02 – Introduction to Structural Dynamics & Aeroelasticity

Vibraciones y Aeroelasticidad
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AEROELASTICITY

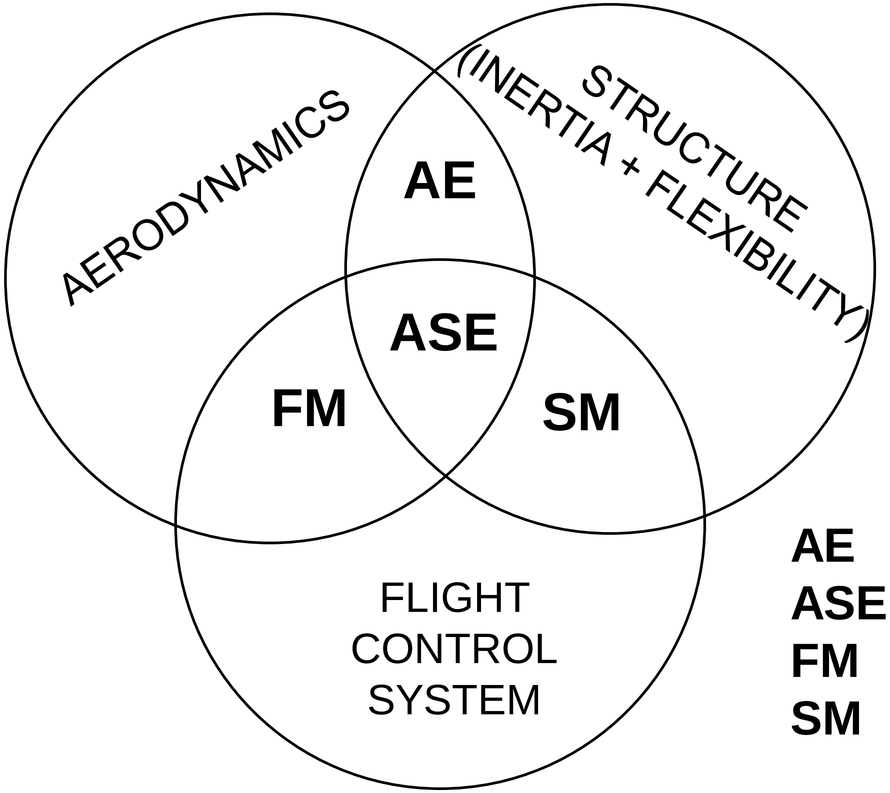
After watching this video… Video (*)

Does anybody have any doubt that structures are flexible ?

After watching this video… Video (**)

Does anybody have any doubt that flexibility plays an important role?

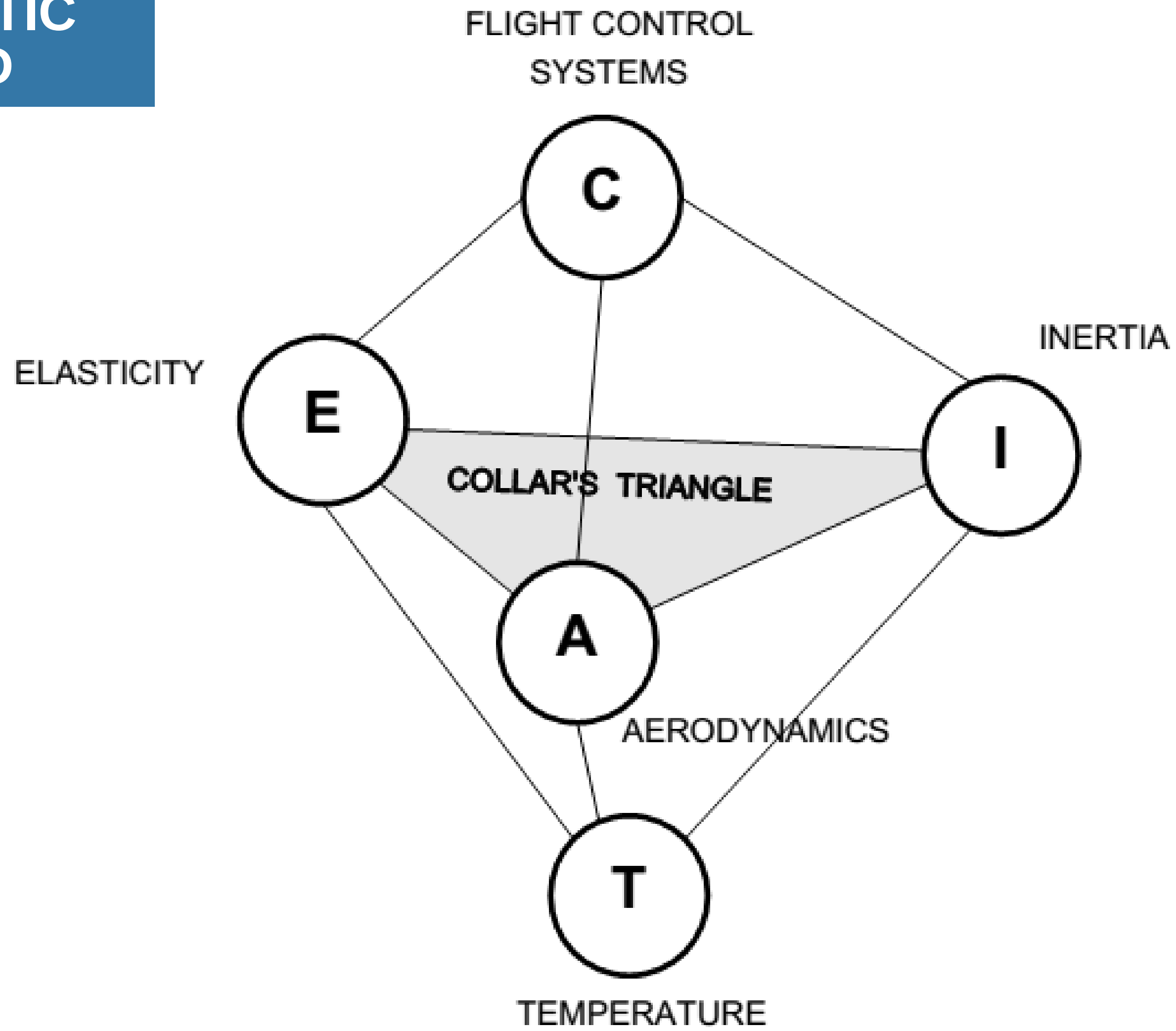
(*) Static structural test of the A350 XWB wing
(**) Flutter of an aeromodel



AE = Classical Aeroelasticity
ASE = Aeroservoelasticity
FM = Flight Mechanics
SM = Structural Mechanics

