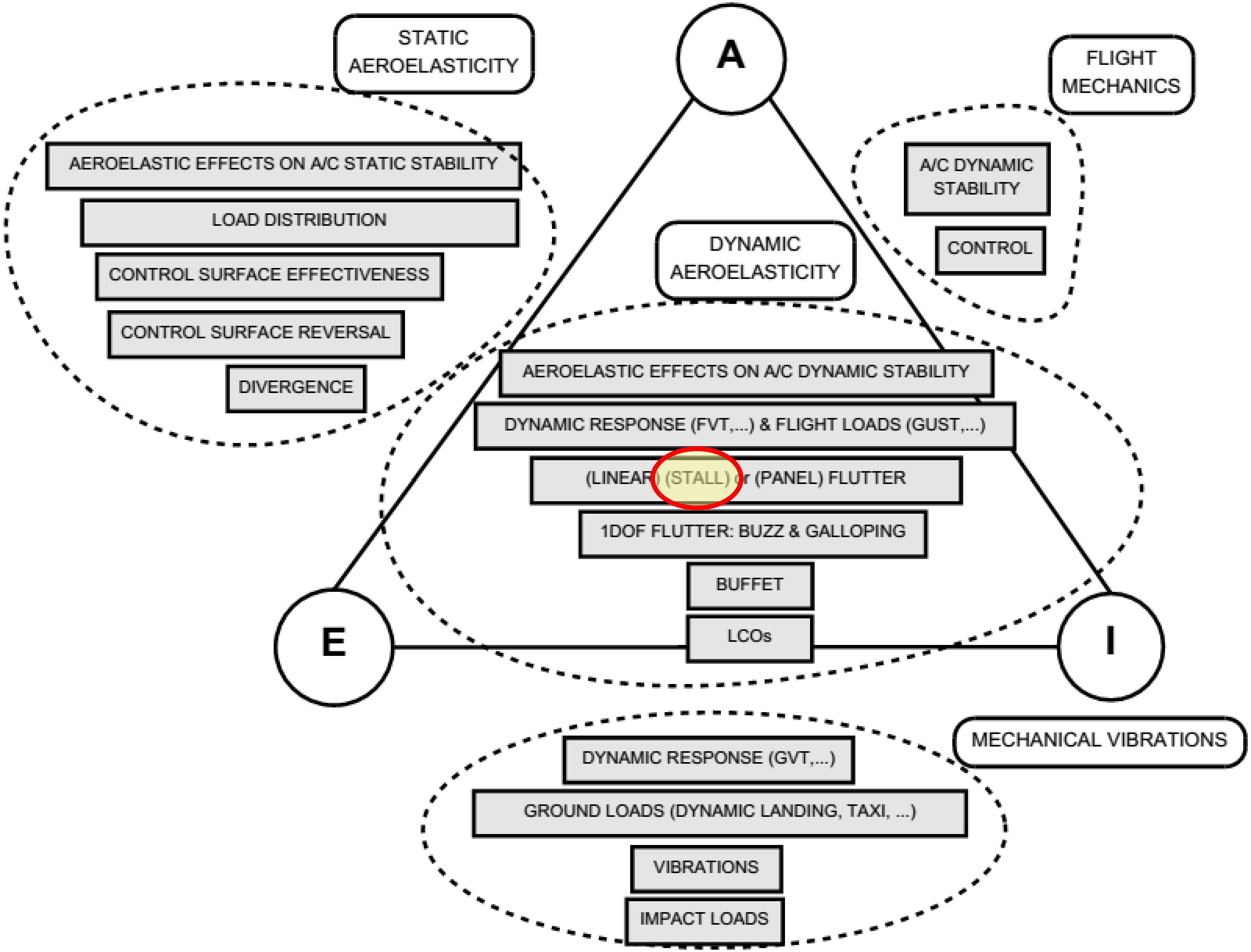
11 – Stall Flutter

Vibraciones y Aeroelasticidad
Dpto. de Vehículos Aeroespaciales
P. García-Fogeda Núñez & F. Arévalo Lozano

