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055738 – STRUCTURAL DYNAMICS AND AEROELASTICITY

Introduction
Academic Year 2021-22

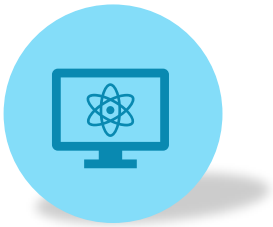
Giuseppe Quaranta

Dipartimento di Scienze e Tecnologie Aerospaziali

Outline

GENERAL INFO, WHERE, HOW, WHEN

COURSE STUFF (SYLLABUS, BOOKS, SOFTWARE, ADDITIONAL MATERIAL)



EXAM

GOALS

WHY STUDY AEROELASTICITY AND STRUCTURAL DYNAMICS (WITH SOME HISTORICAL NOTES)

General Info

Name: Giuseppe Quaranta
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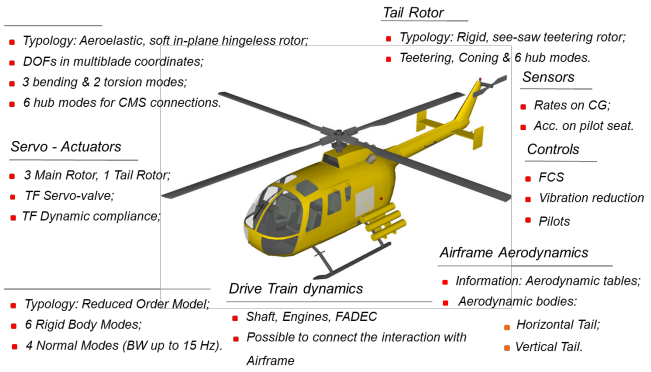
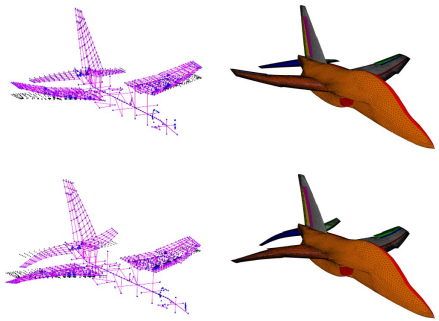
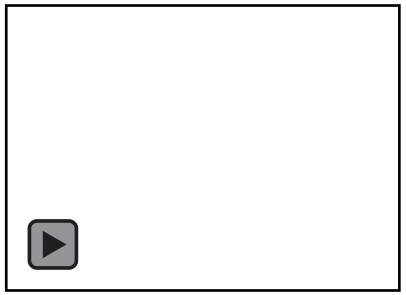


- ✓ Graduation POLIMI year 2000
- ✓ PhD POLIMI year 2004
- ✓ Assistant Professor 2011
- ✓ Full Professor since 2019





When and Where

Schedule

Monday	09:30 – 11:10 AM	BL 28.1.2	Lecture
Tuesday	09:30 – 11:10 AM	BL 28.2.2	Lecture
Wednesday	11:30 – 13:10 AM	B 8.1.2	Lecture/Exercise
Friday	10:30 – 12:10 AM	L 11	Lecture/Exercise

All lectures will be transmitted online using Cisco WebEx
https://politecnicomilano.webex.com/meet/giuseppe.quaranta

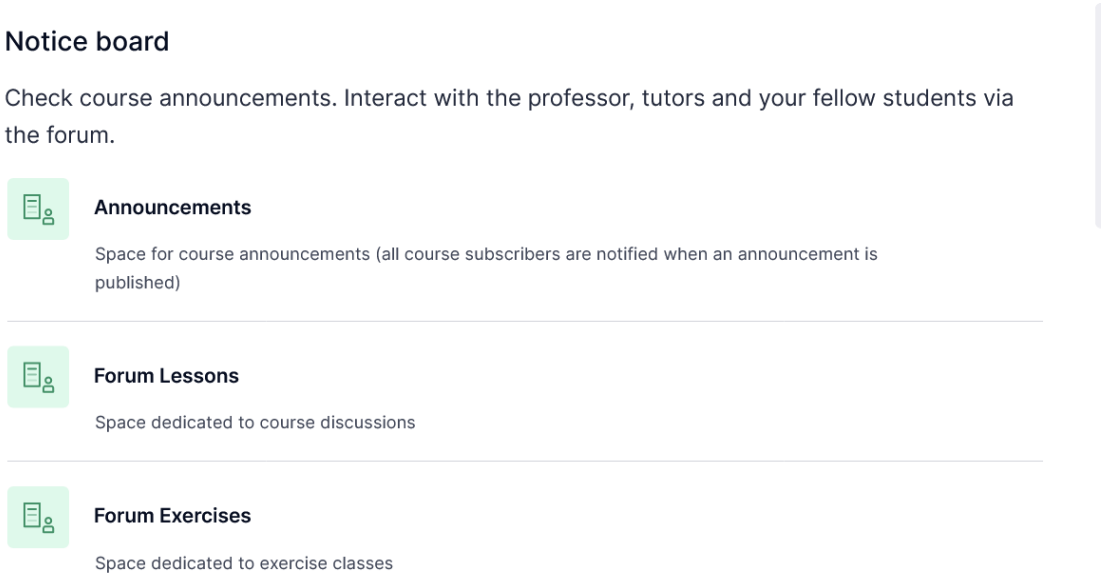
Exercise classes by Andrea Zanoni
https://politecnicomilano.webex.com/meet/andrea.zanoni

Overall Program (10 Credits)

- ✓ 55 h Lectures
- ✓ 45 h Exercises\Computing Labs

Questions & Answers

- ✓ All lessons will be recorded and published on WeBeep.
- ✓ During classes, please **ask questions by voice, I hardly check the chat while teaching.**
- ✓ Outside class, **please send your questions on the WeBeep Forum not via email.** All questions sent by email will be published on Beep Forum and will receive a public answer



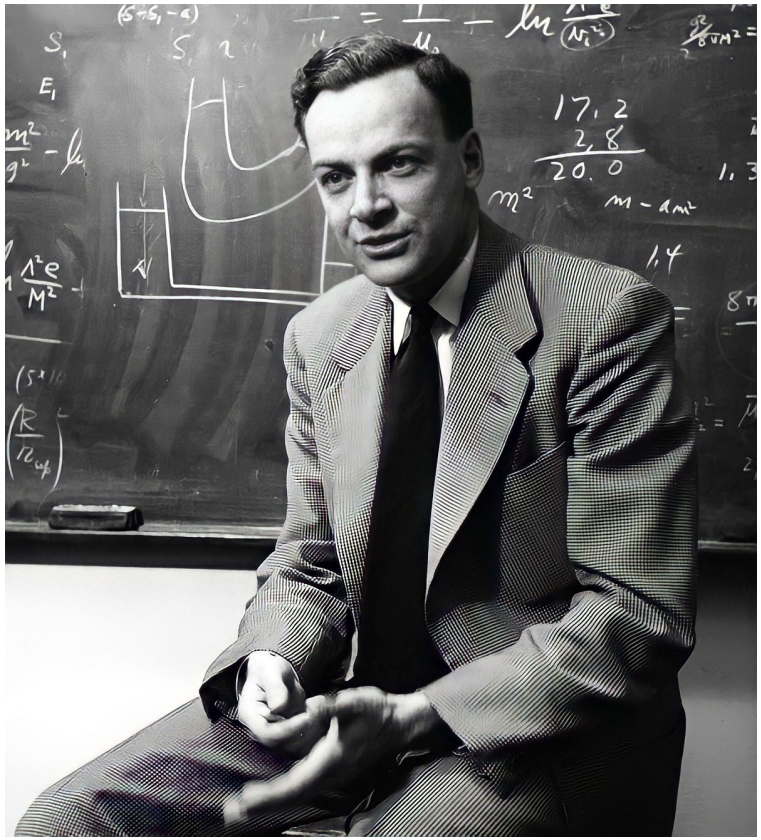
How: exam

- **(1) Assignments: 3-4 assignment will be assigned during the year.** Each assignment will require:
  - To develop procedure to solve the exercise
  - To solve all operation using a symbolic mathematical software (Matlab, Mathematica)
  - Identify the symbolic solution
  - Write a handwritten solution
  - Use the data provided to compute a numeric solution and submit through a webpage the correct numeric answer though a multiple-choice test selection and the copy of the handwritten solution

How: exam

- **(2) Written Test** composed by **3 exercises (statics, stability, dynamic response)** be performed symbolically. In all exercise we expect you to arrive to the results (so only few degrees of freedom) and discuss the engineering meaning of the obtained result. If all assignments are correct, it is required to solve only two exercises.
  - You are **allowed to use books, notes or any other material during the exam**.
  - The written exam is passed if a mark **equal or higher than 15/30** is taken.
  - **Passing the written part with a mark equal or higher than 18/30 does not entail you to pass the exam. No exceptions!!**
- **(3) Oral exam** for those who passed the written exam. The oral exam **should not last more than 30 minutes.**
- **There is no penalization for those who keep coming at a written exam without passing it, other than the self-inflicted one!**

How: Exam



Richard Feynman:
physicist

(1) Learning is underrated. Grades are overrated.

(2) You learn something by doing it yourself, by asking questions, by thinking, and by experimenting.

