Introduction to Fluid-Structure Interactions

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PURPOSE: *This presentation presents an overview of most common aeroelastic phenomena encountered in aeronautical engineering.*

1. Flow Induced Vibrations

1.1 Overview

- Study of the movement or deformations of an *elastic* structure immersed in a moving *flow*.
- *Excessive* loads can reduce the *efficiency* and the *operational range* of the system (fatigue, failure).
- Wide range of engineering sciences : bio-mechanics, civil engineering, marine engineering, nuclear engineering, aeronautic and aerospace engineering.
- FVI are systematically integrated in the *design process* of various mechanical systems: tower and bridge deck, tube bundles, hydrodynamic and marine systems, aircaft, spacecraft, AUV, turbomachinery,...

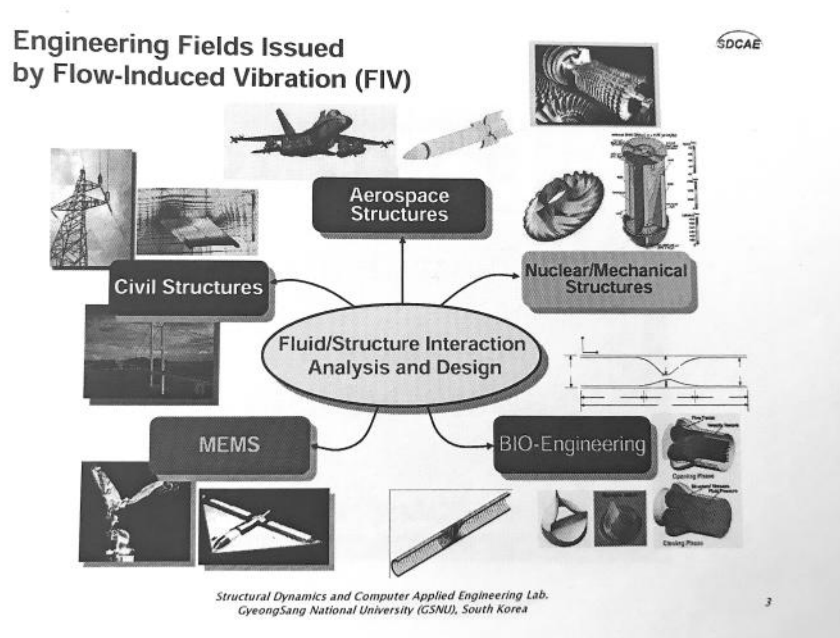

Fig. 1: Research fields in Computational FIV at GyeongSang National University (South Korea, 2006 [11])

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1.2 A famous example of FIV: The FLUTTER (not resonance) of the Tacoma Narrows bridge

- *Collapse* of the Tacoma Narrows bridge (US) in 1940.
- Bridge with a conventional T-shaped deck of 853 m long.
- FVIs were *not* considered during the design process (!)

[Video]: Accident analysis

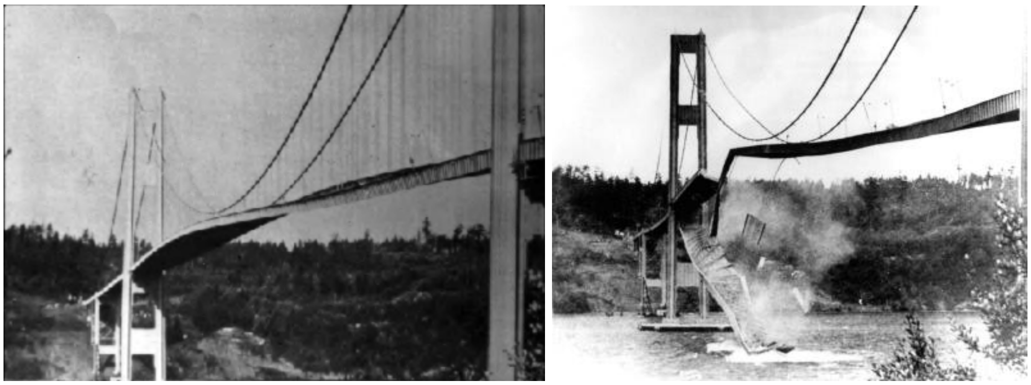


Fig. 2: Torsional dominated flutter of the Tacoma Narrows bridge (left) before collapse (Right)

- First (3h - wind 56 km/h): *bending* **FORCED** oscillations with constant amplitude about 0.45 m.
- Second: (45mn - wind 68 km/h) : switch into *torsional* **SELF-SUSTAINED UNDAMPED** oscillations : 8.5m of amplitude, frequency of 0.2 Hz.
- Main feature: The process of the collapse is *closely related* to the aerodynamic forces acting

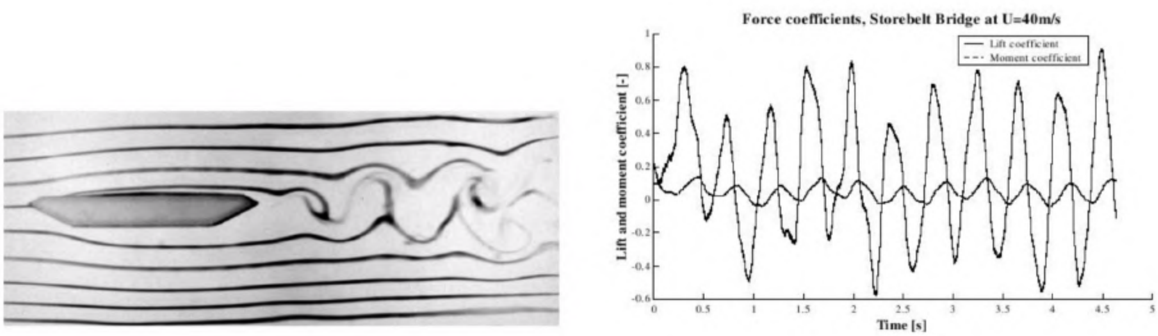


Fig. 3 : Visualization of the vortex sheding in the wake of the typical section of the Great Belt bridge (Denmark)(left). Time history of the corresponding aerodynamic force and moment acting on the deck (right).