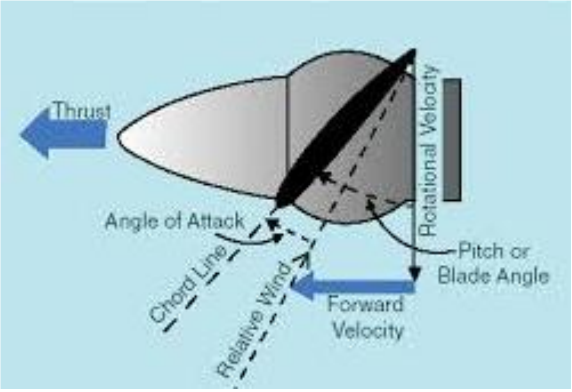
BUFFET
WHERE WE ARE IN THE COLLAR'S DIAGRAM ?



GENERAL CONSIDERATIONS

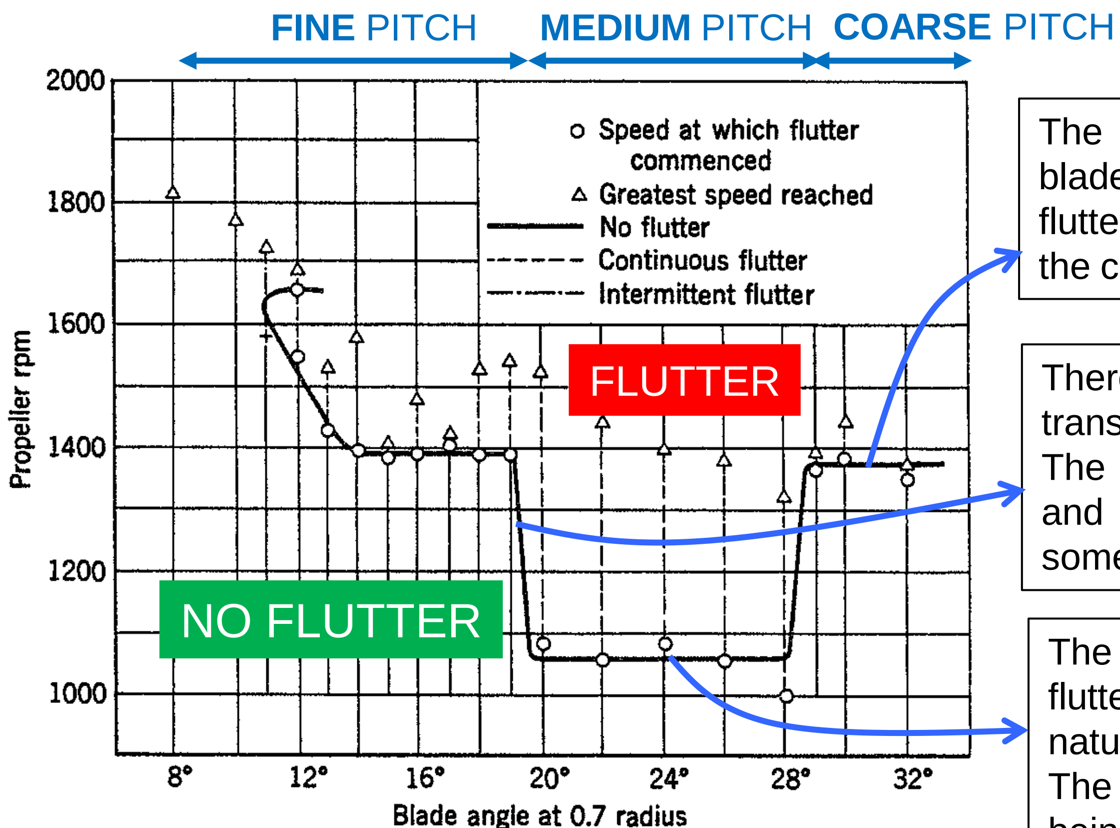
- **STALL FLUTTER**: Aeroelastic instability that leads to non-damped oscillations of a structure with partial or complete separation of the flow
  - The energy transfer does not rely on elastic/aerodynamic coupling or phase lag between a displacement and its aerodynamic reaction
  - The instability is explained in terms of the non-linear force and/or moment

- Serious aeroelastic instability for rotating machineries such as propellers, turbine blades, and compressors, which sometimes have to operate at angles of attack close to the static stalling angle of the blades.