(3) If you don't make mistakes, you're doing it wrong. If you don't correct those mistakes, you're doing it really wrong

How: Exam

Course Syllabus

- ✓ Introduction to aeroelastic phenomena through simple example (crucial for the exam!!)
- ✓ Structural dynamics
  - ✓ Beam-ology (with an explanation on why we like beams)
  - ✓ Modal analysis and stability
  - ✓ Response (Fourier, Laplace & Co.)
- ✓ Response to Random input
- ✓ Unsteady aerodynamics
  - ✓ Foundation and vortex methods
  - ✓ Simple incompressible model: Theodorsen, Wagner, Kussner, etc…
  - ✓ Panel methods for subsonic/supersonic flow (Morino's method)

Course Syllabus

- ✓ The aeroelastic problems
  - ✓ General formulation for the static aeroelastic problem
  - ✓ Flutter: P-K method and time domain
  - ✓ V-f V-g diagrams
  - ✓ Hints of aeroservoelasticity and aeroelastic control

Course Syllabus

For more on aeroelasticity:

AEROSERVOELASTICITY OF FIXED AND ROTARY WING AIRCRAFT (next semester)

- ✓ Numerical Modelling (usage not only theory)
- ✓ Computational Aeroelasticity (using CFD)
- ✓ Nonlinear and Robust aeroelasticity
- ✓ Aeroelastic Control
- ✓ Aeroelasticity of Rotorcraft

Prerequisites

1. **Kinematics**
2. **Dynamics:** dynamics of systems of lumped masses, springs, dashpots; Lagrange equations and Principle of Virtual Works (PVW)
3. **Stability:** stability of solutions of linear, time invariant systems
4. **Response of linear time invariant systems** (free and forced)
5. **Structure:** basic theory of elasticity (De Saint Venant bending, shear, torsion problerms); Consitutive laws; Failure criteria
6. **Control theory:** Laplace and Fourier transforms, linear systems theory; Bode and Nyquist plots; state-space forms; feedback
7. **Aerodynamics:** behavior of airfoils and finite-span wings. Thin-airfoils; Potential theory; Prandtl lifting line
8. **Systems:** Hydraulics, electric motors

Course Material

- ✓ Lecture charts
- ✓ Lecture notes taken during classes
- ✓ Other lecture notes ….
- ✓ Records of lectures
- ✓ Exercises on Beep

Reference books (available through POLIMI library):

- ✓ R. L. Bisplinghoff, H. Ashley, R. L. Halfman, **Aeroelasticity**, Dover, 1996
- ✓ E. Dowell, **A modern course in aeroelasticity**, Springer, 2015
- ✓ J. R. Wright and J. E. Cooper, **Introduction to Aircraft Aeroelasticity and Loads**, John Whiley & Sons., 2015
- ✓ A. Preumont, **Twelve Lectures on Structural Dynamics**, Springer, 2013

Others:

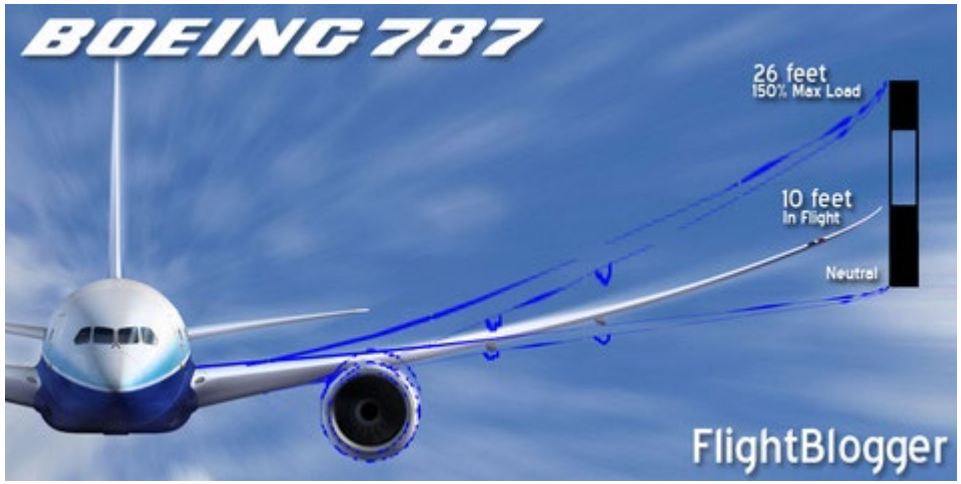
- ✓ Y.C. Fung, An introduction to the theory if aeroelasticity, Dover, 1993
- ✓ The old DCFA 2020 Notes by Prof. Masarati
- ✓ Selected papers and other material uploaded on WeBeep

Goals

I. Understand the basic aeroelastic phenomena
II. Acquire the capability to model and analyze the dynamics of a continuous structural system
III. Grasp the basic elements of unsteady aerodynamics and how to model them
IV. Understand how to build and simulate a multidisciplinary model
V. Understand the repercussions of aeroelasticity on performance of the aircraft and sizing of their structures

What is STRUCTURAL DYNAMICS

Structural dynamics is concerned with the vibrations and dynamic response of the elements of a structure. Aerospace structures differ from other structures due to the combined effect of the request to be lightweight and at the same time extremely performant. This in turn, leads to thin-walled structures, often based on the usage of composite or other multifunctional materials, characterized by large flexibility.



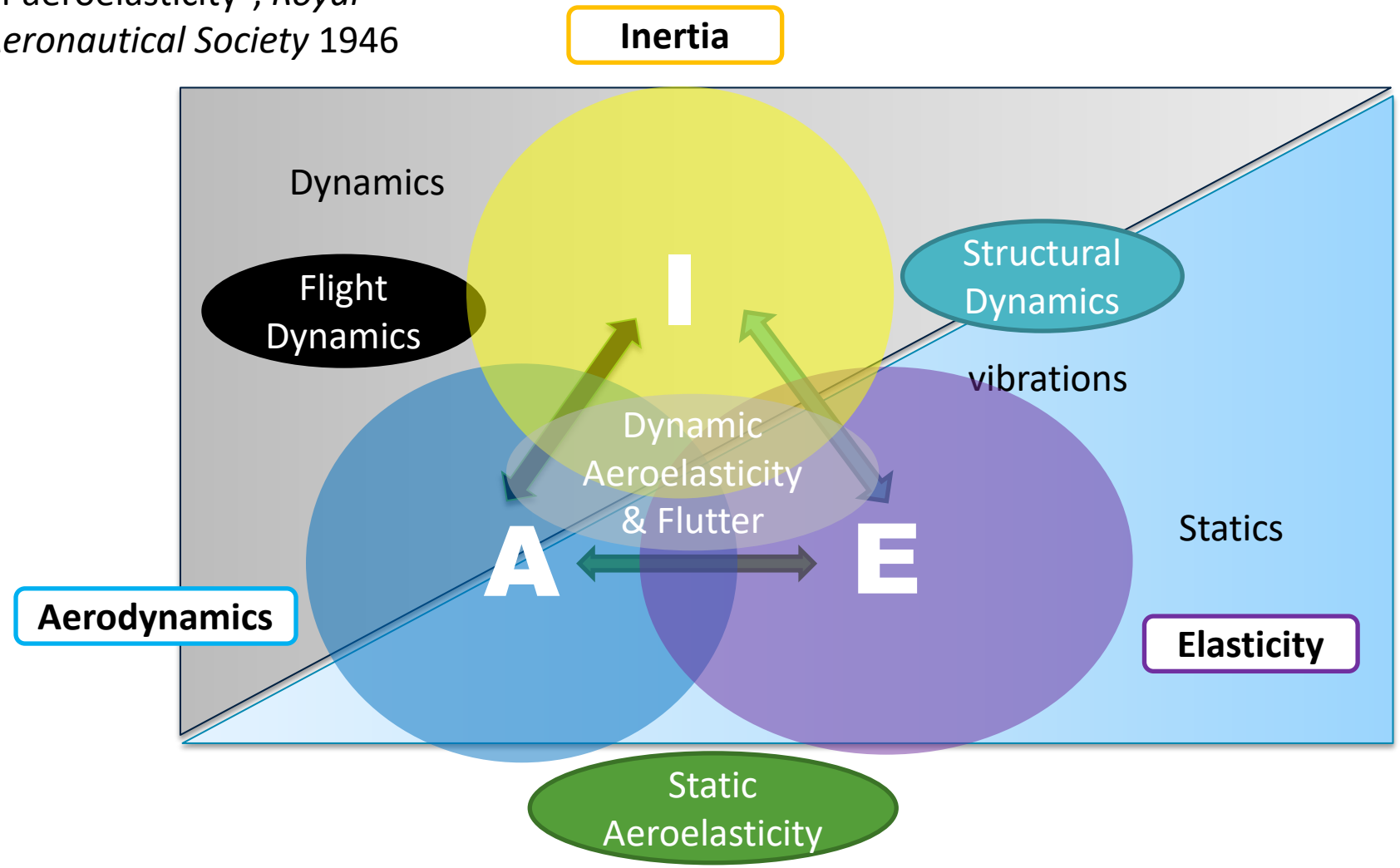
What is AEROELASTICITY

Aeroelasticity is the study of the dynamic of such structures considering the influence of the fluid flows that surrounds them. It studies the interactions between the inertial, elastic, and aerodynamic forces occurring while an elastic body is exposed to a fluid flow.

The most general phenomena are dynamic by nature, but static aeroelastic phenomena (steady state response) can also have a significant impact on the design. Aeroelastic and structural dynamic phenomena can sometimes result in extremely dangerous loading conditions and/or instabilities: divergence and flutter.

