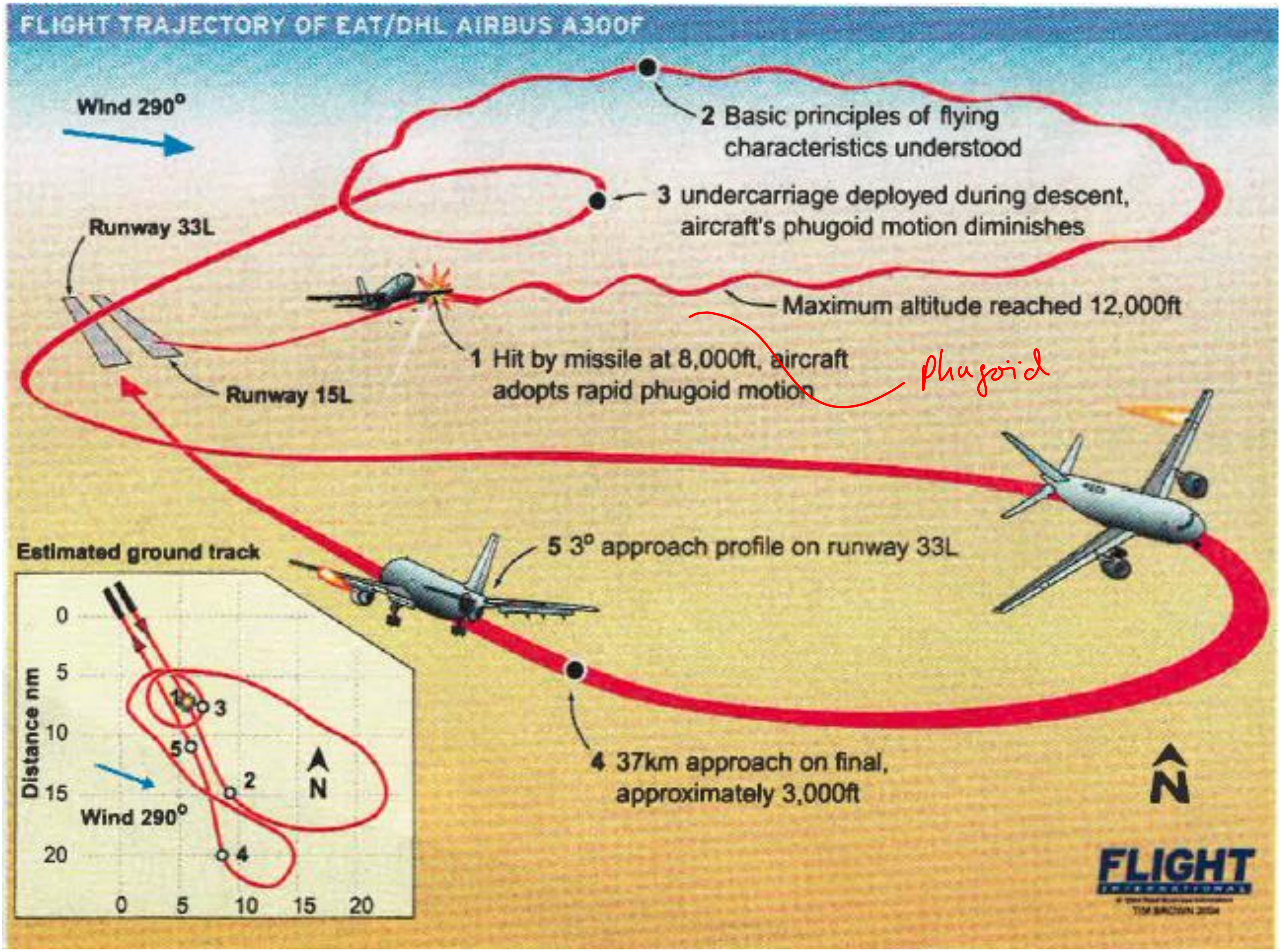
nose goes up & down (oscillates)
i.e. trading pitch w/ airspeed

- Symmetrical change of thrust on both engines will allow to control pitch and then vertical speed. But pitch control will be loose due to the phugoïd, making slope visualisation very difficult.
- Thrust being used for pitch control cannot then be used for speed control. Speed must be accepted as an uncontrolled result of the desired slope.
- When controlling the flight path, the crew will then have to accept the resulting speed and to control the slope through an active control of the pitch via the thrust .

- Assymetrical thrust application will allow to control the roll, but with a delayed response of the aircraft.

- Therefore, A/C control is achievable, but (at the least) demanding…

DHL Airbus A300F



DHL Airbus A300F

Éric Gennotte, Steeve Michielsen and Mario Rofail