- Stall flutter differs from classical flutter:
  - Change of inertia-axis location has little effect on stall flutter, which could occur even when the inertia axis lies ahead of the elastic axis (when it is impossible to obtain classical flutter)
  - The ratio of the uncoupled bending and torsion frequencies in still air has little effect on stall flutter, for which the critical speed is often higher when the ratio is equal to 1 than at other values.
  - Non-linear aerodynamics : **"Aerodynamic hysteresis"** → In a stroke of increasing amplitude, the separation is delayed to an angle of attack appreciable greater than that for a stationary airfoil. On the return movement, re-establishment of a smooth flow is also delayed

SPINNING TEST OF A PROPELLER



The flutter speed rises again as the blade becomes completely stalled. The flutter amplitude becomes very small in the coarse-pitch region.

There is a large phase shift at the transition from classical to stall flutter. The phase difference between bending and torsion drops by about 45º, sometimes vanishing completely

The flutter speed drops severely and the flutter frequency rises slowly toward the natural frequency of the blade in still air. The torsional motion predominates, being the bending oscillations negligible.

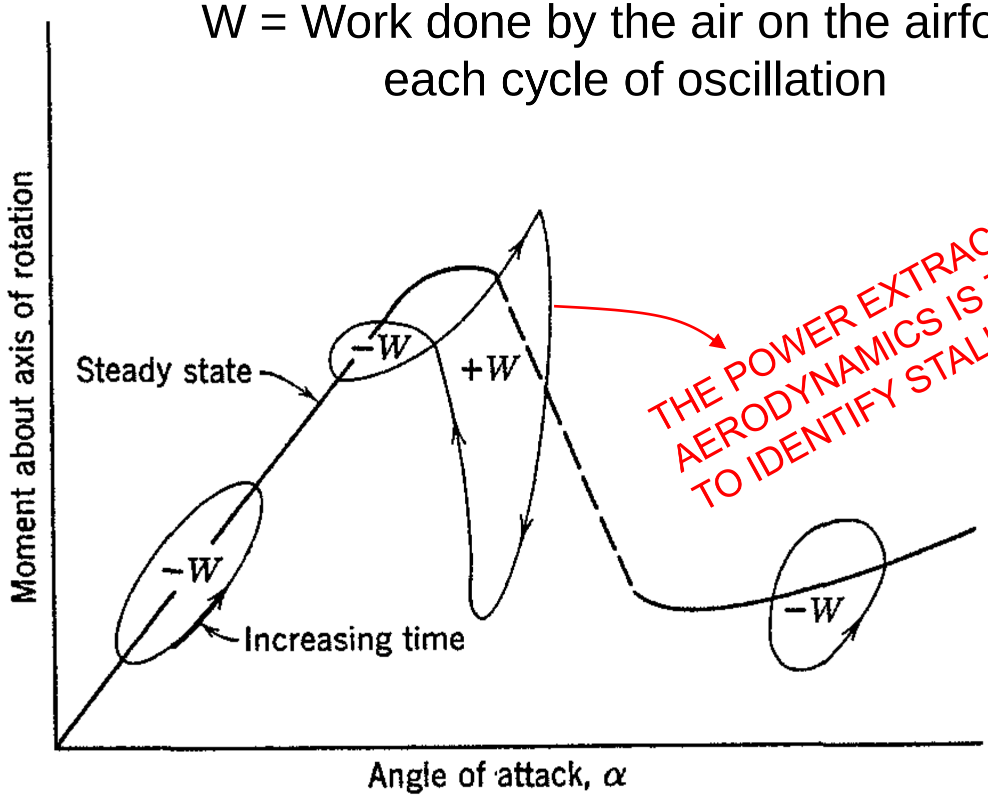
FINE PITCH: Classical flutter

MEDIUM PITCH : The blade settings correspond to the stalling angles of the tip sections. The blade stalls over part of the cycles of the oscillation