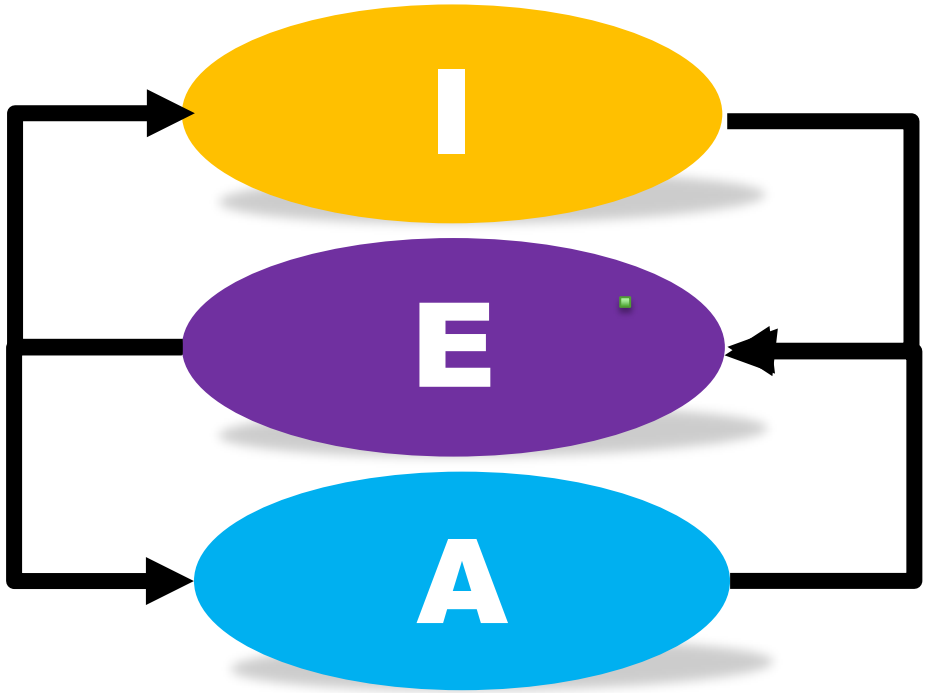
What is AEROELASTICITY

A.R. Collar, "The expanding domain of aeroelasticity", *Royal Aeronautical Society* 1946



What is AEROELASTICITY

Associated with feedback structure there is always the possibility to have an unstable behavior: i.e. self-excited oscillations.



Dynamics

Inertia Forces

Change of shape

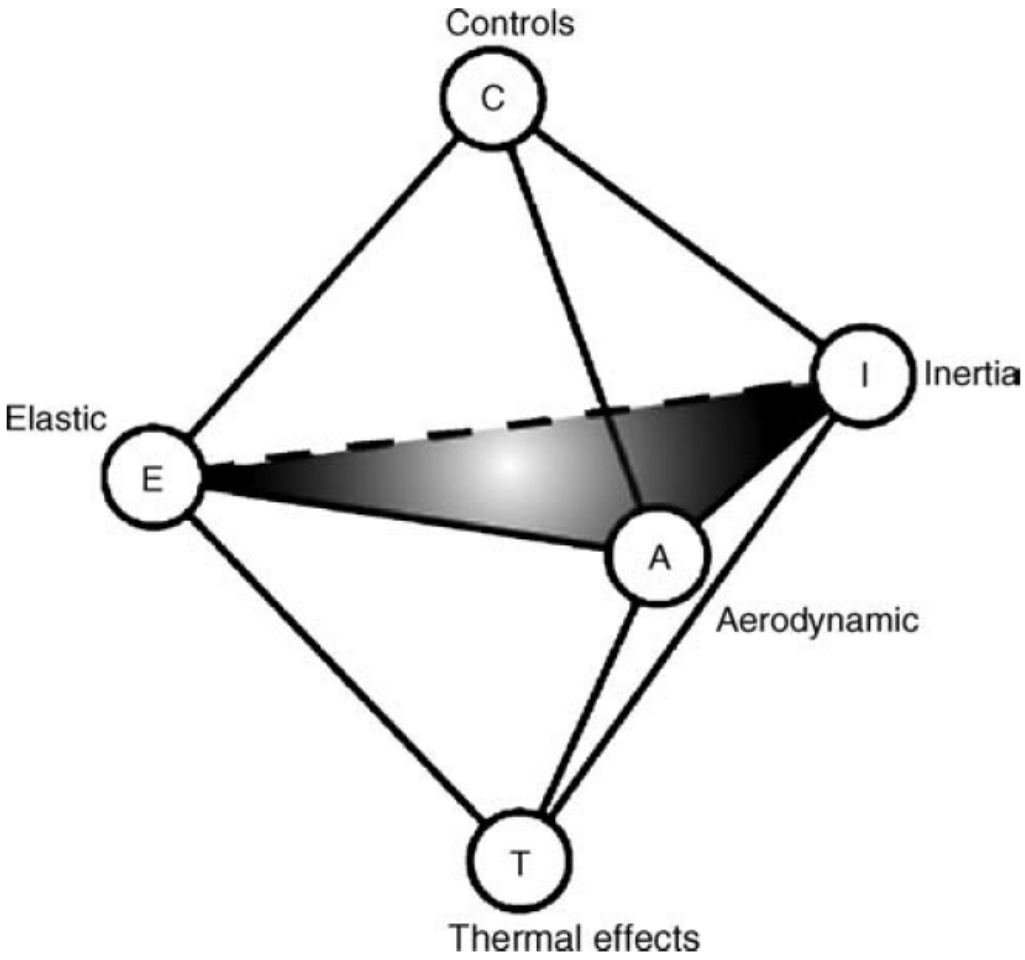
Elasticity

Controls

Aerodynamics

C

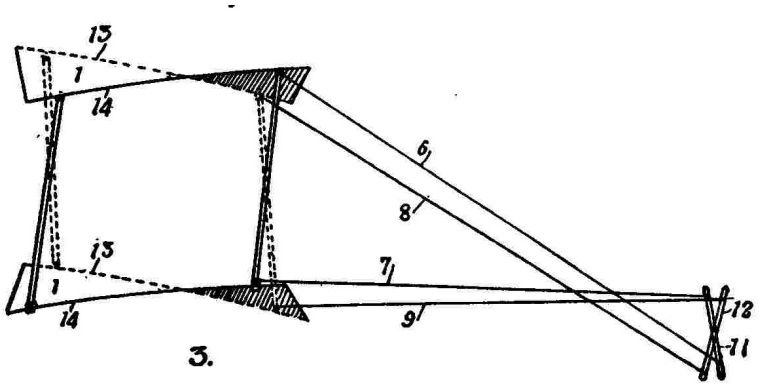
What is AERO(-SERVO(-THERMO))ELASTICITY



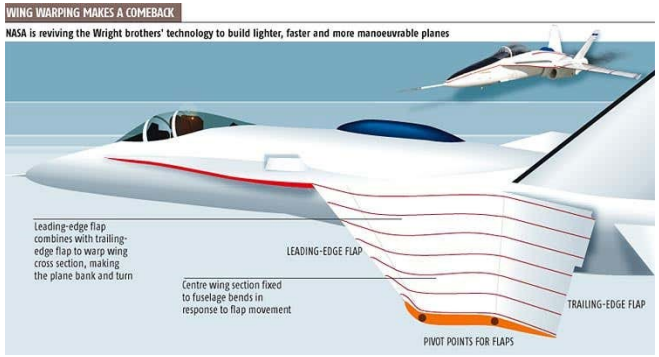
Why Bother?

Flexibility affects the performance

What is AEROELASTICITY

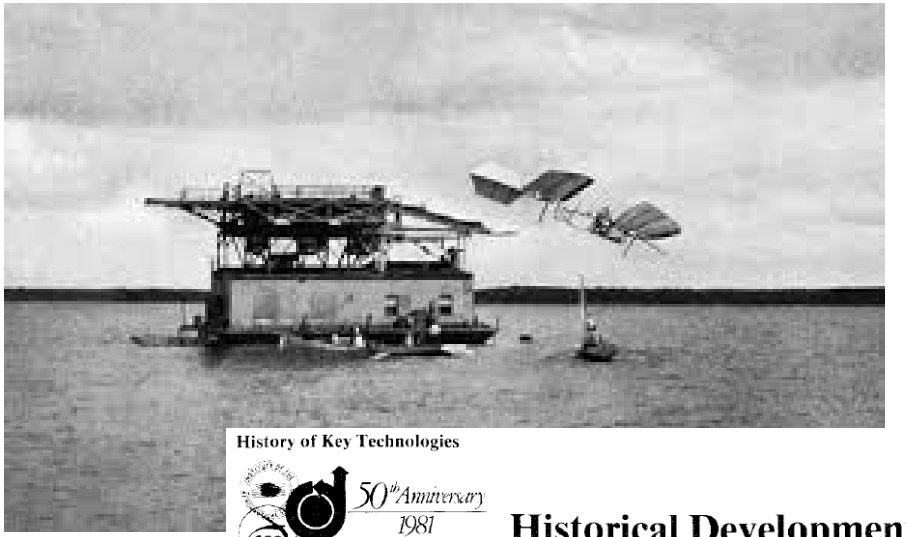


Wright brothers patent for <u>wing warping</u> used to roll the aircraft



What is AEROELASTICITY

Aeroelasticity is intimately connected with human flight since the dawn of aeronautics



Langley Aerodrome tentative flight
December 8, 1903

1st Flight of Wright Brothers
December 17, 1903

History of Key Technologies

50th Anniversary 1981

AIAA 81-0491R

Historical Development of Aircraft Flutter

I. E. Garrick and Wilmer H. Reed III
NASA Langley Research Center, Hampton, Va.

Introduction

AEROELASTICITY, and in particular flutter, has influenced the evolution of aircraft since the earliest days of flight. This paper presents a glimpse of problems arising in these areas and how they were attacked by aviation's pioneers