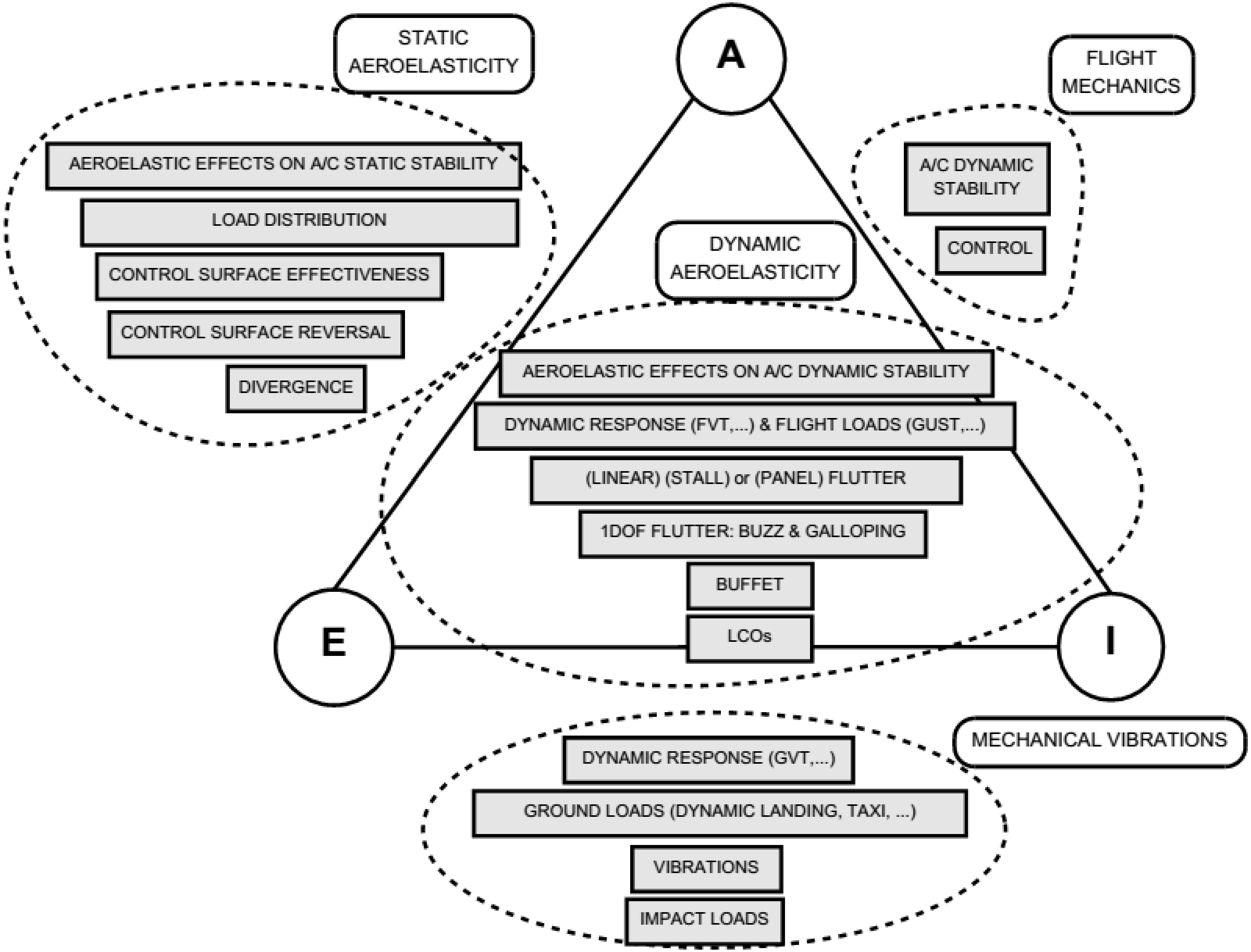
(*) Extracted from "Aeroservoelastic flight control design for a military combat aircraft weapon system", W.Luber & J.Becker, EADS-MAS; proceedings of ISMA2010 including USD2010

AEROELASTIC DIAMOND



- The Aeroelastic Diamond shows the effects to consider in Aeroelastic-type phenomena
- COLLAR'S TRIANGLE = "CLASSICAL AEROELASTICITY" = AERO + ELASTICITY + INERTIA
- This subject is restricted to the so-called "Classical Aeroelasticity"

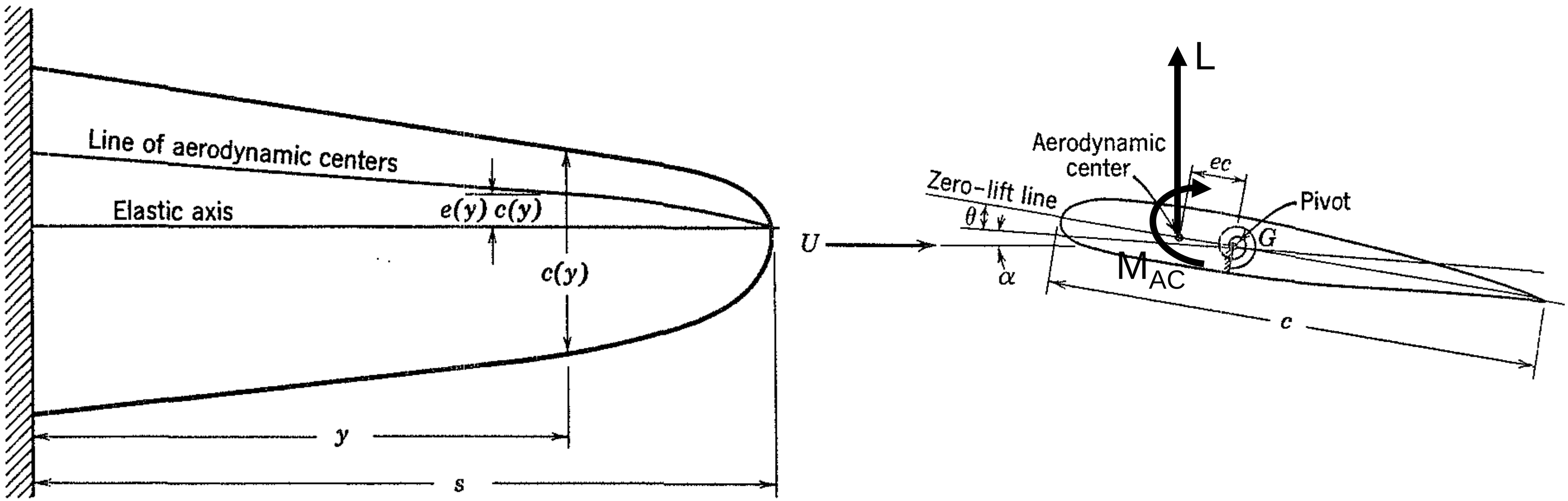
COLLAR'S TRIANGLE



AEROELASTIC PHENOMENA

AEROELASTIC INSTABILITIES	
DIVERGENCE (D)	Flight condition at which elastic forces (proportional to deformation) cannot counteract aerodynamic forces (proportional to dynamic pressure)
CONTROL SYSTEM REVERSAL (R)	The intended effects of displacing a given component of the control system are completely nullified by elastic deformations of the structure
FLUTTER (CLASSICAL)	It is an unstable self-excited vibration in which the structure extracts energy from the air stream and often results in catastrophic structural failure
FLUTTER (NON-LINEAR)	Stall Flutter (airflow about the lifting surface becomes separated during any portion of an unstable oscillatory cycle of the angle of attack), Limit Cycle Oscillations, buzz (transonic shocks oscillating), across-wind and wake galloping (separated flow over bluff bodies), …
EFFECTS OF STRUCTURAL ELASTICITY ON LOADS AND FLIGHT MECHANICS	
LOAD DISTRIBUTION (L)	Influence of elastic deformations of the structure on the distribution of aerodynamic pressures over the structure
CONTROL EFFECTIVENESS (C)	Influence of elastic deformations of the structure on the controllability of an airplane
AEROELASTIC EFFECTS ON STABILITY (SSA & DSA)	Influence of elastic deformations of the structure on dynamic and static airplane stability
RESPONSE-TYPE PROBLEMS	
DYNAMIC RESPONSE (Z)	Transient response of aircraft structural components produced by rapidly applied loads due to gusts, landing, gun reactions, abrupt control motions, moving shock waves, or other dynamic loads
BUFFET (B)	Transient vibrations of aircraft structural components due to aerodynamic impulses produced by the wake behind wings, nacelles, fuselage pods, or other components of the airplane