- The vortex street shed in the wake of the bridge generates *harmonic forces*.
- Normal conditions: the corresponding aerodynamic work *extract energy* from the structure, resulting in *damped motion*.
- Accident conditions: the flow *gives energy* to the structure, resulting to *diverging (unstable)* oscillations.
- Taking into account to the *unsteady behaviour* of the flow in the aeroelastic analysis is of *crucial* importance.

Resonance or Flutter: A controversy since 1940 which should not be...

- "Due to a series of confusions and misrememberings, resonance phenomenon became the prevailing explanation for the failure", Alex Pasternack in The Strangest, Most Spectacular Bridge Collapse (And How We Got It Wrong).
- Donald Olson (Physics professor at Texas State University, 2015): "the failure of the bridge was related to a wind-driven amplification of the torsional oscillation that, unlike a resonance, increases monotonically with increasing wind speed.... Explaining how that happened requires some unpacking (untwisting?), but I don't think it's that hard to understand"[14].
- Bernard Feldman (Physics professor at the University of Missouri, 2006): "The real mystery is why the physics community has not taught the correct explanation for all the years since 1950"[13].
- Read more: Science Busts The Biggest Myth Ever About Why Bridges Collapse, by Ethan Siegel.

2. Aeroelasticity in Aeronautical Engineering

WARNING: An airplane is a **FLEXIBLE** structure !

- Airbus A340 at cruise conditions : M=0.82, Alt=35000ft, Mass=200 t
- Wingtip deflexion = 1.4 m (>3m certified) , Wintip untwist angle : 4 deg.

Video : Boeing 787 :

Fig. 4: Wing flexibility effects on a typical modern commercial airplane

2.1 Aeroelasticity science

- Study of *deformation* and *oscillations* of slender *elastic* structure in low or high-speed *airflows*.
- *Undesirable aeroelastic phenomena* : Loss of the aerodynamic performance, self sustained oscillations, sudden collapse.
- Aeroelastic prediction and optimization is required to guarantee *safe flight enveloppe*.

2.2 Aeroelastic fields

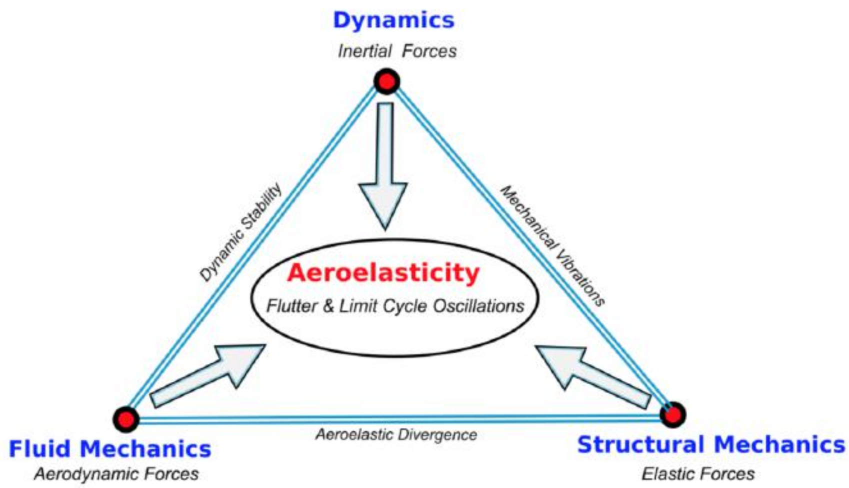


Fig. 5: Collar's Aeroelastic triangle of forces (1946) [6]

- **Structural dynamics** : Response of the structure due to mechanical vibrations (GTV, Landing impact, birds)
- **Static aeroelasticity** : Change in the *aerodynamic performances* of the wing due to its *elastic deformations*. Effect of steady aerodynamic loads on the *static stability, control surfaces effectiveness* and *reversal*. Sudden loss of control surface by aeroelastic *divergence*.
- **Flight mechanics** : Dynamic stability of the aircraft and its control.
- **Dynamic aeroelasticity** : Interactions of the elastic, inertial and aerodynamic forces.

  => **FLUTTER and LIMIT CYCLE OSCILLATIONS are very DANGEROUS !**

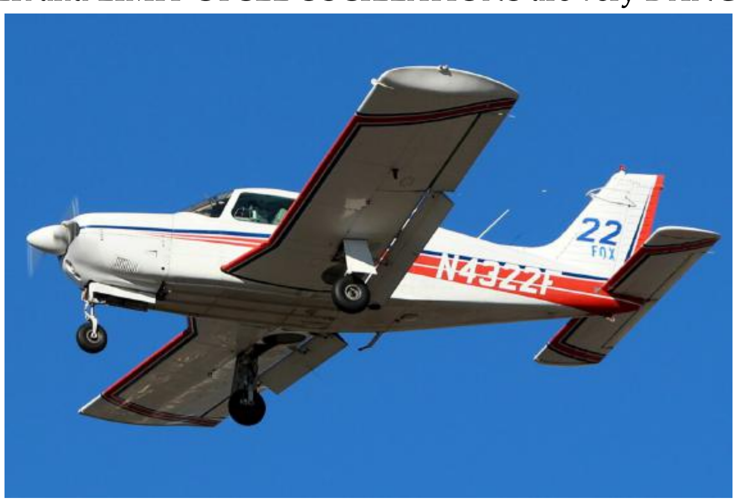


Fig. 6: Piper Cheerokee Arrow 2. Where could the flutter appear ?