COARSE PITCH: The blade remains stalled throughout the cycles

AERODYNAMIC HYSTERESIS

W = Work done by the air on the airfoil in each cycle of oscillation

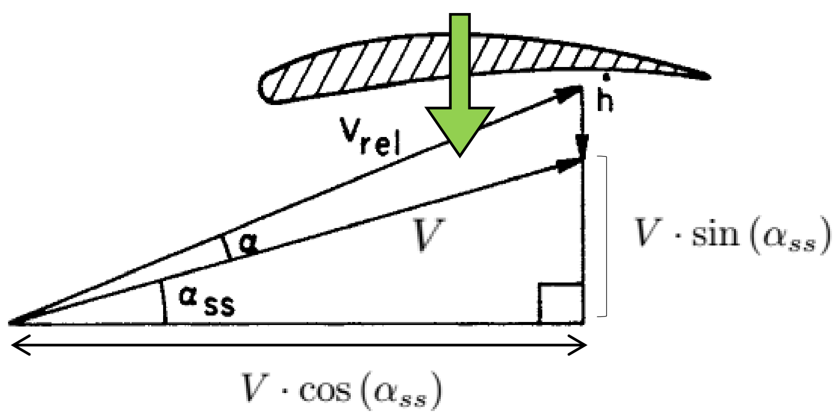


THE POWER EXTRACTED FROM THE AERODYNAMICS IS THE MAIN PARAMETER TO IDENTIFY STALL FLUTTER

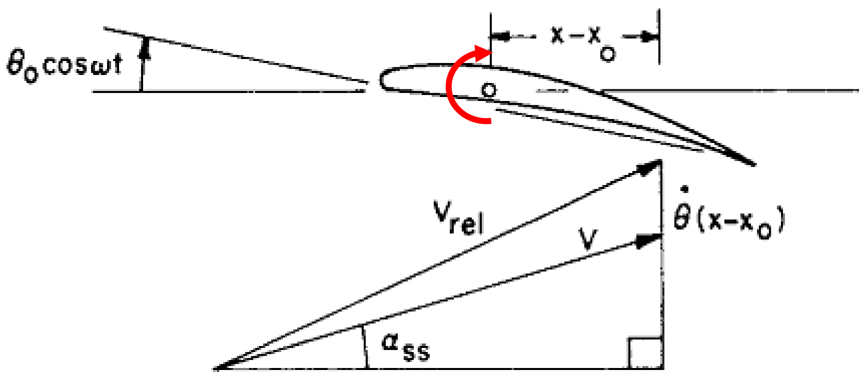
Sketch showing typical forms of hysteresis loop corresponding to simple-harmonic oscillations in pitch. At smaller angles of attack, the loop is elliptical, as predicted by the linearized theory. At angles of attack in the neighborhood of the static stall angle, the loop is of the shape of the figure (the left-hand side loop may become very small or disappear entirely, leaving a loop which indicates all positive work). At large angles of attack, the loop becomes oval again.

- Let's consider two 2D cases: BENDING and TORSIONAL Stall Flutter
- For both cases, the AERODYNAMIC WORK (or POWER) is calculated and:
  - ► POWER < 0 → DAMPED (Damped system)
  - ► POWER > 0 → FLUTTER (The system extracts energy from the air)