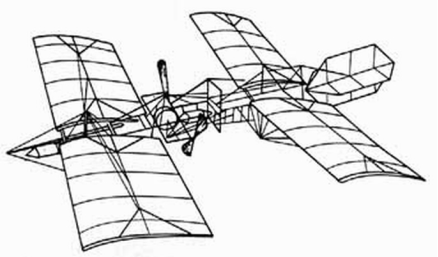
Work in flutter has been (and is being) pursued in many countries. As in nearly all fields, new ideas and developments in flutter have occurred similarly and almost simultaneously in diverse places in the world, so that exact assignment of priorities is often in doubt. Moreover, a definitive historical

What is AEROELASTICITY

1903- 1930

Torsional divergence

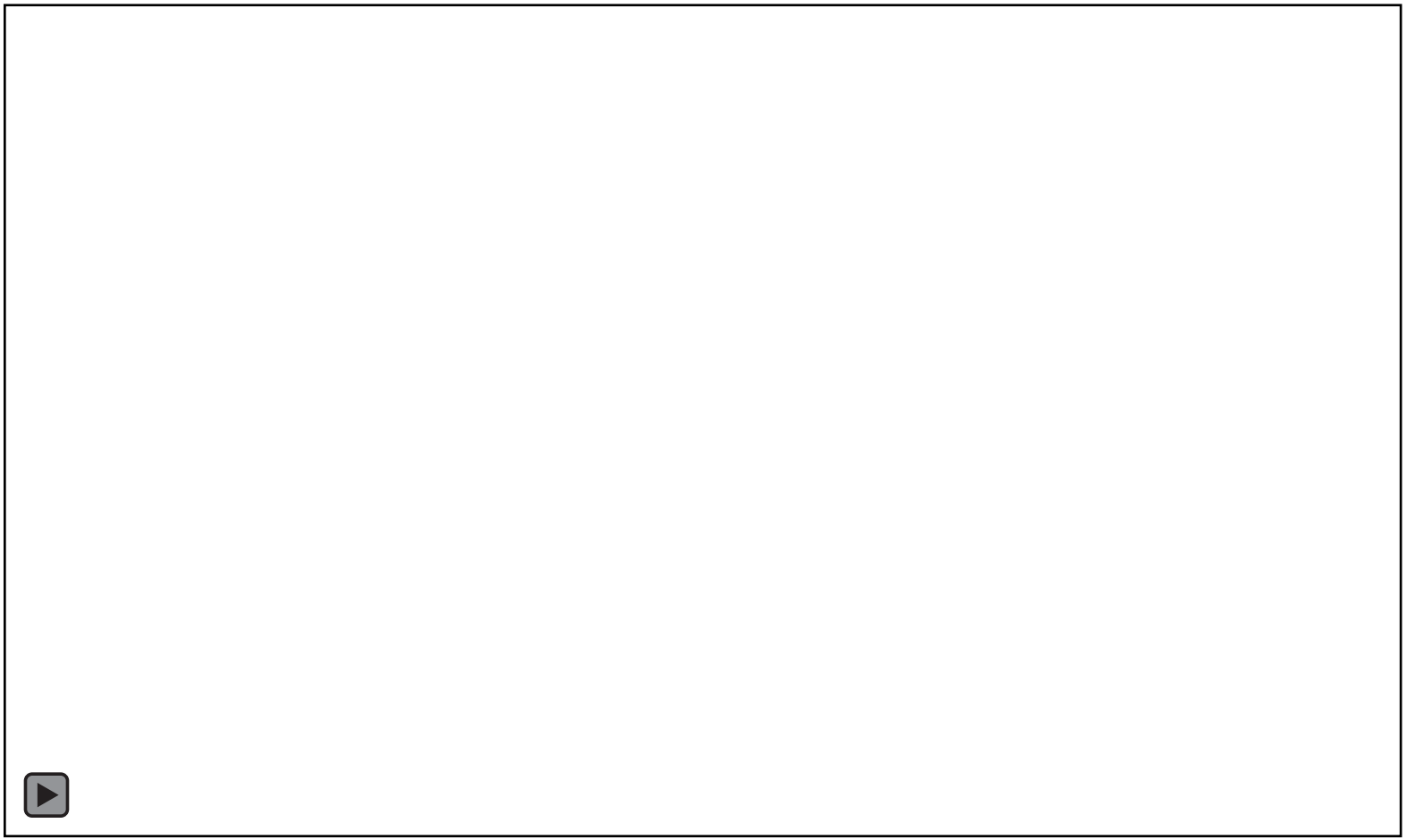
Langley Aerodrome



Fokker D-VIII

"The D-VIII was not in combat more than a few days before wing failures repeatedly occurred in high-speed dives. Since the best pilots and squadrons were receiving them first, it appeared possible that the flower of the German Air Corps would be wiped out" BAH

What is AEROELASTICITY

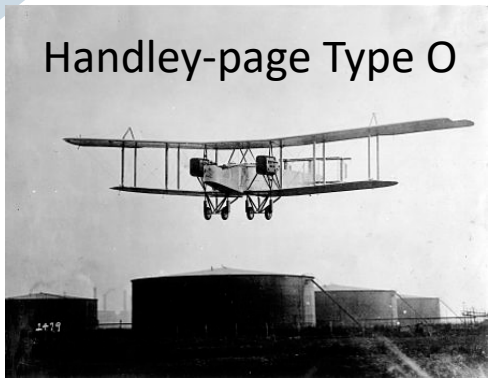


What is AEROELASTICITY

1903- 1930
Torsional divergence

1916 – now
Control surface Flutter

Handley-page Type O



Lockheed P-80

What is AEROELASTICITY

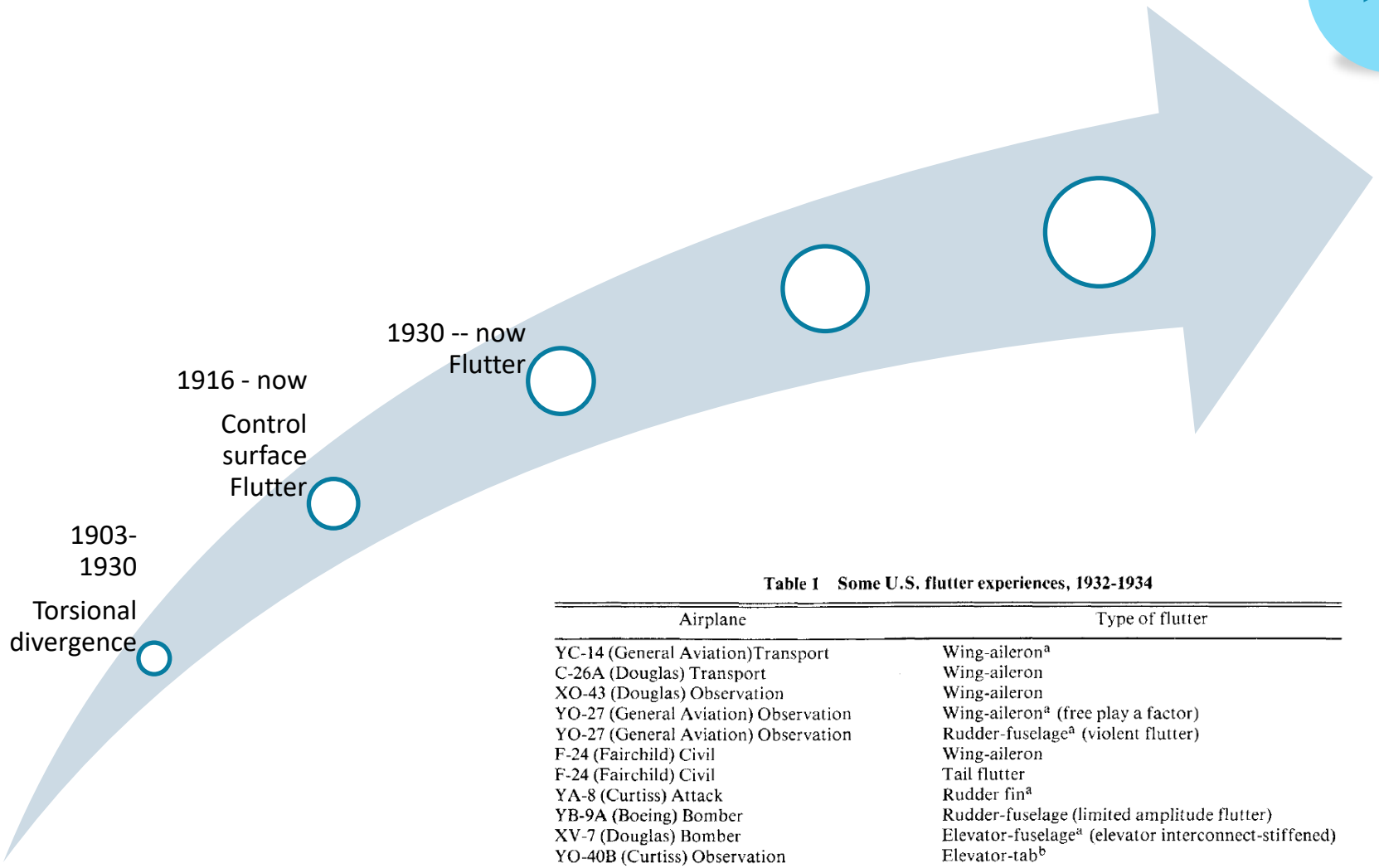
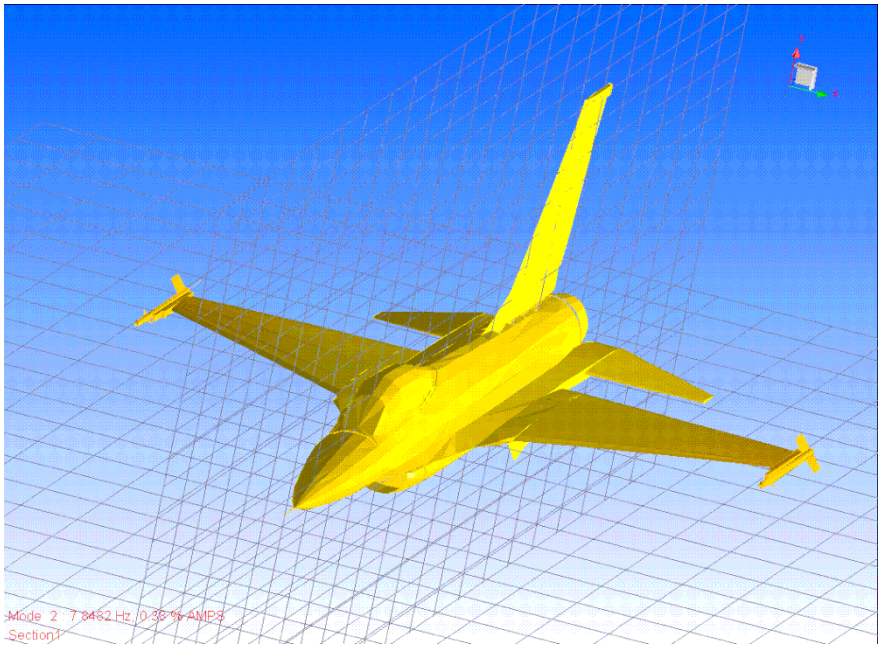