2.3 A (very) short History of Flutter

Aeroelastic effets known since earliest days of aeronautical research. See Garrick and REED III[1] for an excellent review of historical development of aircraft flutter until eighties.

- **First flight tentative of S. P. Langley on December 1903 (USA)**

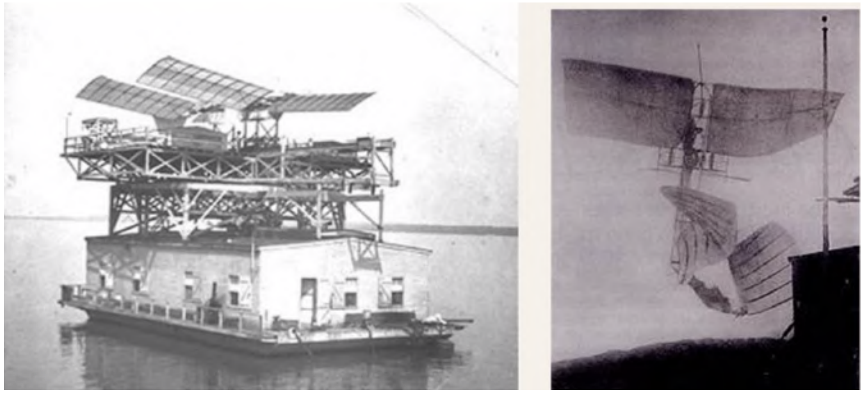


Fig. 7: Langley's aerodrome on the Potomac river which suffred from wing structural failure by insufficient torsional stiffness under aerodynamic loads [1]

- **First analysis of accident caused by flutter**

Fig. 8: The Handley Page O/400 bomber in 1916 (UK) suffered from torsional vibrations due to the flutter (whose mecanism was clearly distinguished from the resonance mecanism) of the tail[15].

- *Antisymetric elevator oscillations* coupled with fuselage torsion type oscillation
- Solution: Increase stiffness of the airplane by *coupling elevators*.

• 1915 - 1930

- German fighters affected by Aeroelastic divergence during the World War I.: Albatros D-III, Fokker D-VIII [1].
- *Wing-aileron flutter*: van Berkel W.B. airplane (Netherland 1923), Gloster Grebe (1925, England).
- *Horizontal tail flutter*: Navy MO-1 airplane.
- *US Air racers flutter*: Curtis R-6, Gee-bee, Verville-sperry R-3.
- **Flutter prevention**: Align the centre of gravity close to the hinge point using *mass balance systems*.

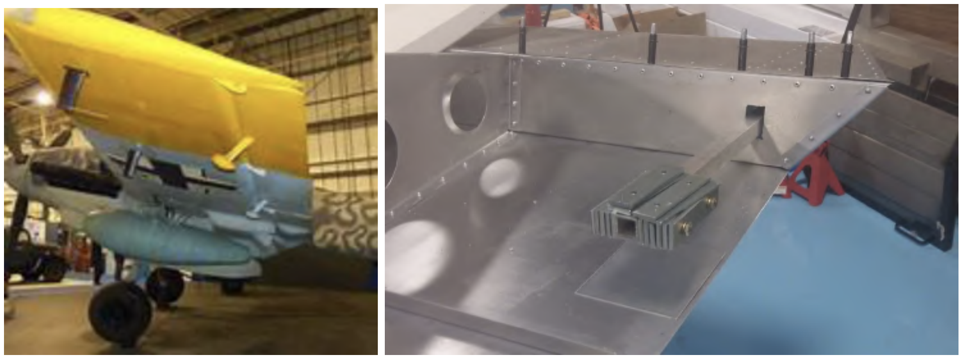


Fig. 9: External and Internal mass balancing devices for avoiding control reversal.

- **1930 - 1960**

  - A **dozen** of US airplanes subject to flutter between 1932-1934! [1].
  - More than **50** flutter incidents for US military aircrafts between 1947-1956! [1].
  - *Rudder-fuselage flutter*: General Aviation YO-27, Boeing YB-9A.
  - *Rudder-fin flutter*: Curtiss YA-8.
  - *Wing-aileron flutter*: General Aviation YC-14, Douglas C-26A and XO-43.
  - *Tail flutter*: Fairchild F-24.

Fig. 10 : B-52 bomber : Loss of the entire vertical rudder due to flutter (1964).

- **Transonic flutter**

  - *Transonic aileron buzz* aeroelastic instabilities (P-80, F-100, F-14).
  - Modern combat fighters : external stores *LCO* and *buffeting* (F-16, F-18, F-111).
  - Elevon-wing flutter of the F-117 : Insufficient actuator-elevon stiffness caused by the missing of four fasteners connecting the actuator to the wing.

- **Supersonic flutter**

  - Bell X-1 (1947), X-15 (Mach 7, 300000-ft)
  - *Panel flutter* : More than 70 accident of the V-2 rocket [1], Saturn V rocket.