"PURE"
BENDING STALL FLUTTER

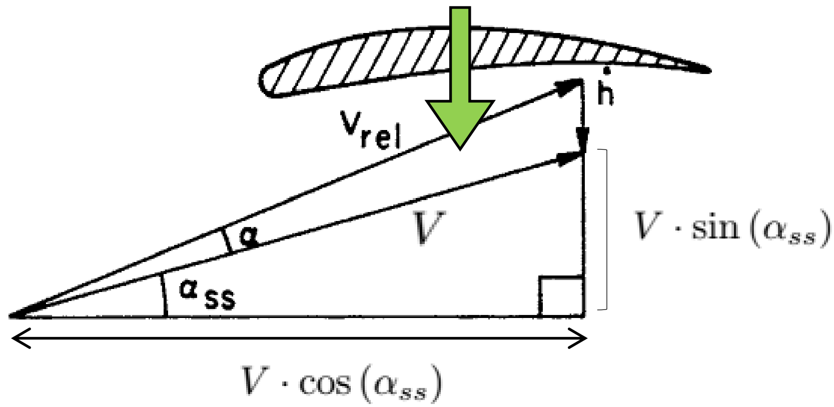


"PURE"
TORSIONAL STALL FLUTTER



STALL BENDING FLUTTER

DERIVATION OF NORMAL FORCE $N = q_{rel} \cdot (2b) \cdot C_N$



$$N = q_{rel}\,(2b)\,C_n$$

$$q_{rel} = \frac{1}{2}\rho V_{rel}^2 = \frac{1}{2}\rho\left[V^2\cos^2\alpha_{ss} + \left(V\sin\alpha_{ss} + \dot{h}\right)^2\right] = \frac{1}{2}\rho V^2\left[1 + 2\sin\alpha_{ss}\frac{\dot{h}}{V} + \left(\frac{\dot{h}}{V}\right)^2\right]$$

$$C_n = -\sum_n a_n\,(\alpha_{ss})\,\alpha^n$$

$$\alpha = \tan^{-1}\left(\tan\alpha_{ss} + \frac{\dot{h}}{V\cos\alpha_{ss}}\right) - \alpha_{ss} = \cos\alpha_{ss}\frac{\dot{h}}{V} - \frac{\sin 2\alpha_{ss}}{2}\left(\frac{\dot{h}}{V}\right)^2 - \frac{\cos 3\alpha_{ss}}{3}\left(\frac{\dot{h}}{V}\right)^3 + \frac{\sin 4\alpha_{ss}}{4}\left(\frac{\dot{h}}{V}\right)^4 + \ldots$$

C_n = Force coefficient defined with a polynomial approximation : $\dot{h}/V << \alpha_{ss}$
h = Normal displacement (positive downward). Harmonic motion is assumed: $h = h_0\cos(\omega t)$
N = Normal force (positive in the same direction as the displacement “h”)
q_{rel} = Dynamic pressure relative to a coordinate system fixed to the airfoil
V = Steady-state relative velocity
V_{rel} = Relative velocity including harmonic oscillations of the airfoil
α = Instantaneous departure from the steady state angle of attack α_{ss}
α_{ss} = Steady-state mean angle of attack

- The question of amplification or subsidence of the amplitude of the initial motion is decided on the basis of the work done by the aero force acting on the displacement:

$$\frac{\text{Work}}{\text{Cycle}} = \int_0^T N\dot{h}dt = \frac{1}{\omega}\int_0^{2\pi} N\dot{h}d\left(\omega t\right)$$

$$P = \text{Power} = (\text{Work/Cycle})\cdot(\text{Cycles/sec}) = \frac{1}{2\pi}\int_0^{2\pi} N\dot{h}d\left(\omega t\right)$$

$$\left.\frac{\dot{h}}{V}\right|_{q_{rel}} = -\frac{\omega h_0}{V}\sin\omega t = -k\frac{h_0}{b}\sin\omega t \rightarrow$$