- The aero loads could induce elastic deformations that increase the aero loads → INCREASE OF LIFTING SURFACE EFFECTIVENESS
- **Divergence speed**: the increment in aerodynamic torsional moment due to an arbitrary increment in twist angle is equal to the increment in elastic restoring torque

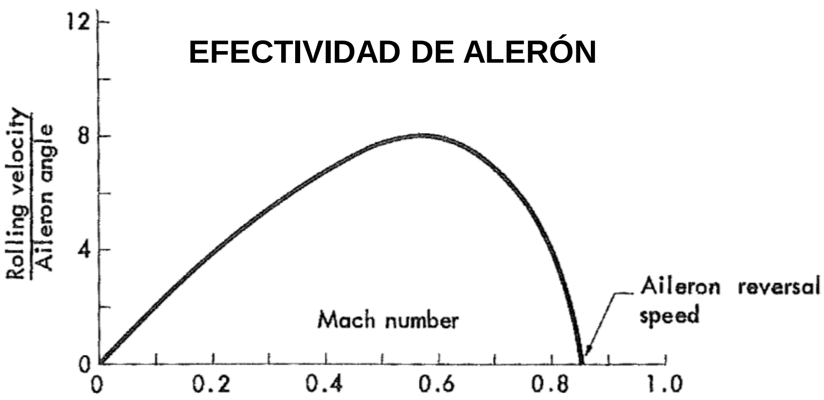


Note:

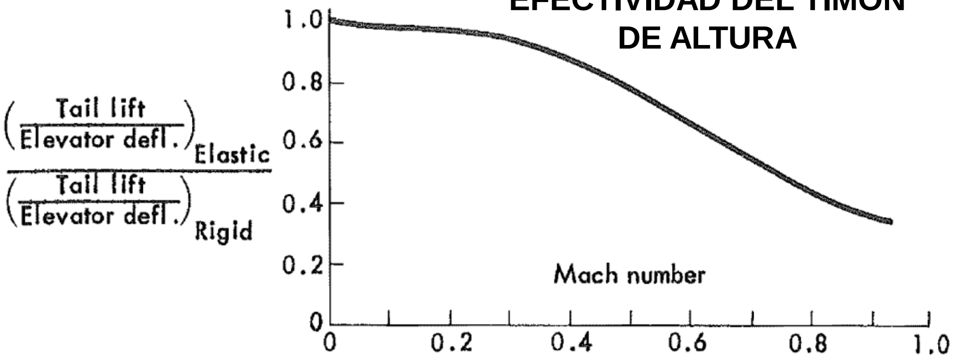
Swept wing vs. straight wing

- The Control Surface deflection induce elastic deformations that change the aero loads and modifies the **control surface effectiveness**
- **Control Reversal**: flight condition at which the deflection of the Control Surface leads to ZERO aero loads

EFECTIVIDAD DE ALERÓN



EFECTIVIDAD DEL TIMÓN DE ALTURA



☝ Note:

Swept wing vs. straight wing

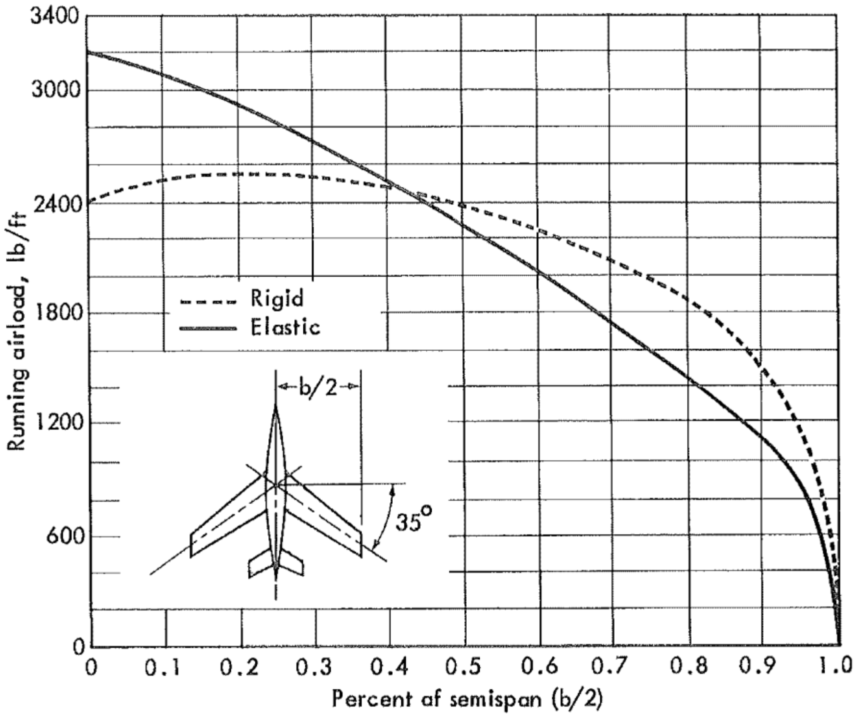
Avoidance of aileron reversal in a straight wing with conventional ailerons is almost entirely a matter of providing sufficient wing torsional stiffness. In the case of swept-back wings, where aileron reversal is a very serious problem, bending stiffness must also be increased in order to raise the aileron reversal speed. Increases in bending and torsional stiffnesses are often accompanied by prohibitively large increases in weight, and hence other means must be sought. Alternative methods of producing rolling moments, such as spoilers and all-moving wing tips, have proved beneficial.

☝ Note:

Aileron vs. Elevator control reversal

LOAD DISTRIBUTION

- During high-speed flight, deflections of the structure tend to redistribute the airloads, and may cause their distribution to be significantly different from that computed on the assumption of complete rigidity
- The problem of finding the load distribution on a wing is one of computing the twist distribution along the wing corresponding to this condition of stable equilibrium



SUSTENTACIÓN EN FUNCIÓN DE LA ENVERGADURA PARA DOS ALAS CON FLECHA 35 [deg] EN UNA MANIOBRA A 2 [g]: LINEA CONTNUA CORRESPONDE A ALA FLEXIBLE, MIENTRAS QUE LÍNEA DISCONTINUA CORRESPONDE AL MISMO ALA CONSIDERADA PERFECTAMENTE RÍGIDA.