Fig. 11: Rudder and flaperon damange on a F-16 (left). Crash of a F-117 during an airshow in 1997 (Maryland, USA)

3. Ground vibration test

- Analysis of the deformations and vibrations due to *external mechanical excitations*.
- Extraction of *modal properties* of the structure (structural damping, natural frequency).
- Used to improve or to calibrate a Finite Element Model of the structure.
- **Examples**:

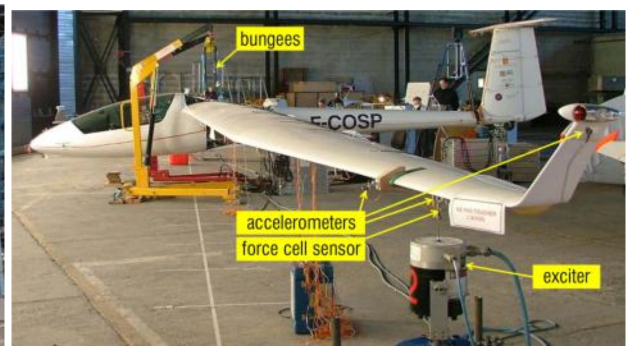



Fig. 12: High flexibility of the Airbus A350 wing under static loads (left). Glider GVT at ONERA (right [3])

4. Why GVT is not sufficient to predict flutter

- Let $\{q(t)\}$ the vector of the N Degrees Of Freedom (DOF).
- Governing equations of the aeroelastic motion

$$[M_s]\{\ddot{q}\} + [C_s]\{\dot{q}\} + [K_s]\{q\} = \{F_{aero}(V_\infty, t)\} + \{F_{GVT}(t)\} + \{F_{gust}(t)\} \tag{1}$$

• Right hand side: Structural operator
- $[M_s]$: the mass matrix
- $[C_s]$: the damping matrix - $[K_s]$: the stiffness matrix

• Left hand side
- $F_{gust}(t)$: external aerodynamic forces due to atmospheric gust
- $F_{GVT}(t)$: GVT external forces applied by means of excitation devices

- $\{F_{aero}(t)\}$: Aerodynamic forces depend on V_∞ and on q, $\dot{q}$ and $\ddot{q}$.

- **Final form or the motion** (stability study only)

$$[([M_s]-[M_{aero}])\{\ddot{q}\}+([C_s]-[C_{aero}])\{\dot{q}\}+([K_s]-[K_{aero}])\{q\}=0 \qquad (2)$$

- **Conclusion**
  - Flutter, is **NOT** a simply resonance of free vibration modes
  - Flutter means new mode shapes: namely *aeroelastic* mode shapes

5. Frequently encontoured aeroelastic mecanisms

5.1 Reponse-type aeroelastic phenomena

- **Gust response** : Transient vibrations in the presence of transitional aerodynamic load due to wind gust, wake effects or turbulence.
- **Buffet** : Transient vibrations produced by unsteady flow separation or shock-waves.

5.2 Elastic deformation

- **Aerodynamic loads** : the distribution of the pressure over the structure is *modified by the elastic deformation*.
- **Control effectiveness** : *loss of efficiency* of the control surfaces due to the elastic deformation of the wing.
- **Reversal speed** (V_R) : flight speed corresponding to *zero* aerodynamic loads when acting on the control surface.

5.3 Divergence is a **static aeroelastic instability** where the elastic stiffness of the structure is not sufficient to support the aerodynamic load.

- Divergence occurs when the aerodynamic moment is greater than the elastic restoring torque.
- The flight speed at which divergence occurs is called the **divergence** speed V_D.

[Video]: Aeroelastic Divergence Experiments of Forward Swept Wings

Fig. 13: Aeroelastic Divergence Experiments of Forward Swept Wings (NASA Langley CRGIS)

5.4 Flutter is a **dynamic aerelasticity** where the aircraft is subject to *undamped self-sustained oscillations*.

- Flutter can lead to *catastrophic* failure during flight.
- Generally, the flutter speed V_f is encountered before V_D.

Depending the nature of the aeroelastic system, several mecanisms of flutter are observed:

- **Classical flutter**, or coupled mode flutter is a *linear* aeroelastic instability:

  - Unstable aeroelastic modes results from *mode coupling*.
  - Such phenomenom can be predicted using *inviscid* flow theory.

Fig. 14: Antisymmetric flutter mode of a glider (left). Piper PA-30 Twin Comanche Aircraft Tail Flutter Test (right).

- **Limit cycle oscillations** (LCO) : self sustained oscillations of a *non-linear* dynamic system.

  Nonlinear effects may be caused by :
  - freeplay or hysteresis in the command.
  - geometrical nonlinearities such as external stores.

Fig. 15: Limit cycle oscillation of the F-16 fighter with store configuration.

- **Stall flutter** : Non-linear flutter where the dynamic instability is driven by *stalled flows*.

6. Aeroelasticity in aeronautical engineering field

- Aeroelasticity plays a significant role in the design of aircraft.
- **The big issue of the engineer in aeroelasticity** :

=> How to accurately predict the aeroelastic behavior of a complete aircraft at the earlier steps of the design process ?