Table 1 Some U.S. flutter experiences, 1932-1934

Airplane	Type of flutter
YC-14 (General Aviation)Transport	Wing-aileron[a]
C-26A (Douglas) Transport	Wing-aileron
XO-43 (Douglas) Observation	Wing-aileron
YO-27 (General Aviation) Observation	Wing-aileron[a] (free play a factor)
YO-27 (General Aviation) Observation	Rudder-fuselage[a] (violent flutter)
F-24 (Fairchild) Civil	Wing-aileron
F-24 (Fairchild) Civil	Tail flutter
YA-8 (Curtiss) Attack	Rudder fin[a]
YB-9A (Boeing) Bomber	Rudder-fuselage (limited amplitude flutter)
XV-7 (Douglas) Bomber	Elevator-fuselage[a] (elevator interconnect-stiffened)
YO-40B (Curtiss) Observation	Elevator-tab[b]

[a] Solution: mass balance. [b] Solution: increased tab frequency.

STRUCTURAL DYNAMICS



What is AEROELASTICITY

What is AEROELASTICITY

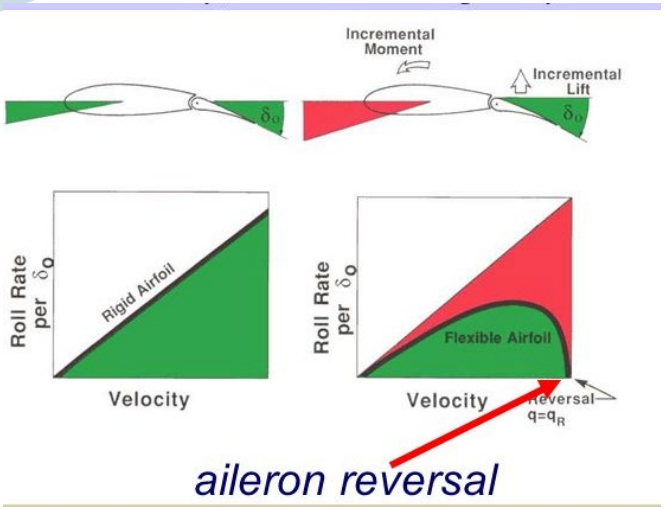
What is AEROELASTICITY

1903-1930
Torsional divergence

1916 - now
Control surface Flutter

1930 --now
Flutter

1940-now Control Reversal



What is AEROELASTICITY

1916 - now
Control surface Flutter

1903-1930
Torsional divergence

1930 --now
Flutter

1940 - now
Control Reversal

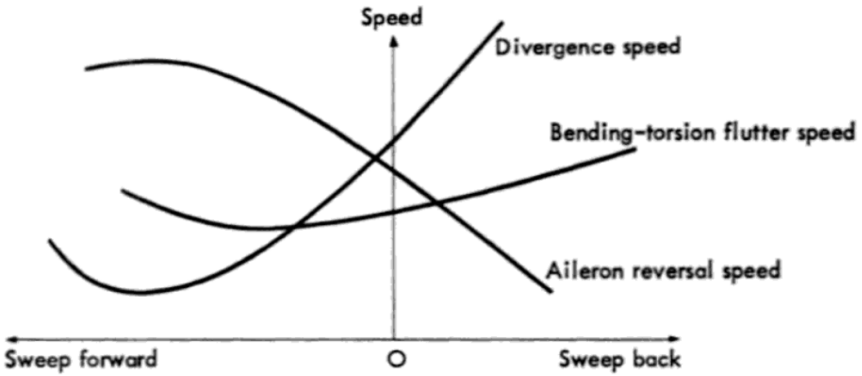
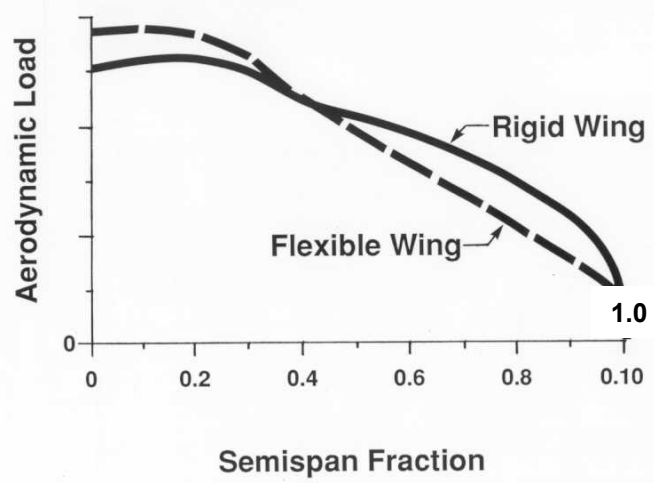
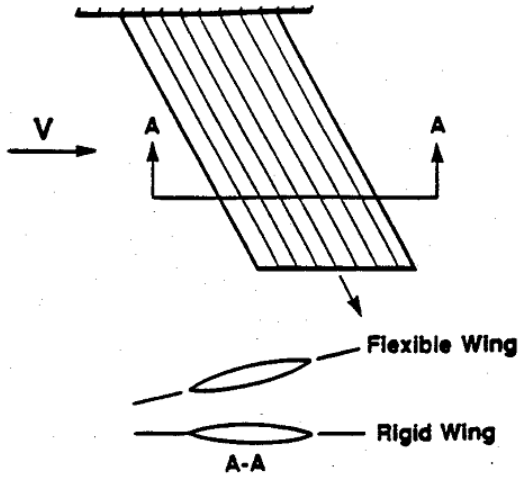


Fig. 1–8. Comparison of wing critical speeds.

What is AEROELASTICITY



Total lift is the same.
Spanwise center of pressure moves inboard to reduce root bending moment



What is AEROELASTICITY

A lot of elements of current design are aeroelasticity related/driven

- Spoilers
- Engine mount position
- Stiffness distribution

What is AEROELASTICITY

Future Configurations

What will be the aeroelastic design of those aircraft?