Note:

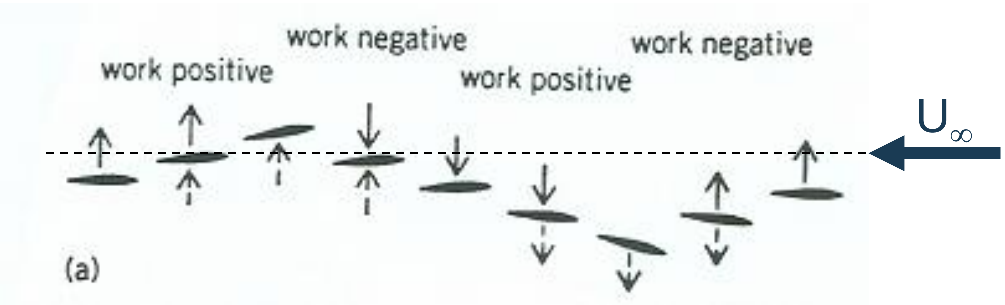
Swept wing vs. straight wing

CLASSICAL FLUTTER

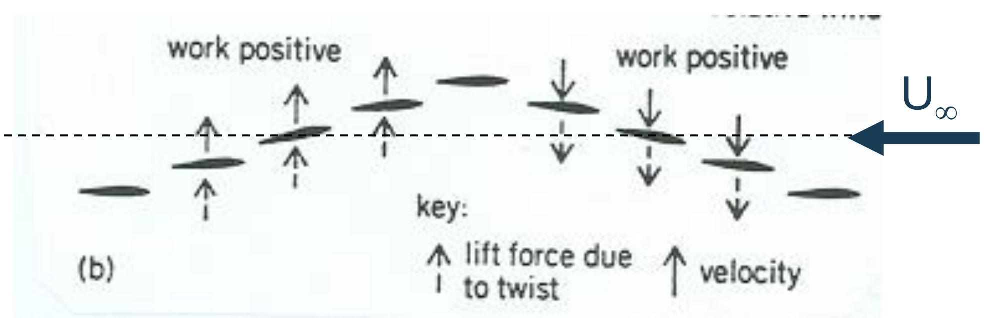
- **Flutter**: Dynamic instability of a flexible structure in an airstream
- Two examples: “Lifting Surface” Flutter and “Control Surface” Flutter

“LIFTING SURFACE” FLUTTER

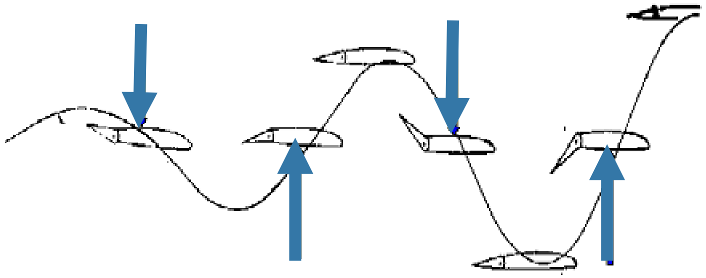
(a) Bending & Torsion in phase → **NO FLUTTER**



(b) Bending & Torsion OUT-OF-PHASE 90 [deg] → **FLUTTER**

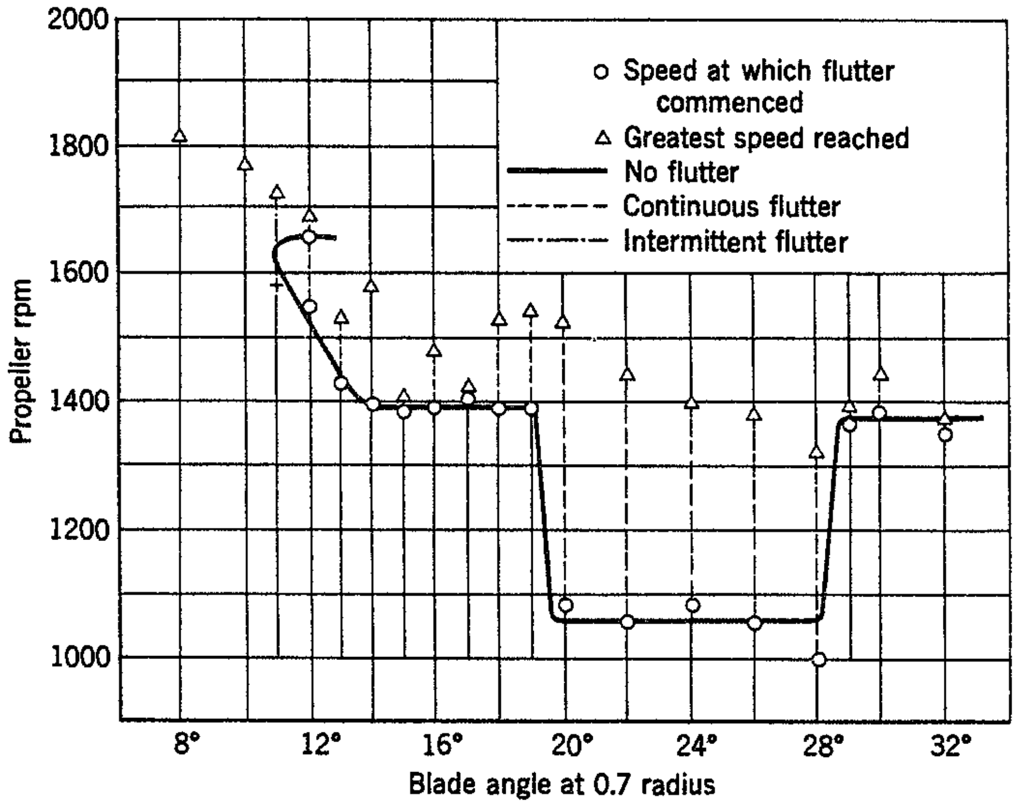


“CONTROL SURFACE” FLUTTER

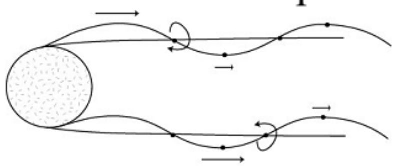


Incremental lift induced by control surface rotation

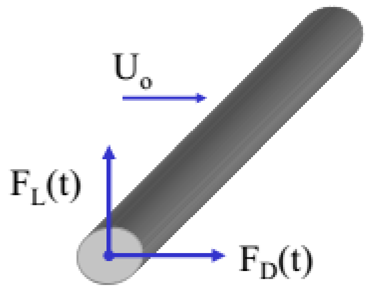
- **Stall Flutter**: phenomenon which occurs with partial or complete separation of the flow from the airfoil occurring periodically during the oscillation.
- The basic instability and its principal features must be explained in terms of nonlinear normal force and moment characteristics.
- Stall flutter is a serious instability for rotating machineries such as propellers, turbine blades, and compressors, which sometimes have to operate at AoA close to the static stalling angle.