- **Why ?**
  => *Prevent the airfract normal flight enveloppe from aeroelastic instabilities !*

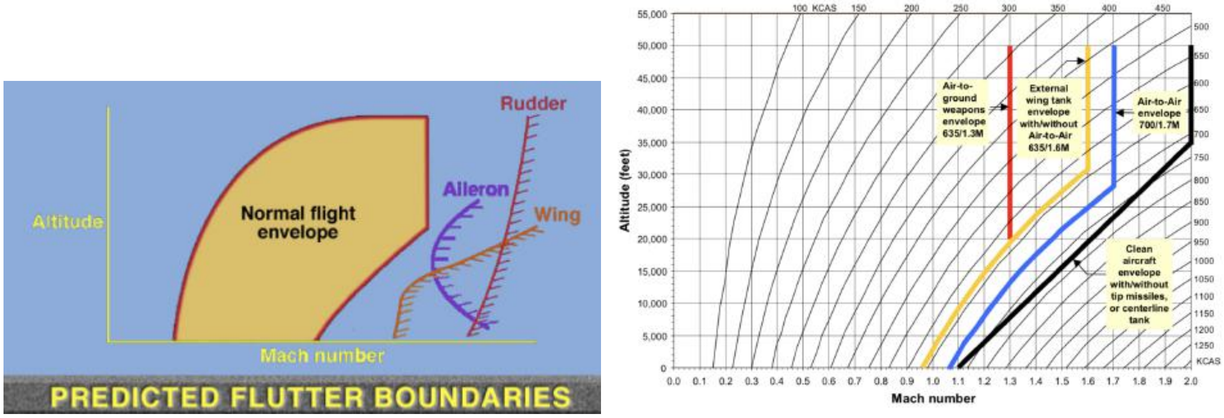


Fig. 16: Typical flutter free operating map (left). Reduced operating map of the F-18 fighter due to store induced LCOs [12](right)

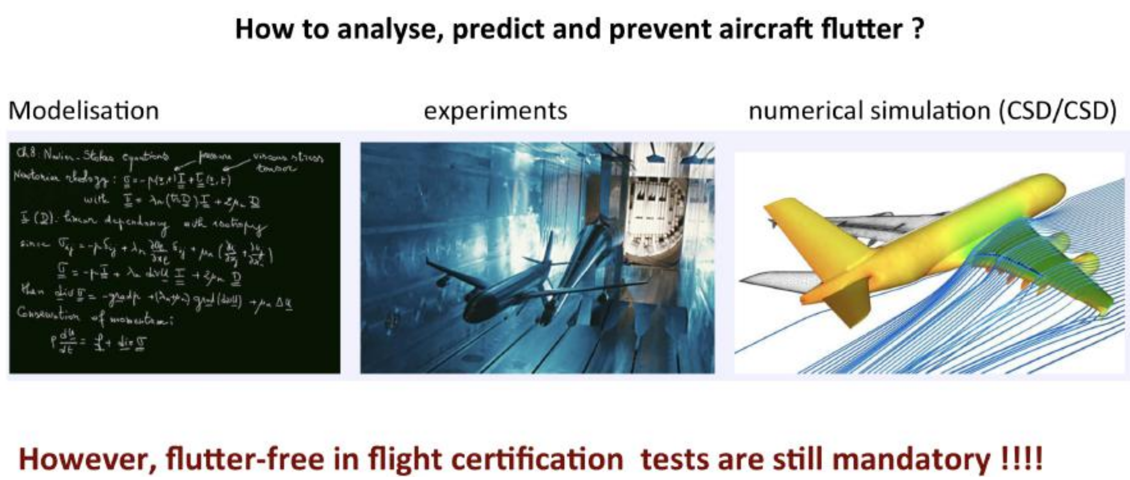


Fig. 17: Nowadays, modeling, experiment and numerical simulation are routinely employed in the aerelastic design of modern airfracts and UAVs.

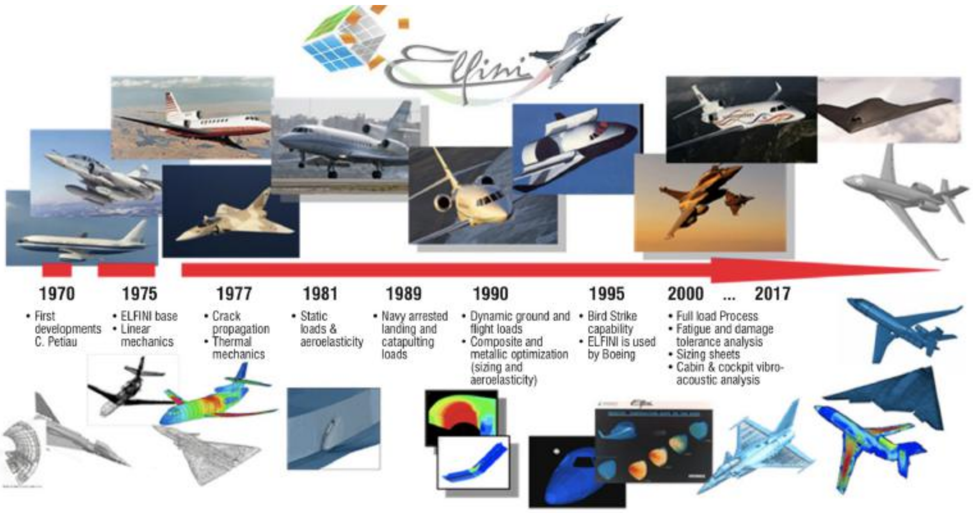


Fig. 18: History development of numerical simulation tools for aeroelastic studies at Dassault Aviation (from [9])

7. Flight flutter test and certification

7.1 How to proceed ?

- Push the aircraft to its *maximum speed* and wait...
  => insufficient, very dangerous, no informations about damping and flutter margin.
- **1st formal in-flight test:** Von Schlippe in 1935 (Germany)

  1. Vibrate the aircraft at (structural) *resonant frequencies* during flight at different speeds
  2. Measure the *maximum response amplitude* at the sensors.
  3. Plot the response vs excitations and *extrapolate* results to estimate V_f.