What is AEROELASTICITY

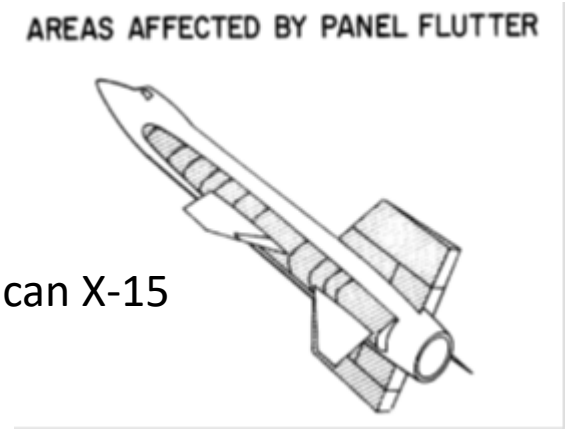
1903-1930
Torsional divergence

1916 - now
Control surface Flutter

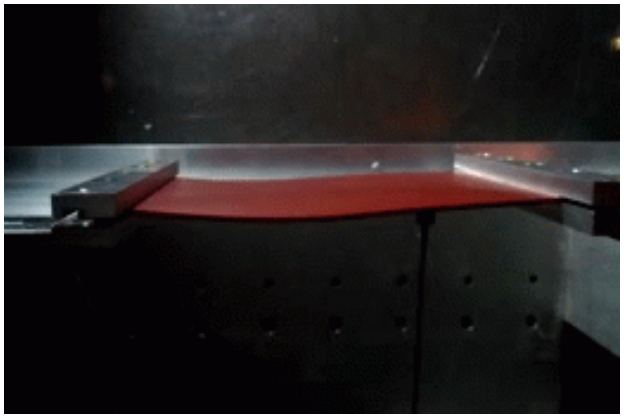
1930 -- now
Flutter

1940 – now
Control Reversal

1959-now Panel Flutter
Stall Flutter



North American X-15



What is AEROELASTICITY

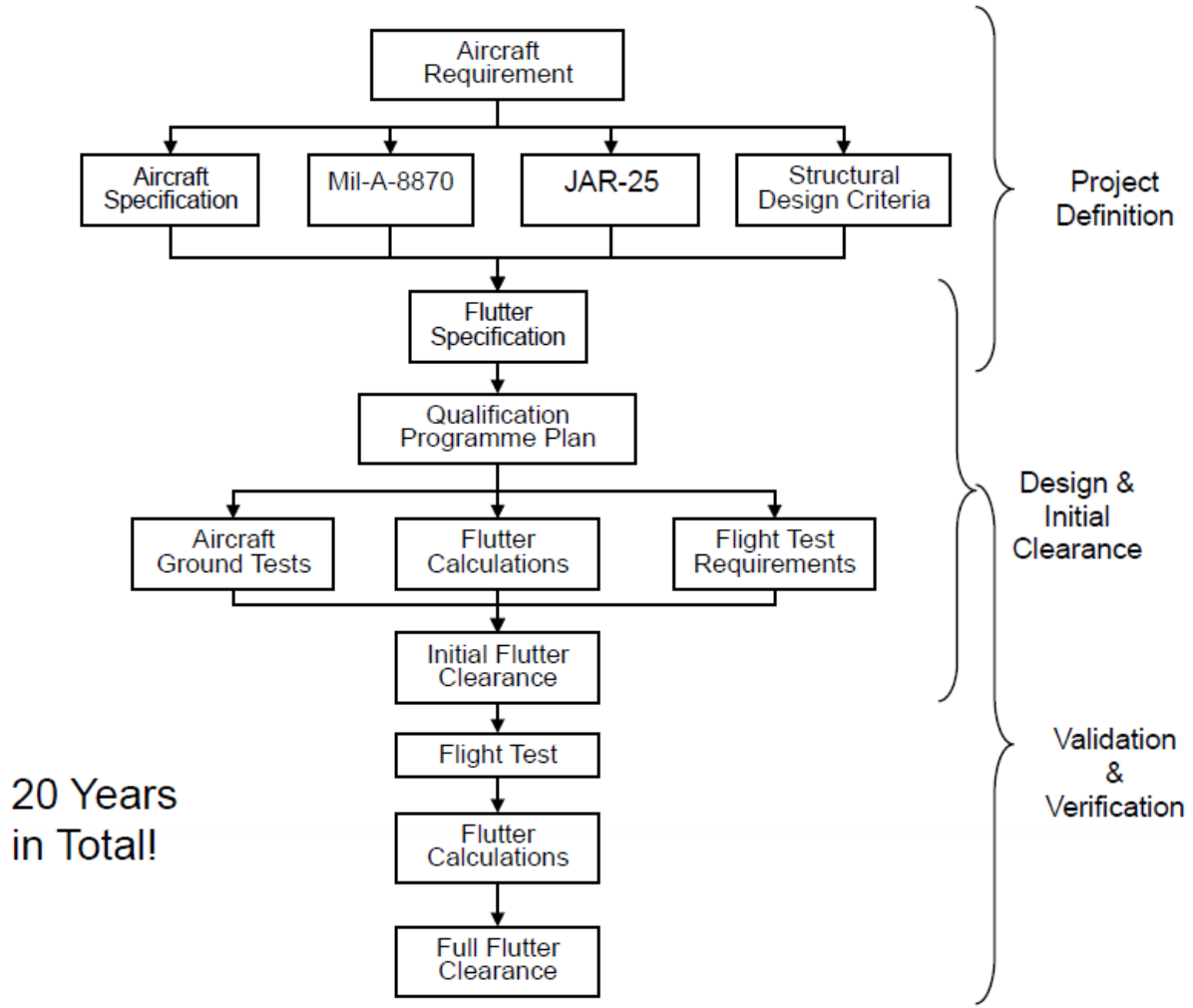
Experiencing flutter in flight is **never part of a test program**, but sometime unexpectedly it appears, and is never a nice experience!

What is AEROELASTICITY

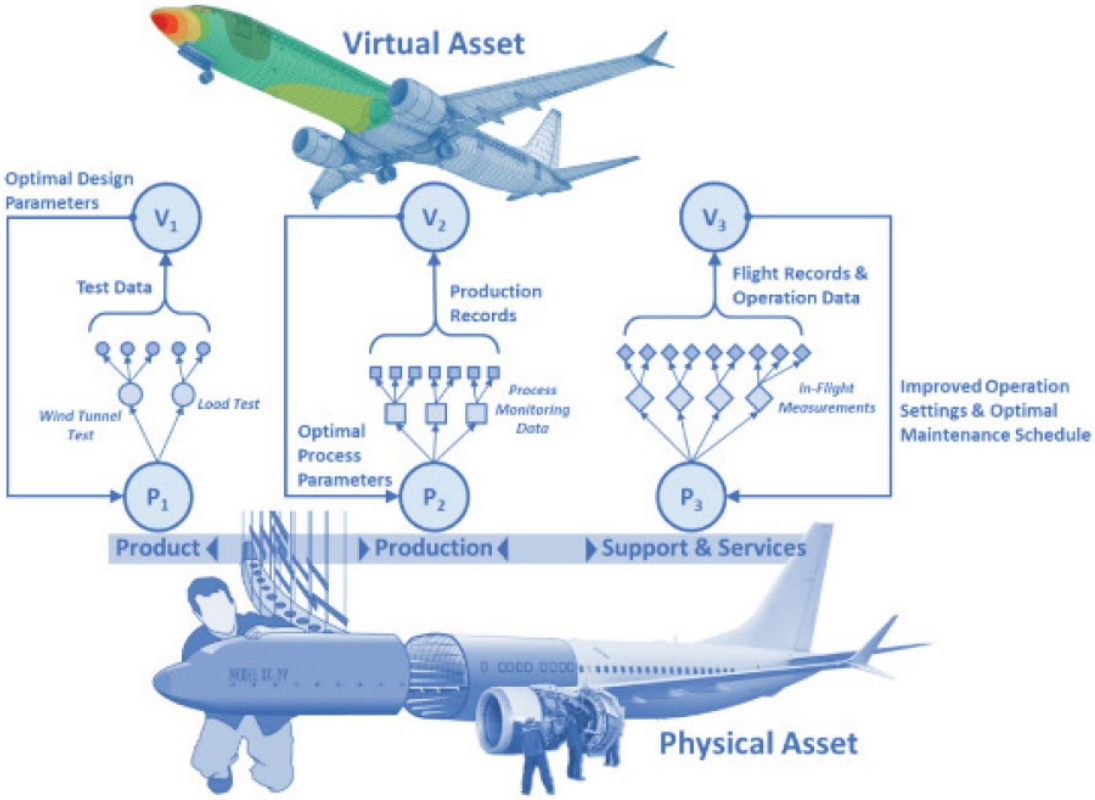
How to avoid aeroelastic problems:

- ✓ Usage of numerical simulation
- ✓ Ground Vibration Testing and Wind Tunnel testing to validate numerical modelling
- ✓ Flight Flutter Testing (Demonstrate the flight envelope is flutter free)
  - ✓ Often this involves the necessity to clear a large number of configurations, considering
    - ✓ Mass distributions
    - ✓ Admissible failures (fail-safe design)

What is AEROELASTICITY



What is AEROELASTICITY
Aeroservoleastic models: Digital Twin



A **Digital Twin** is a **virtual** representation of a **connected** physical asset

https://www.aiaa.org/docs/default-source/uploadedfiles/issues-and-advocacy/policy-papers/digital-twin-institute-position-paper-(december-2020).pdf

What is AEROELASTICITY

FAA TO ISSUE AIRWORTHINESS DIRECTIVE FOR BOEING 747-8 WING FLUTTER

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FAA to Issue Airworthiness Directive for Boeing 747-8 Wing Flutter