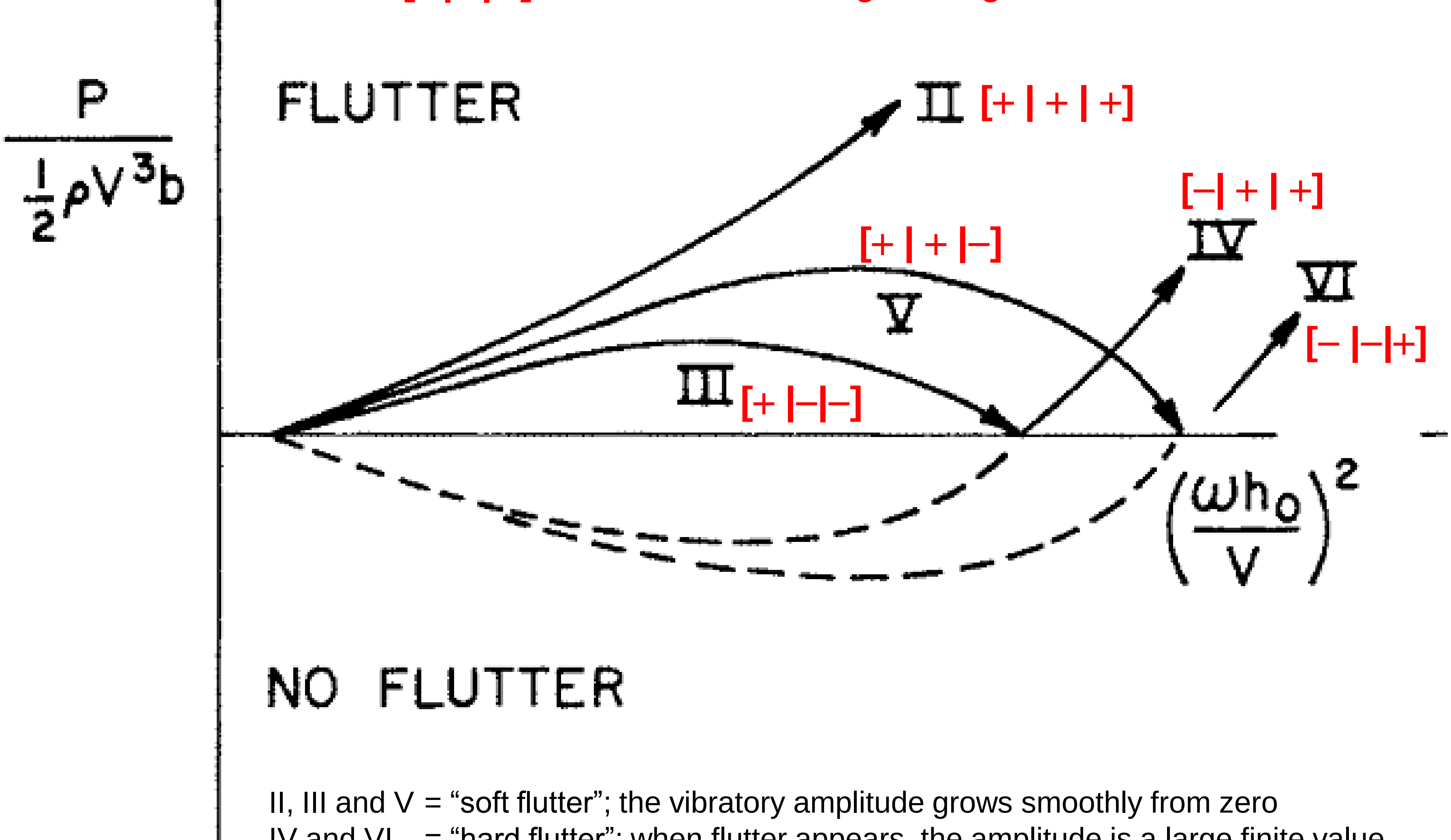
q_{rel} is assumed to respond instantaneously to "α" or " dh/dt "

$$\left.\frac{\dot{h}}{V}\right|_{\alpha} = -k\frac{h_0}{b}\sin\left(\omega t + \Psi\right) \rightarrow$$

Phase introduced in the formulation of the force "N"