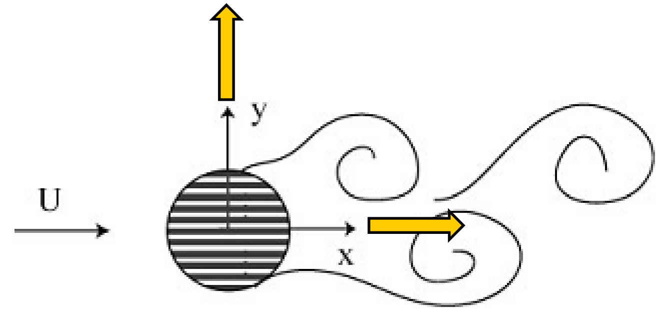


Shear layer instability causes vortex roll-up

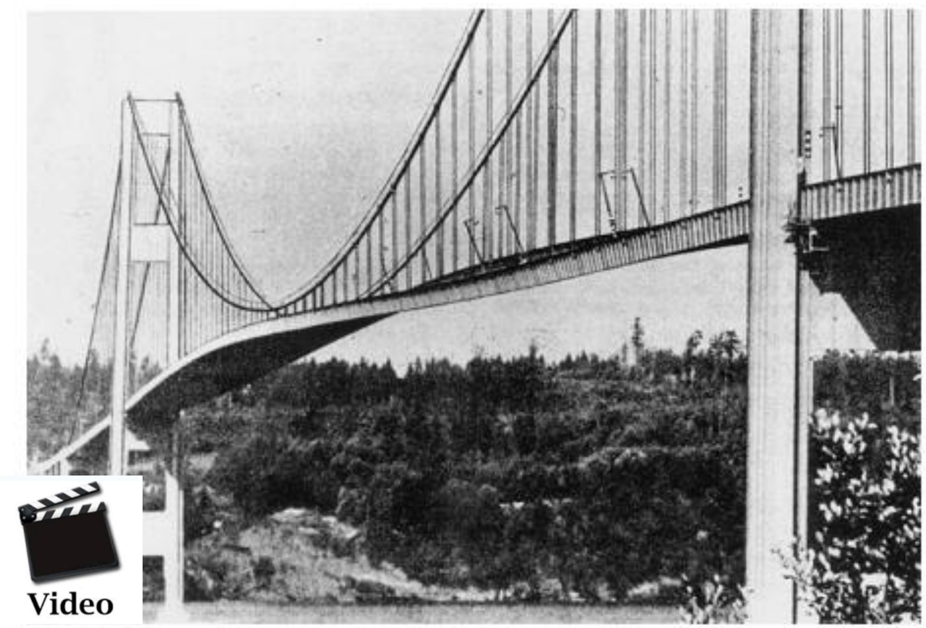


- Flow speed outside wake is much higher than inside
- Vorticity gathers at downcrossing points in upper layer
- Vorticity gathers at upcrossings in lower layer
- Induced velocities (due to vortices) causes this perturbation to amplify





Due to the alternating vortex wake ("Karman street") the oscillations in lift force occur at the vortex shedding frequency and oscillations in drag force occur at *twice* the vortex shedding frequency.

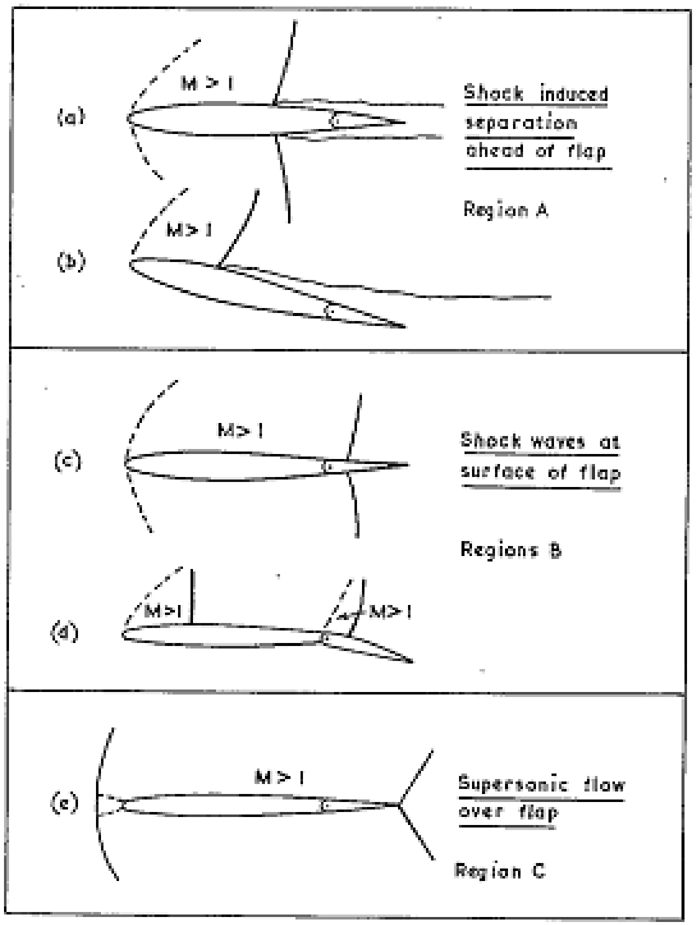


Offshore Platforms

1 DOF FLUTTER: “GALLOPING”

- **Galloping**: the shedding of vortices in the wake of a body give rise to an asymmetric flow and, therefore, to an asymmetric pressure field which induces fluctuating lift & drag forces
  - Across-wind galloping (ice-landen cables)
  - Wake galloping (bundle-powered transmission-line cables)

- **Buzz**: Formation of a shock wave at the surface of a lifting surface and that a backwards and forward motion accompanies the oscillation of the control surface
  - ► Transonic of low supersonic speeds



(1) Flap in subsonic flow; boundary-layer separation induced by a shock wave situated at the surface of the aerofoil ahead of the hinge. Figs. 3a and 3b.

(2) Mixed supersonic and subsonic flow over the flap with a shock wave at one or both surfaces between the hinge line and the trailing edge. Separation has been observed but this may not be an essential feature. Figs. 3c and 3d.

(3) Supersonic flow locally over the entire flap with the main shock waves attached to the trailing edge. This type of buzz would be expected to correspond to the negative damping of the flap predicted by potential-flow theories. Fig. 3e.

LIMIT CYCLE OSCILLATIONS (LCOs)

- ❑ **Nonlinearities** lead to non-damped oscillations of the structure
- ❑ Types of nonlinearities:
  - ► Aerodynamics
    - Flow detachment
    - High AoA maneuvers (buffet, stall flutter, …)
  - ► Structural:
    - Distributed
    - Concentrated (freeplay)