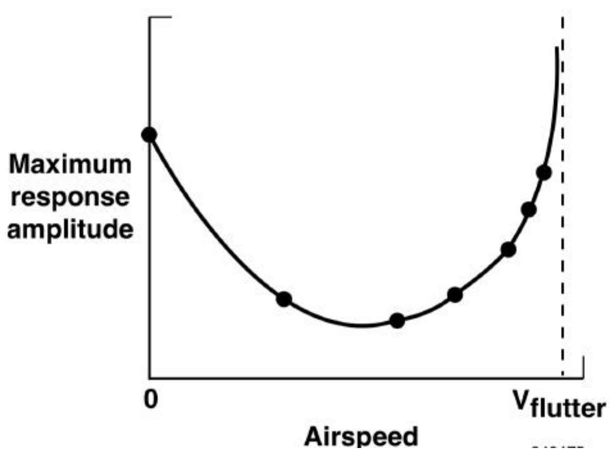


Fig. 19: Von Schlippe's flight flutter test method [5]

7.2 Flutter test process

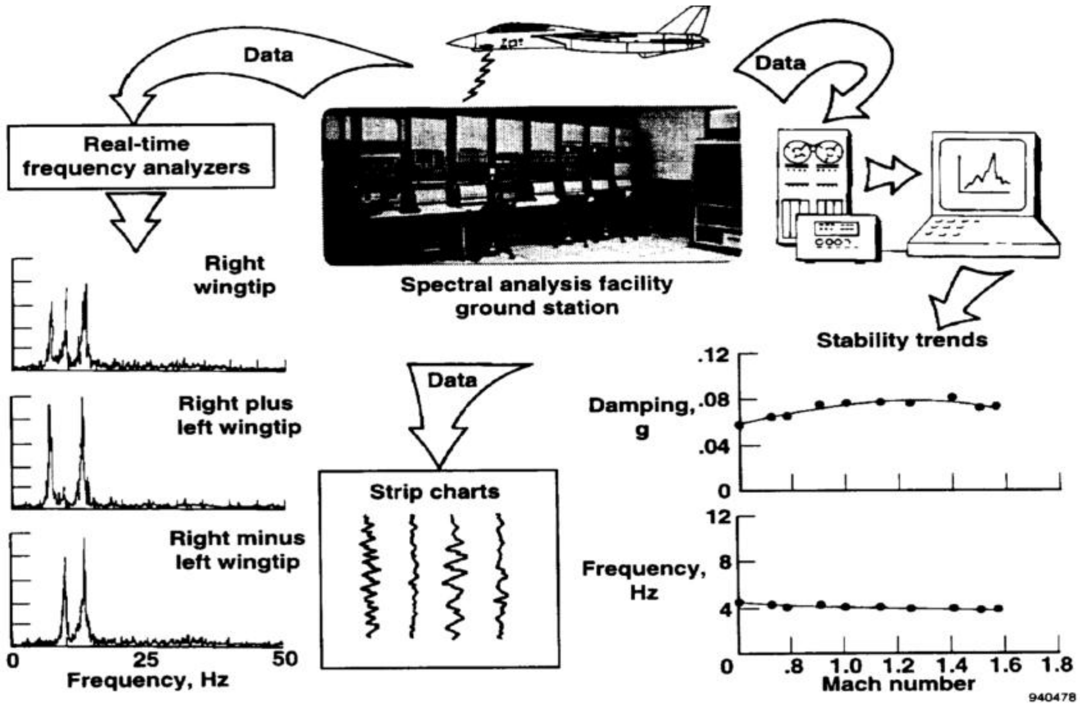


Fig. 20: Typical flutter analysis due to Aero tab excitation on F-111 aircraft [5]

- [Video]: Airbus A380 Flutter test
- F/A-18 Hornet - Rudder Flutter at Slow Speed Tight Turn , Temora (USA) 2013

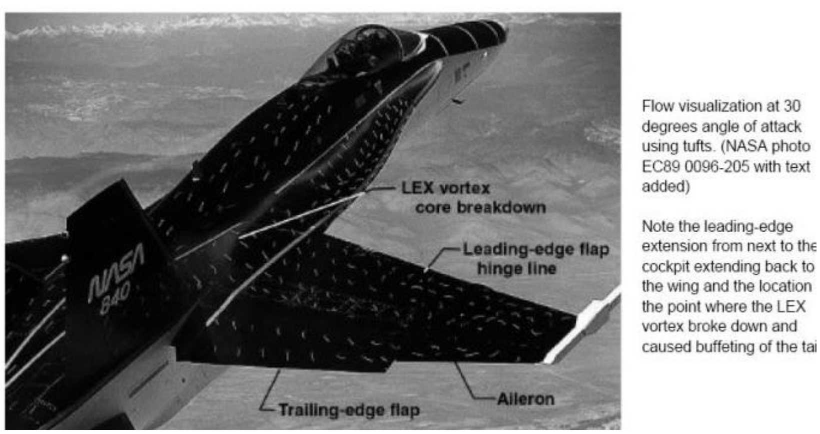


Fig. 21: F-18 fighter - Ruder excitation due to Leading Edge Extension (LEX) vortex (credit: NASA photo EC89-0096-205)