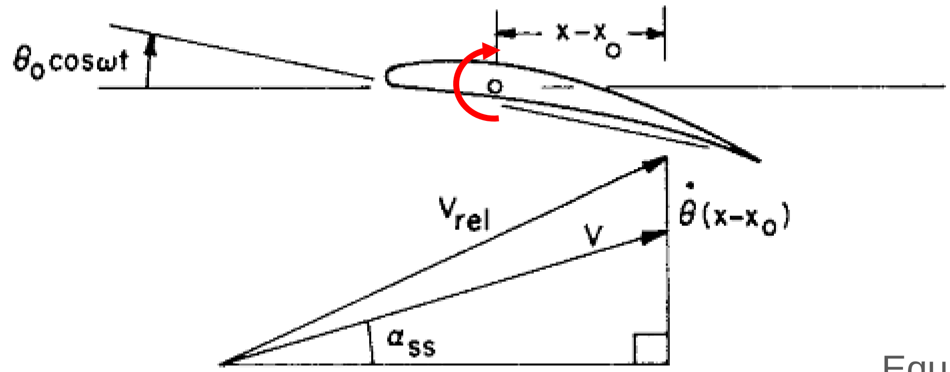
$$\frac{P}{\frac{1}{2}\rho V^3 b} = A\left(\alpha_{ss},\Psi,a_0,a_1,\ldots\right)\left(\frac{\omega h_0}{V}\right)^2 + B\left(\alpha_{ss},\Psi,a_0,a_1,\ldots\right)\left(\frac{\omega h_0}{V}\right)^4 + C\left(\alpha_{ss},\Psi,a_0,a_1,\ldots\right)\left(\frac{\omega h_0}{V}\right)^6 + \ldots$$

[A|B|C] = Vector containing the signs of A, B and C



II, III and V = “soft flutter”; the vibratory amplitude grows smoothly from zero
IV and VI = “hard flutter”; when flutter appears, the amplitude is a large finite value

TORSIONAL STALL FLUTTER



Equivalent to **(dh/dt)/V**
in bending stall flutter

"typical" incidence

$$x - x_0 = eb$$

$$-ek\theta_0 \sin\omega t$$

$$\alpha = \alpha_0 + \tan^{-1}\left[\tan\alpha_{ss} - \frac{(x-x_0)\,\omega\theta_0}{V\cos\alpha_{ss}}\sin\omega t\right] - \alpha_{ss} \rightarrow \alpha_0 + \tan^{-1}\left[\tan\alpha_{ss} - \frac{eb\omega\theta_0}{V\cos\alpha_{ss}}\sin\omega t\right] - \alpha_{ss}$$

$$q_{rel} = \frac{1}{2}\rho V_{rel}^2 = \frac{1}{2}\rho V^2\left\{1 + 2\sin\alpha_{ss}\frac{\dot{\theta}\,(x-x_0)}{V} + \left[\frac{\dot{\theta}\,(x-x_0)}{V}\right]^2\right\} \rightarrow \frac{1}{2}\rho V^2\left\{1 + 2\sin\alpha_{ss}\frac{\dot{\theta}eb}{V} + \left[\frac{\dot{\theta}eb}{V}\right]^2\right\}$$

For very slow oscillations (terms proportional to higher powers of the frequency can be ignored)

$$\frac{P}{\frac{1}{2}\rho V^3 b} = -4k\sin\boxed{\Psi}\sum_{n=odd} b_n\theta_0^{n+1}\frac{1\cdot 3\cdot 5\cdots n}{2\cdot 4\cdot 6\cdots(n+1)}$$

Dependence on the time lag between the oscillatory motion and the aero moment

PREVENTION OF STALL FLUTTER

- Increase the frequency of the free torsional oscillation of the blade:
  - Increase torsional stiffness
  - Reduce mass moment of inertia

- Prevent stalling:
  - Choose the proper airfoil section
  - Working angle of attack below the stalling angle

- "Divergence speed" as a relevant value in propellers, blades,… :
  - If the rotational speed of a propeller is so high that the relative wind speed is close to the critical-divergence speed, the airfoil will be twisted excessively, possibly beyond the stalling angle, and thus causing stall flutter

“Escuela Técnica Superior de Ingeniería Aeronáutica y del Espacio”

UNIVERSIDAD POLITÉCNICA DE MADRID