Video

(*) Limit cycle oscillation in a F-16 aircraft

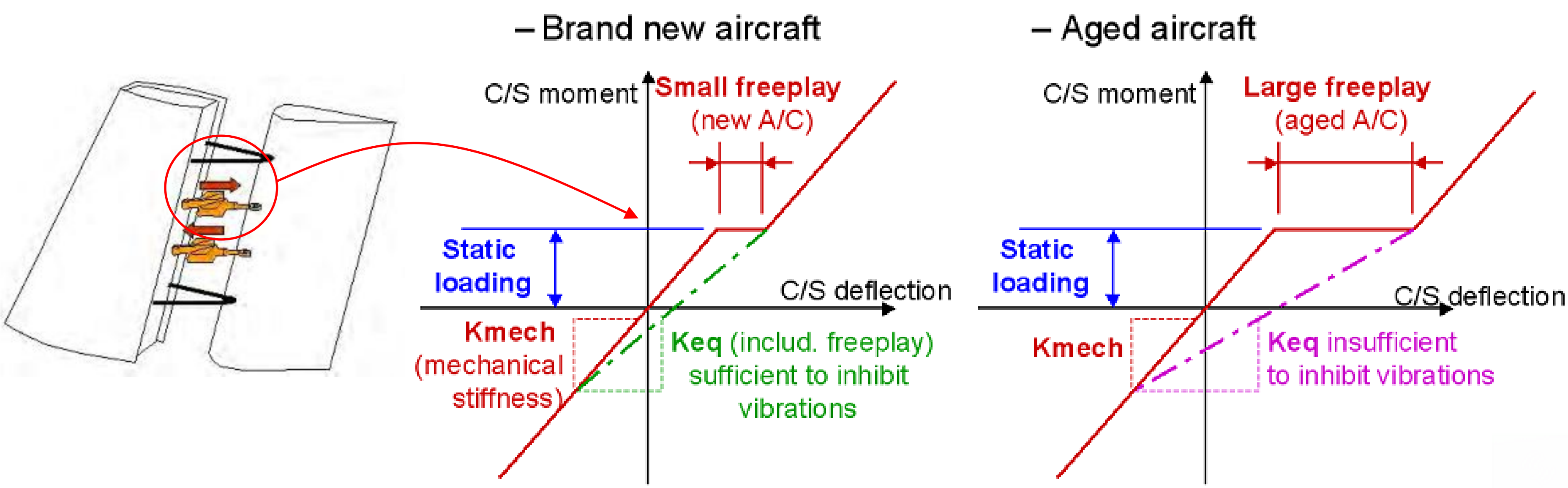


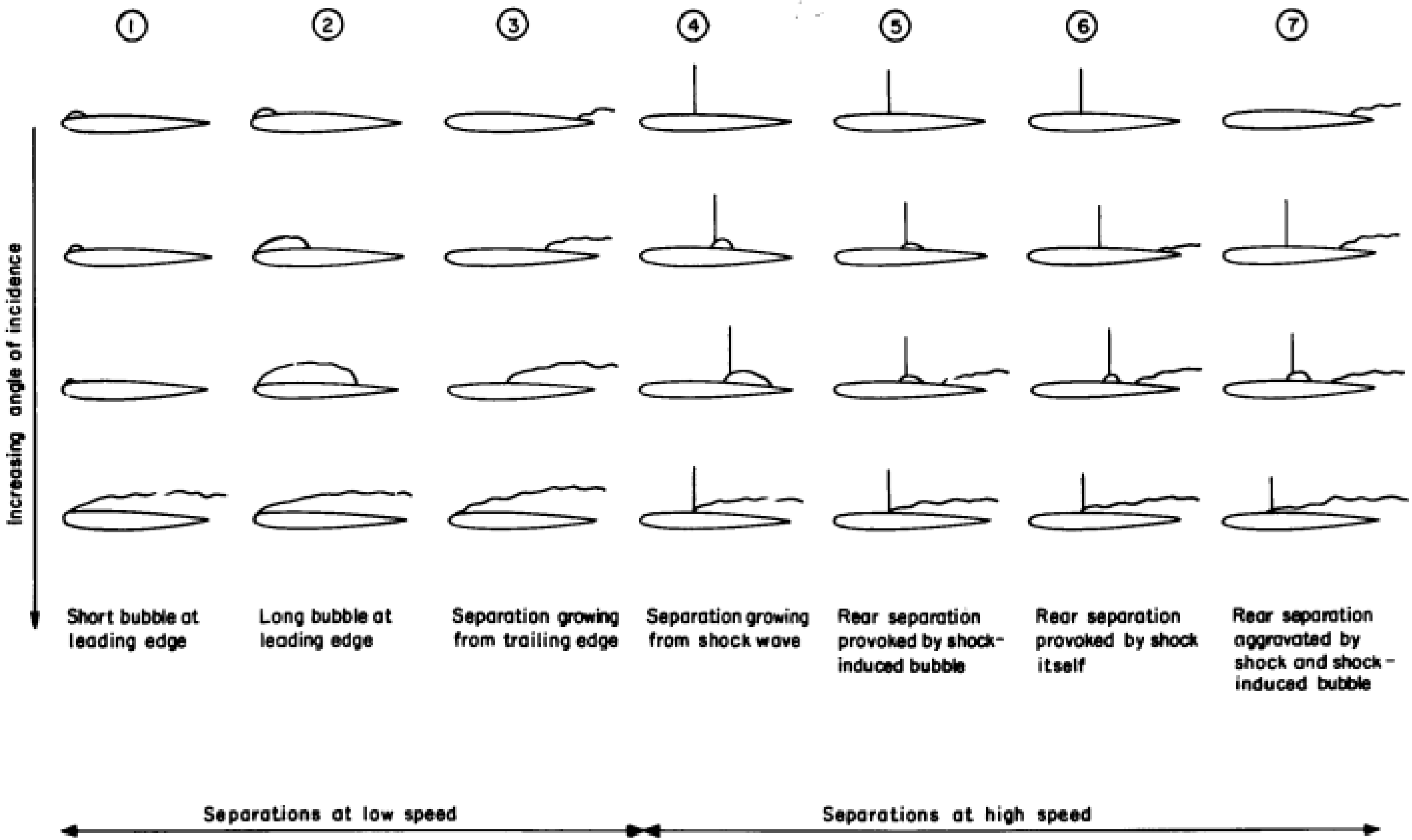
FIGURE: Non-linear restoring force of an actuator with freeplay

- Def.: Transient vibrations of aircraft structural components due to aerodynamic impulses produced by flow separation, wakes, shock wave transient motion, …
- Buffet is NOT a stability problem
- Buffet is a RESPONSE problem
- Typical conditions:
  - ► High-speed or high-AoA maneuver
    - Fighter-type aircrafts: High-Mach & High-AoA
    - Civil Transport A/C: M~1 transonic regime
    - Pod/Pylon surroundings
  - ► A/C wakes:
    - Tanker-receiver configuration

Flow Visualization of Vortex from the LEX Bursting ahead of the Vertical Tail

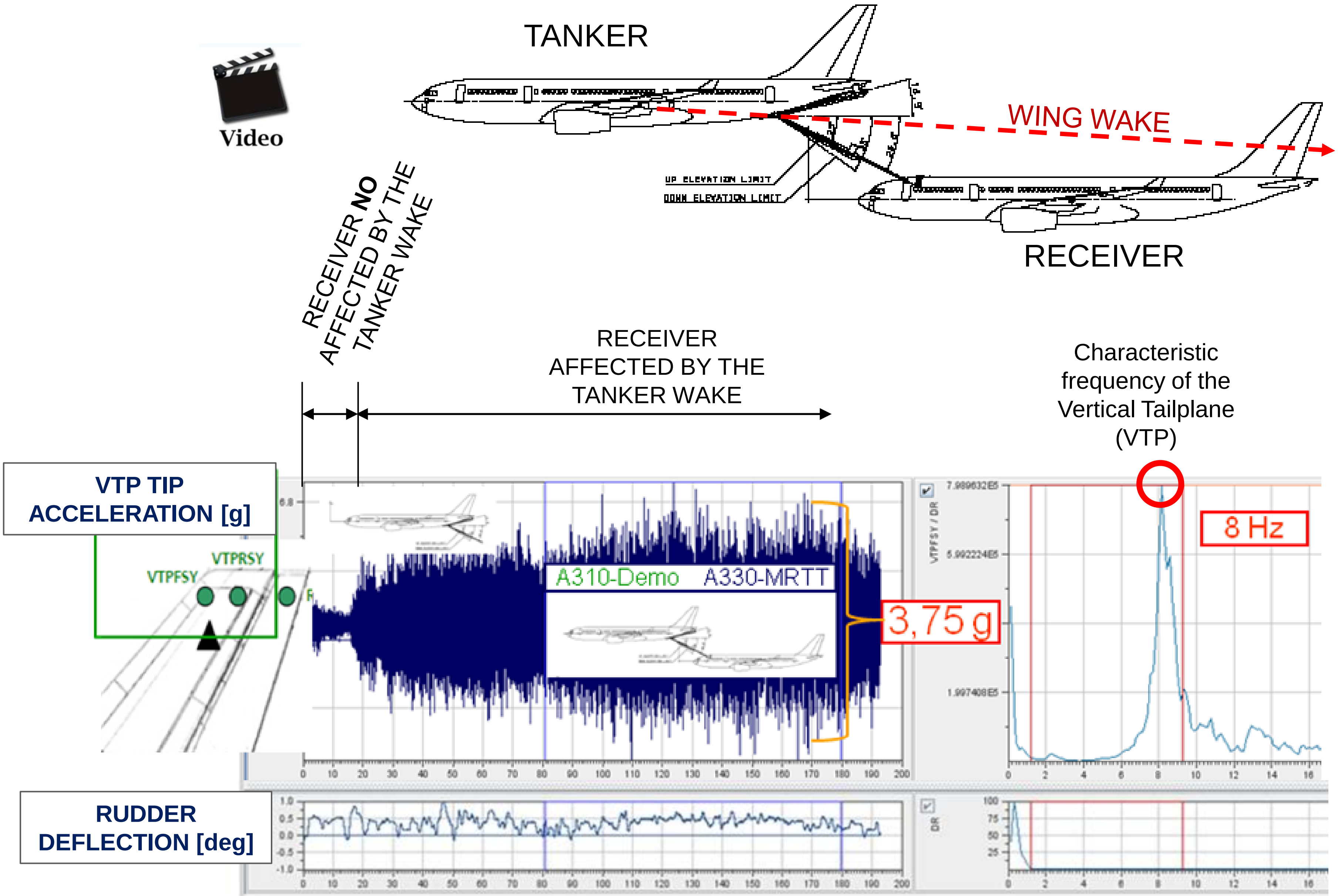
(*) More information of F18 buffet problem in web page **http://www.aerospaceweb.org/question/planes/q0176.shtml**