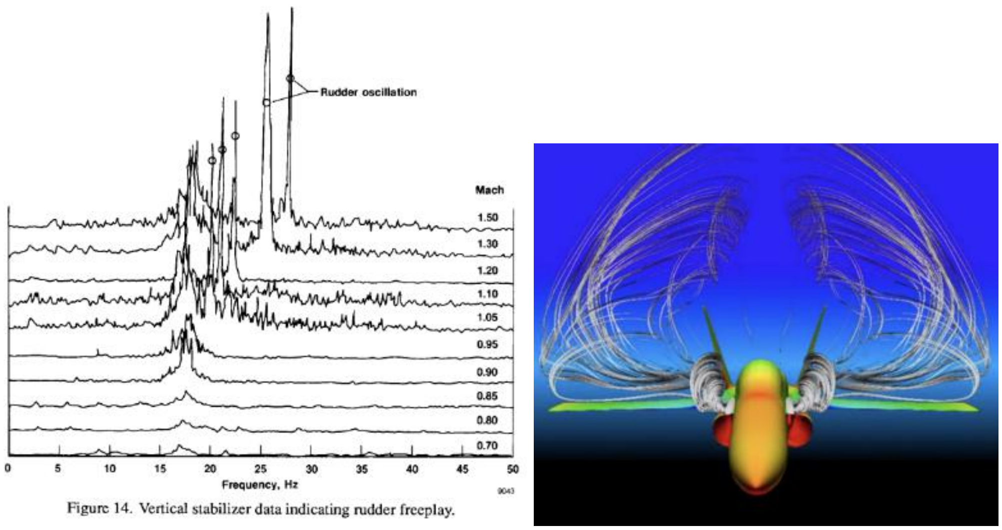


Fig. 22: F-18 fighter - Excitation frequencies of tail vibrations vs Mach number (left). CFD computation of LEX vortex [10] (right)

Fig. 23: F-18 fighter oscillation preventing devices - LEX Fences and structural brackets on the vertical tails [10]

8. Wind tunel flutter test

- Asses the aeroelastic design and performances of scaled models.
- Experimental measurements can also be used to validate new theoretical or numerical aeroelastic solvers.

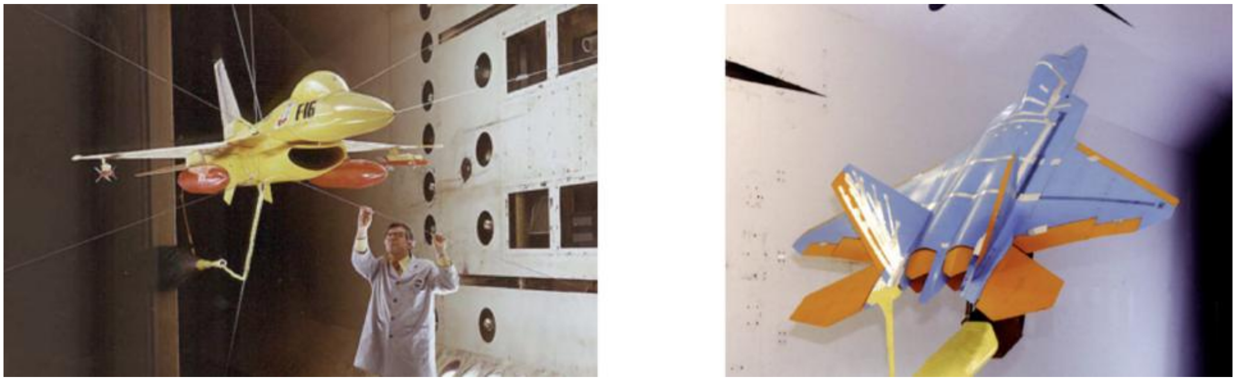


Fig. 24: F-16 model for flutter tests (left), F-22 model for buffet tests (right)

(!) However several *similarity laws* must be respected to mimic in-flight physical aeroelastic phenomena

- **Geometry** similarity (e.g model dimension).
- **Dynamics** similarity : Reynolds numbers (Re) and reduced frequencies ($k = \omega L/V$).
- **Turbulence** similarity: respect of turbulence scales, turbulence intensity, mean flow velocity.
- **Mass and damping** ratios similarity.

Experimental flutter studies are costly to deploy with generally a limited number of spatial resolution. Moreover results may be altered due to incomplete similarity laws, wall boundary layer effects

- **Langley Transonic Dynamics Tunnel** (1960 -> present)
  - Location: Langley Research Center (Hampton, Virginia)
  - test section: 4.9x4.9 m^2
  - Max. Speed: Mach 1.2 (medium: freon)
  - Some models: Apollo, F-15, F-16, F-22, Space Shuttle, HiMAT, Boeing C-17

Fig. 24: NASA Langley 16-Foot Transonic Dynamics Tunnel, Building 648; 1995

10. High Altitude Pseudo Satellites

- Solar powered Unmanned Aerial Vehicles (UAV) are being increasingly developped.
- Massive use of composite material for structures with high flexibility.

Fig. 27: The Zephyr High-Altitude Long-Endurance (HALE) Unmanned Aerial Vehicle (UAV)

- **Warning**: HAPS are **VERY** sensitive to atmospheric gusts !
- **Helios accident (2003)** : High Altitude Long Endurance (HALE) UAV (wingspan of 75m)

Close-up of Helios Prototype solar-electric flying wing during climb on its last flight.