July 16 12:42 2015

by Roberto Leiro

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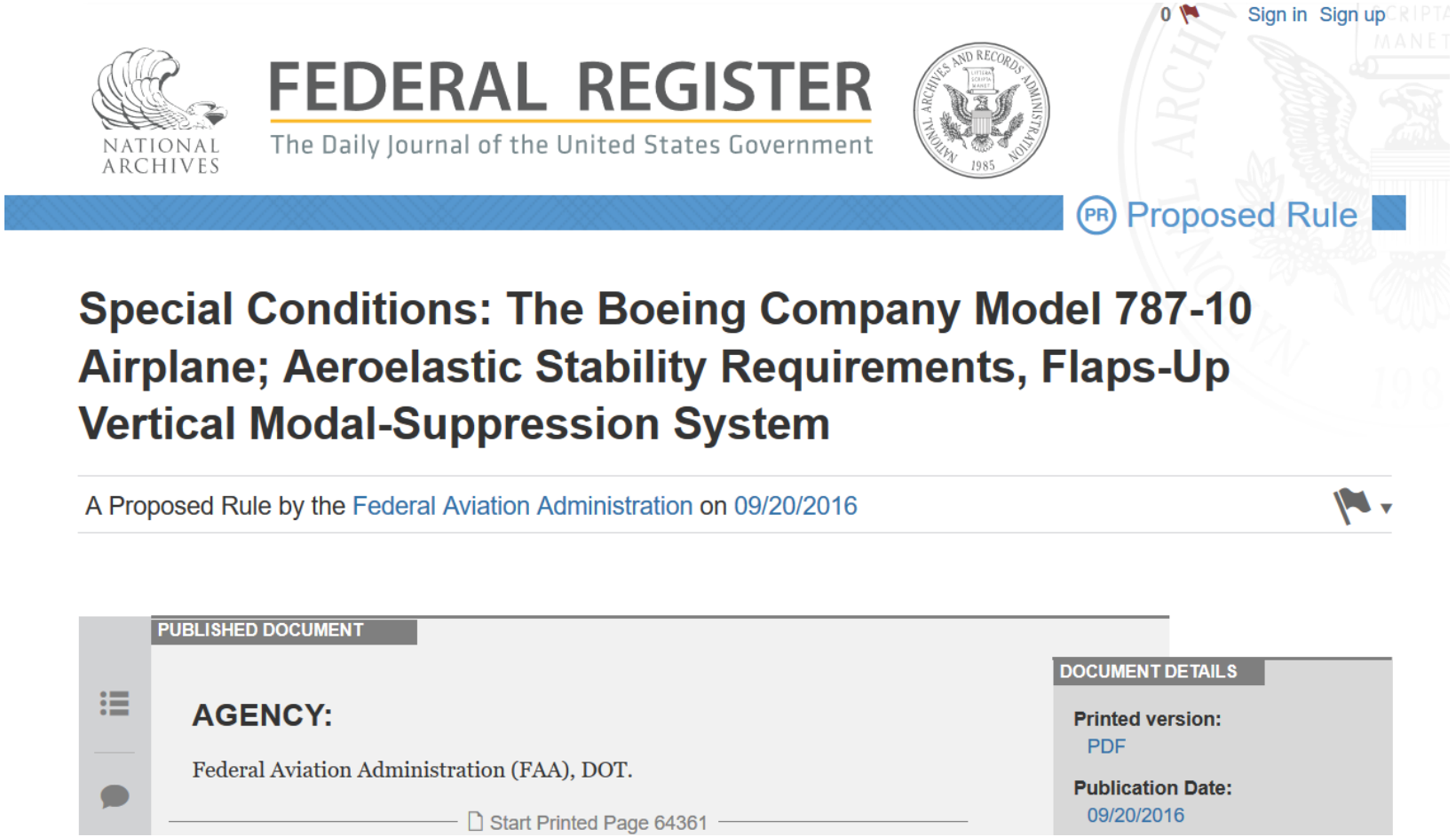
Back in October 2010, the 747-8 program delayed approximately six months the initial deliveries due to flutter issues on the wingtips, an issue solved by an award-winning software implemented by a team led by Dr. Pio Fitzgerald.

For more information reed the "**Proposed special conditions for installation of flutter suppression system applicable to Boeing B747-8F/-8**" issued by **EASA on 11 May 2011** (available on Beep).

What is AEROELASTICITY



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NATIONAL ARCHIVES

FEDERAL REGISTER

The Daily Journal of the United States Government

PR Proposed Rule

Special Conditions: The Boeing Company Model 787-10 Airplane; Aeroelastic Stability Requirements, Flaps-Up Vertical Modal-Suppression System

A Proposed Rule by the Federal Aviation Administration on 09/20/2016

PUBLISHED DOCUMENT

AGENCY:

Federal Aviation Administration (FAA), DOT.