BUFFET INDUCED BY FLOW SEPARATION
FLOW SEPARATION CAUSED BY HIGH AOA OR HIGH MACH NUMBER



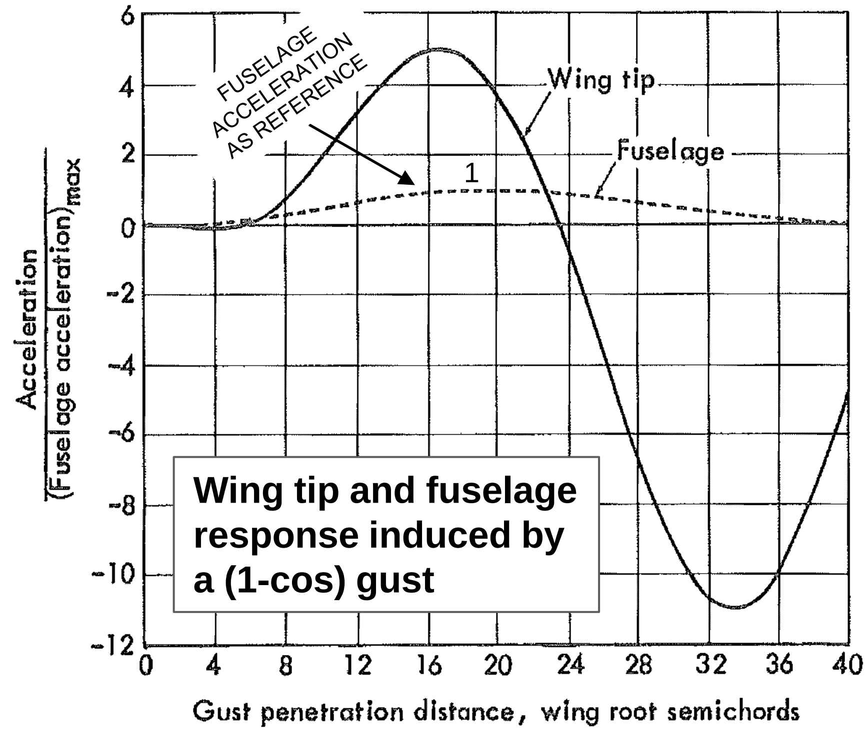
(*) Figure extracted from ESDU 87012

BUFFET INDUCE BY EXTERNAL EXCITATION
TANKER A/C WING WAKE IMPACTING ON RECEIVER AIRCRAFT



GROUND & FLIGHT DYNAMIC LOADS

- ❑ **Gust / Turbulence conditions:**
  - ► (1-cos) Discrete Tuned Gust & Continuous Turbulence
  - ► Loads alleviation systems
- ❑ **Dynamic Landing:**
  - ► Sink Speed: 10 fps MLW & 6fps MTOW
  - ► 2 points / 3 points
- ❑ **Taxi:**
  - ► Unpaved runways
- ❑ **Impact conditions:**
  - ► Bird & ice impacts
  - ► Blade loss (turboprop)



Wing tip and fuselage response induced by a (1-cos) gust

A400M Landing in an unpaved runway

IMPACT LOADS

- Impact conditions:
  - ► Bird & ice impacts
  - ► Blade loss (turboprop)
  - ► Vulnerability
  - ► Crash Landing / Ditching