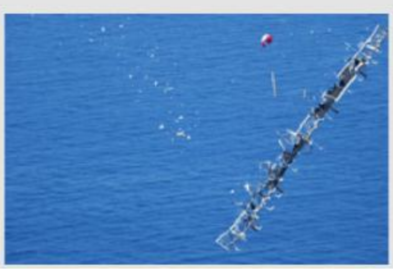
Photo number ED03-0180-1

This close-up telephoto from a chase aircraft of the Helios Prototype solar-electric aircraft while climbing on its last flight on June 26, 2003 shows essentially normal dihedral (upward bending) of the long proof-of-concept flying wing prior to its entering turbulent air.

Helios Prototype at high wing dihedral prior to structural failure and in-flight breakup.

Photo number ED03-0180-2

This view of the Helios Prototype from a chase helicopter shows abnormally high wing dihedral of more than 30 feet from wingtip to the center of the aircraft that resulted after the Helios entered moderate air turbulence on its last test flight. The extreme dihedral caused aerodynamic instability that led to an uncontrollable series of pitch oscillations and overspeed conditions, resulting in structural failures and partial breakup of the aircraft.



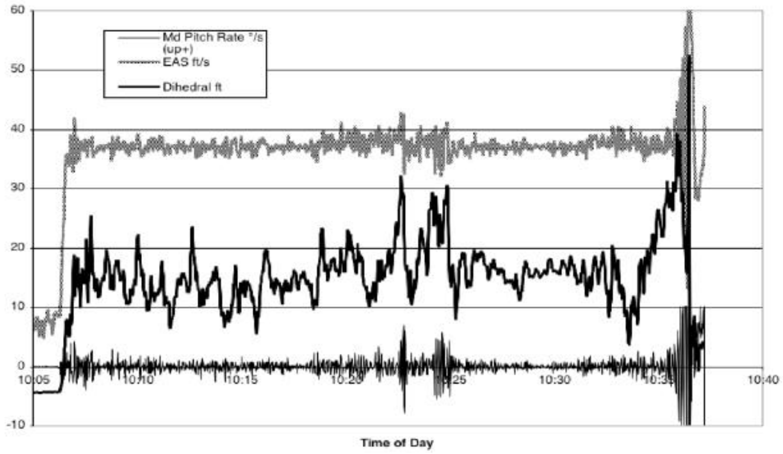


Fig. 28: Sensors history of failure of HELIOS (2003, NASA PHOTO ED03-0180-1/4, [8])

11. Academic Flutter test at d'Alembert

On all pictures presented hereafter, the incoming flow in going from the left to the right.

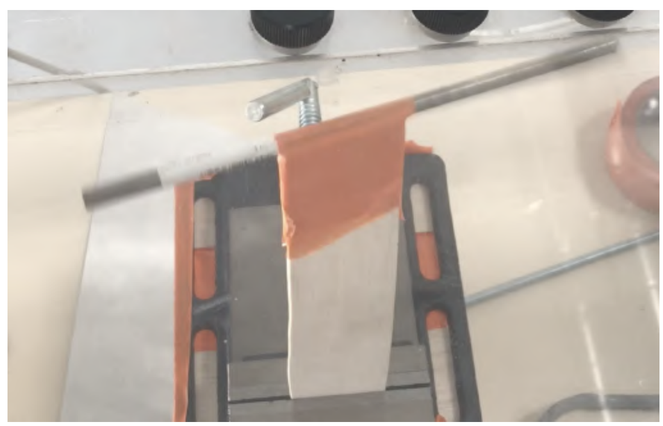


Fig. 29: Right: LCOs of a swept aluminium plate at 35 m/s. Left: Low speed (10 m/s) harmonic LCOs of a straight plate in balsa with tip store

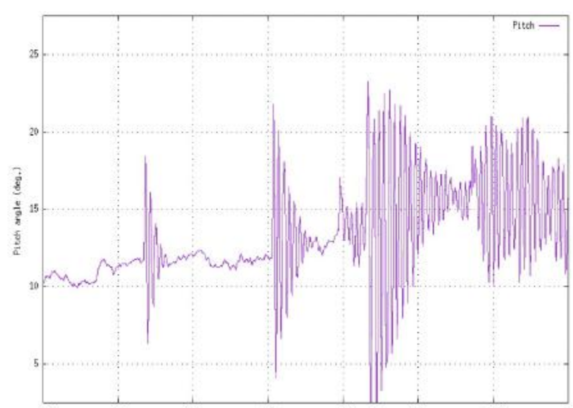


Fig. 30: Flutter of a 2DOF Pitch And Plunge Airfoil at 5 m/s with time signal in pitch motion

12. Some active Labs in Aeroelasticity Research

- Aeroelasticity Group at Duke University (Durham, North Carolina, U.S.)
- Georgia Tech Aeroelasticity and Structural Dynamics Group (Atlanta, U.S.)
- Farhat Research Group at Stanford University (California, U.S.)
- SDCAE Research Lab at Gyeongsang National University (Chinju, South Korea)
- Fluid and Aerodynamics Research Group at University of Bristol (England)
- Institute of Aeroelasticity of the German Aerospace Center (DLR)
- Politecnico di Milano Wind Tunnel laboratory (GVPM, Italy)
- Aeroelasticity and Experimental Aerodynamics at University of Liege (Belgium)
- Aeroelasticity Group at The French Aerospace Lab (ONERA, France)

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