Start Printed Page 64361

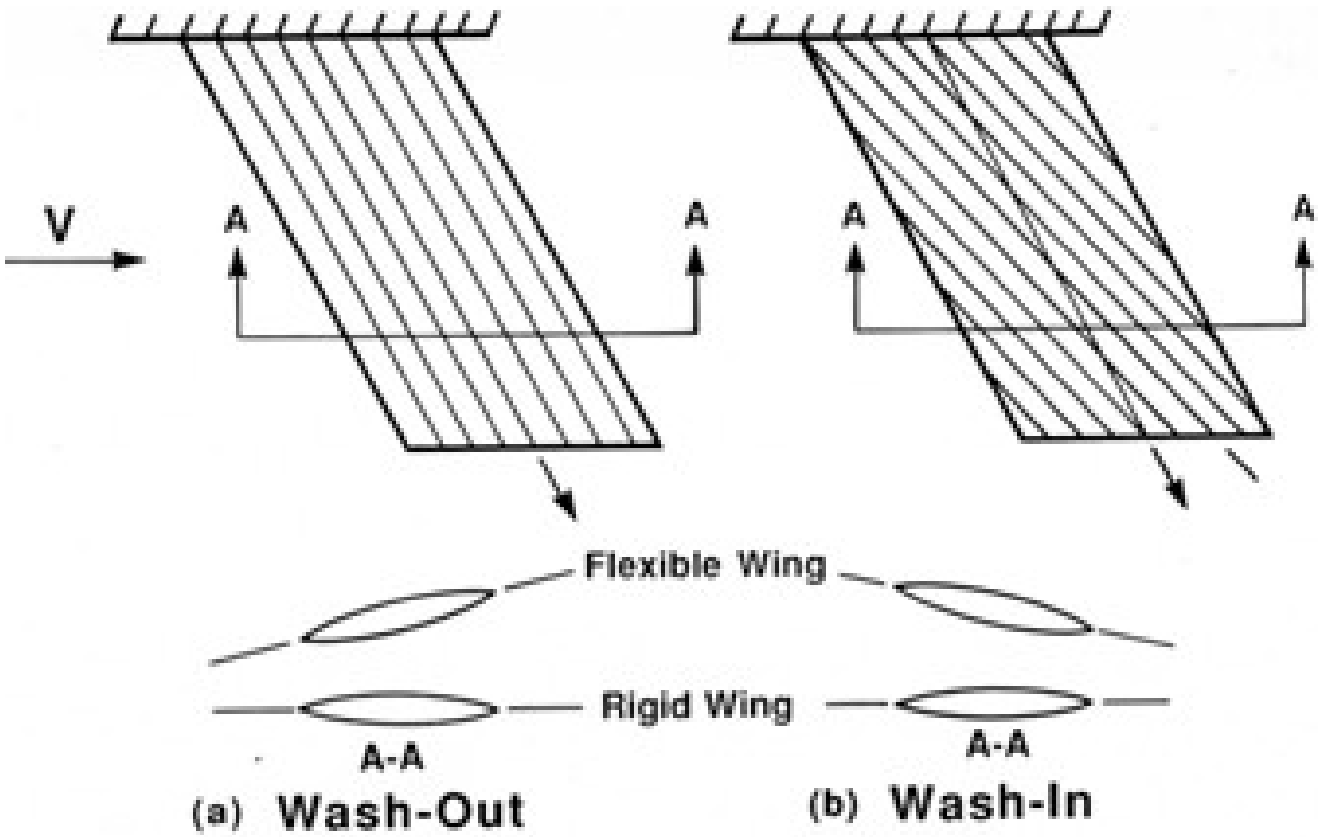
DOCUMENT DETAILS

Printed version:
PDF

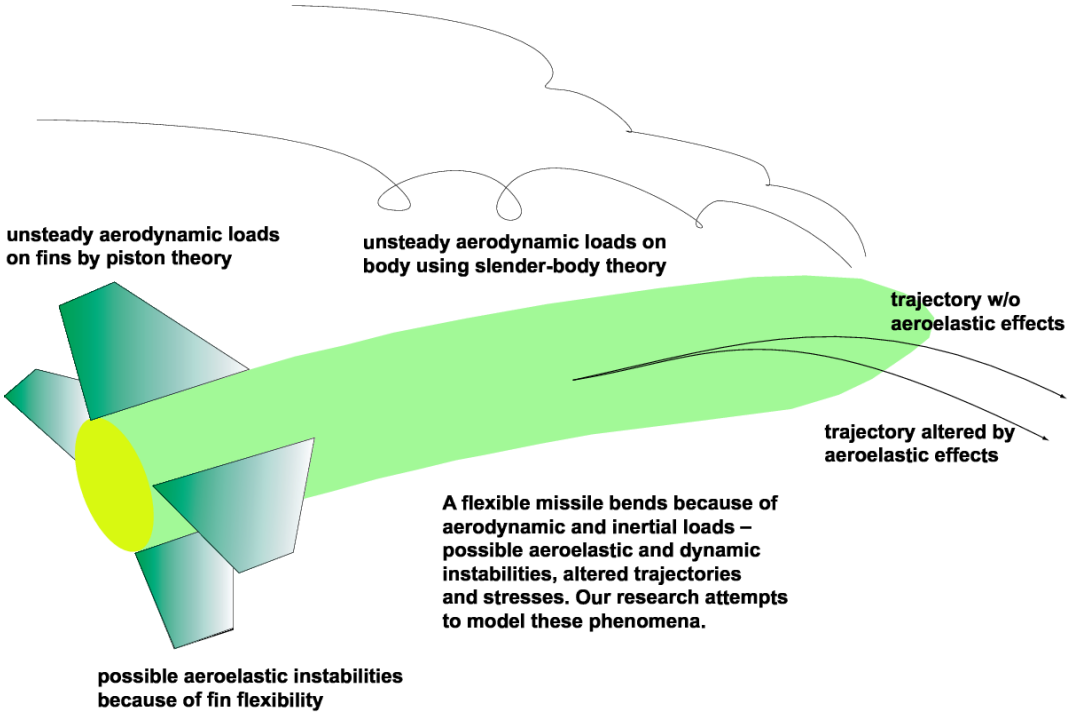
Publication Date:
09/20/2016

What is AEROELASTICITY

Aeroelastic Tailoring

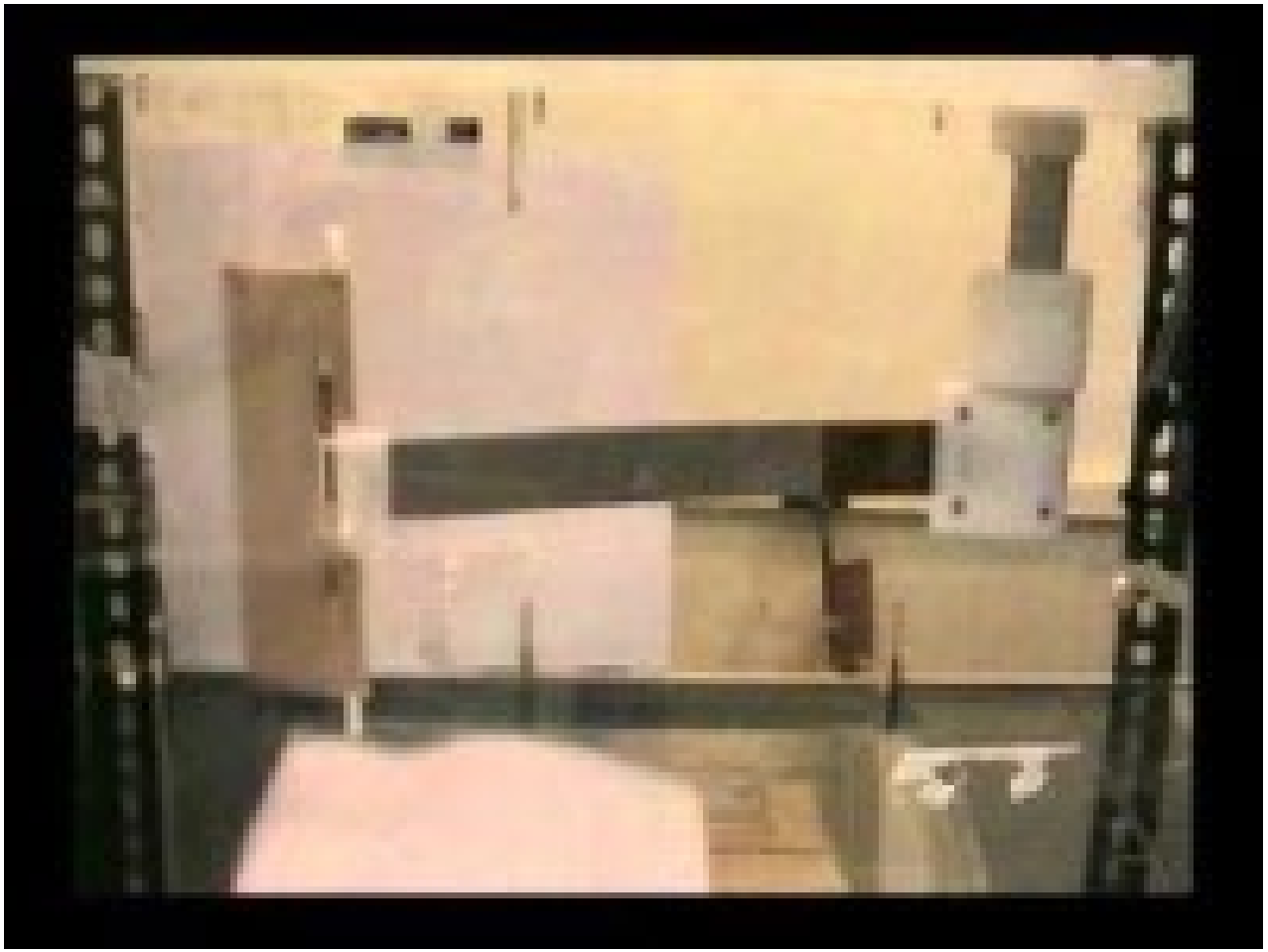


Is aeroelasticity an aircraft only subject?



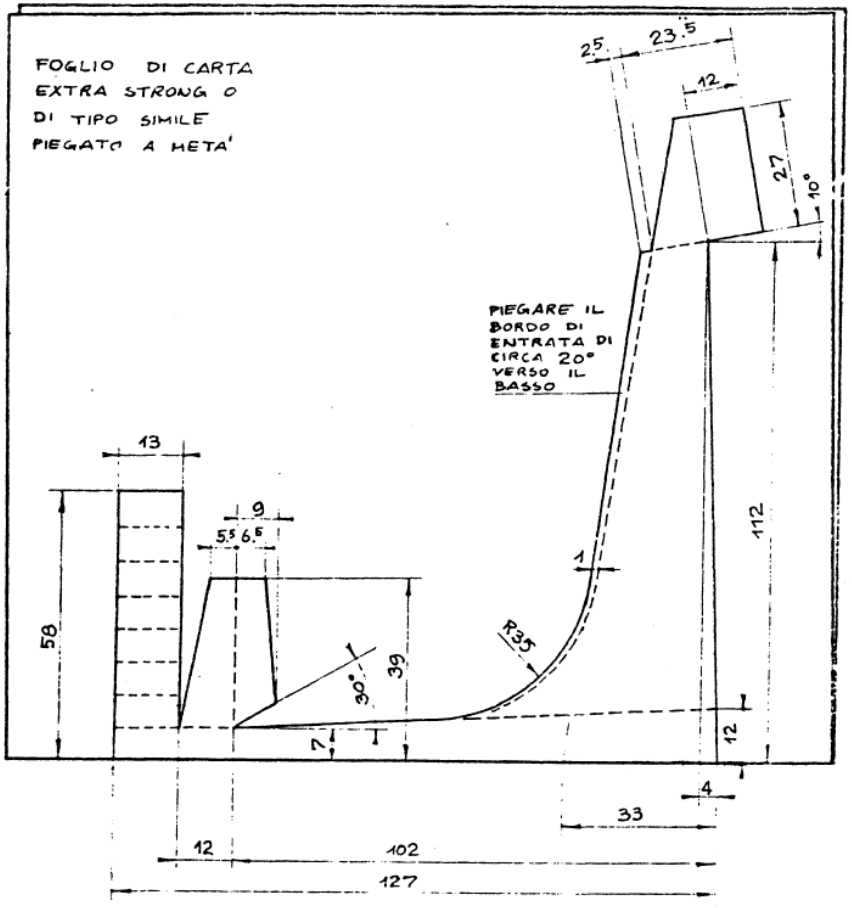
https://www.spacex.com/media/mission_reusability.webm

Is aeroelasticity an aircraft only subject?



Energy harvesting exploiting flutter

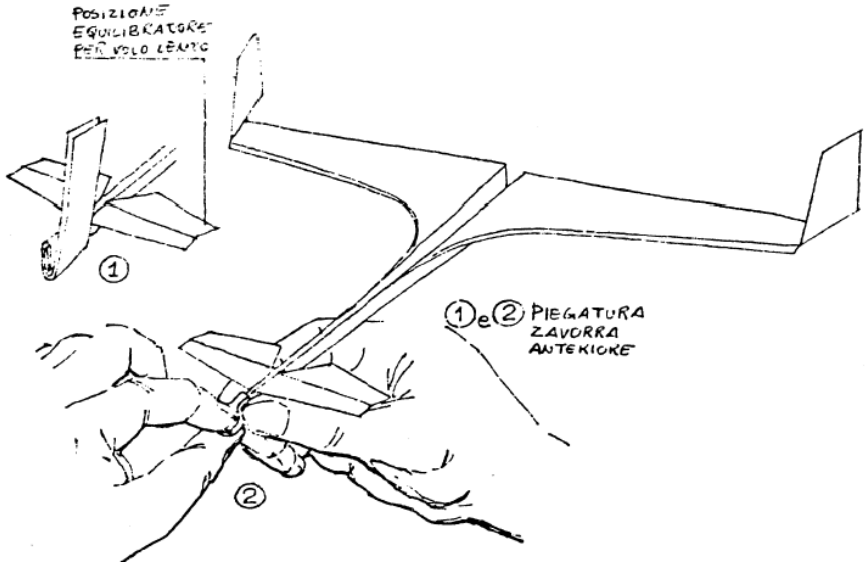
Do you want to experience flutter?

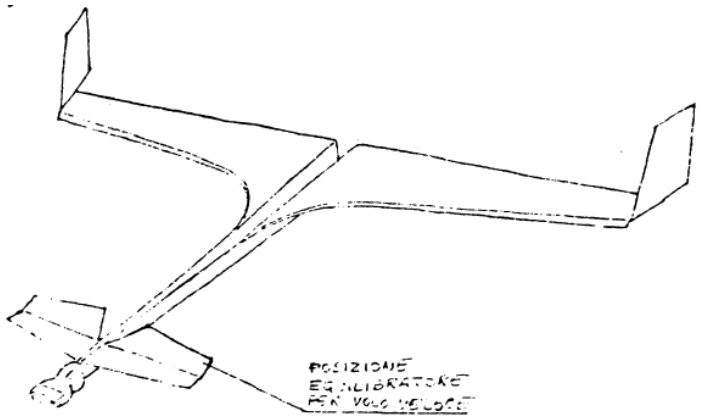


Paper panel model to experience flutter:

- Measures in millimeters
- Use extra strong paper for printers 130 g/m2
- Use the rudder surfaces on the winglets to correct the tendency to roll
- Use the elevons on the canard to fly slower (lower are the elevons slower will be the flight speed)
- At «high speed» you will experience a bending-torsional flutter

Do you want to experience flutter?





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