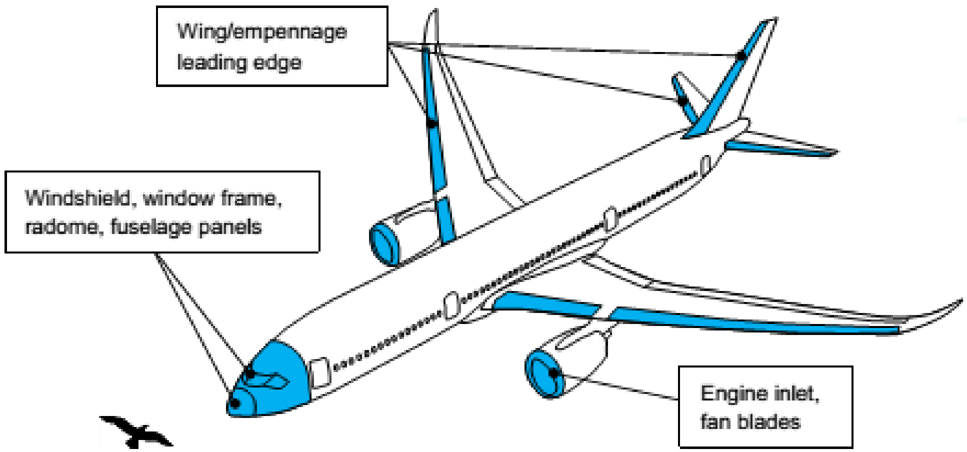


Fig. 1: Illustration of aircraft components exposed to the risk of bird strike

Video

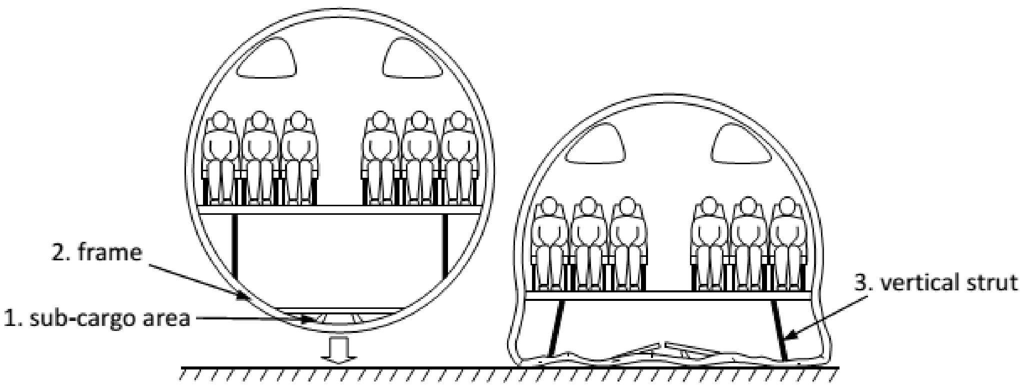
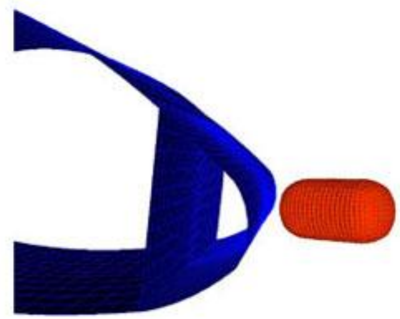
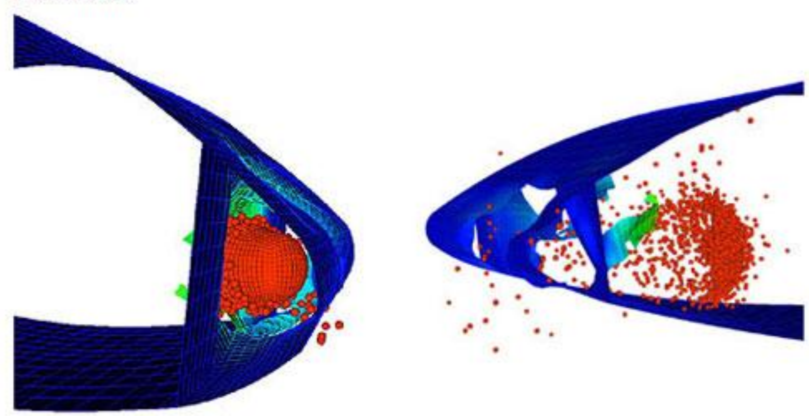


Fig. 8: Illustration of aircraft fuselage drop test for crashworthiness evaluation



Initial model



Meshless bird penetrates wing

- The aircraft structure is subjected to external excitations (aerodynamics, engines, pintle loads, …) that lead to different vibration levels during the flight

- Mechanical & electronic hardware must be designed to withstand the vibration levels:

  - ► Guidelines RTCA-DO-160 and MIL-STD-810 define test conditions to check hardware robustness.

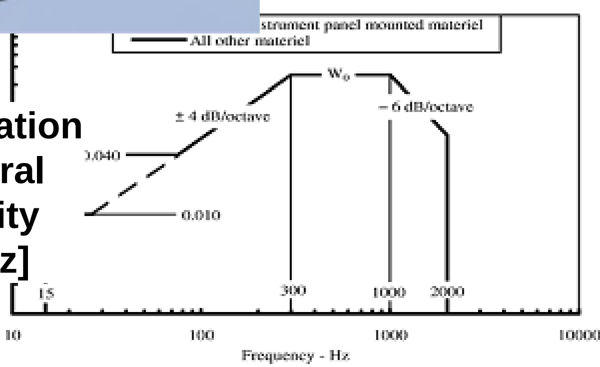
  - ► Engineering methods to prevent problems (“vibration map”)

  - ► If a problem is detected, then re-design could be needed:
    - Stiffening of the local structure
    - Dampers (engines, equipment mountings,…)

A/C Environmental vibration

Turbofans/turbojets

Dominated by aerodynamic boundary layer excitation



Acceleration Spectral Density [g^2/Hz]

Frequency [Hz]

Turboprops

Dominated by power plant propeller excitation

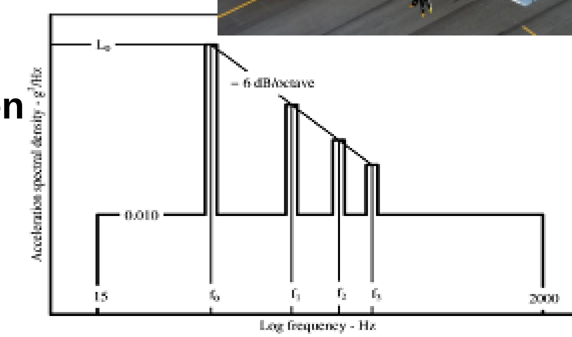


FIGURE 514.5C-9. Propeller aircraft vibration exposure.

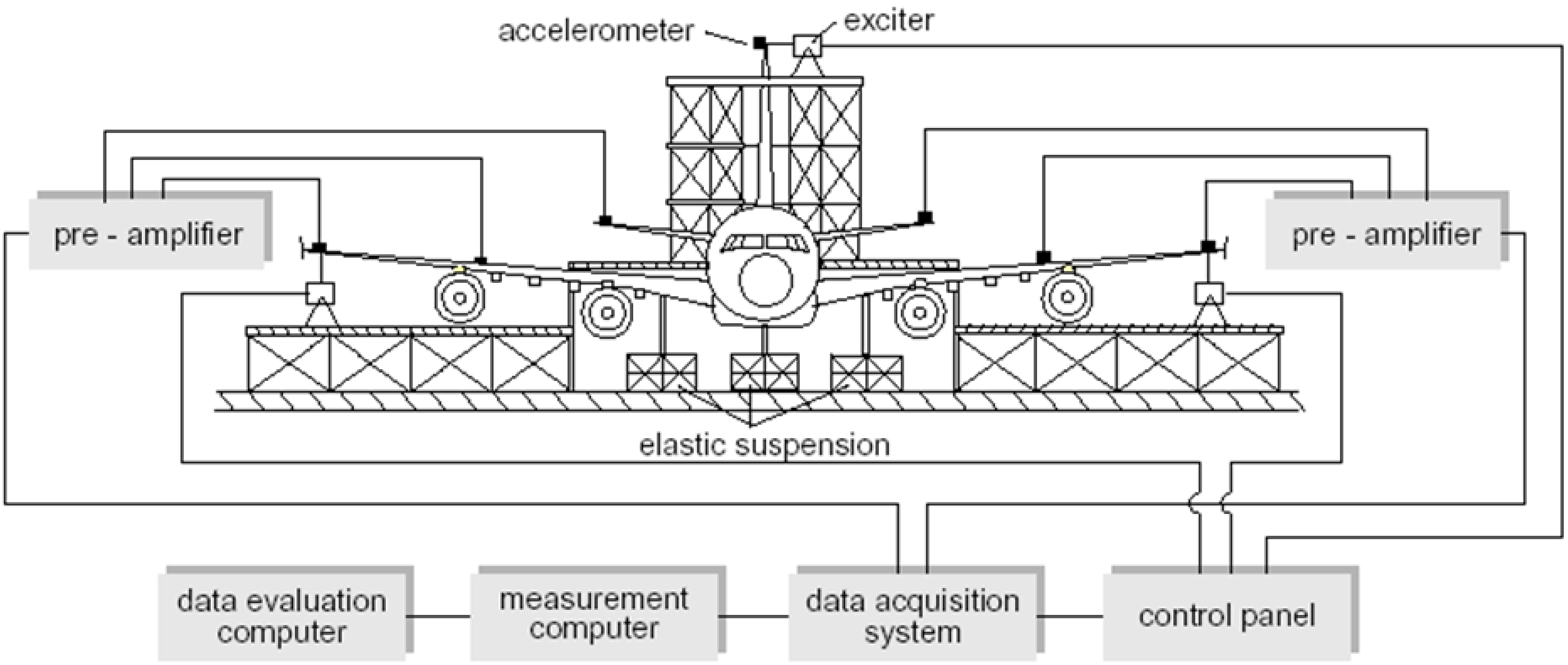
Acceleration Spectral Density [g^2/Hz]

Frequency [Hz]

(*) C-SERIES GVT

Video

- Ground Vibration Test (GVT):
  - ► Analysis of aircraft response to external sweep/random excitations



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