European Union Aviation Safety Agency

Aeroelastic certification with EASA: Methods, challenges and lessons learnt

Elena Garcia

EASA Structures Expert

(elena-beatriz.garcia-sanchez@easa.europa.eu)

Unrelated to aeroelasticity, meet Sunny Swift, GA pilot

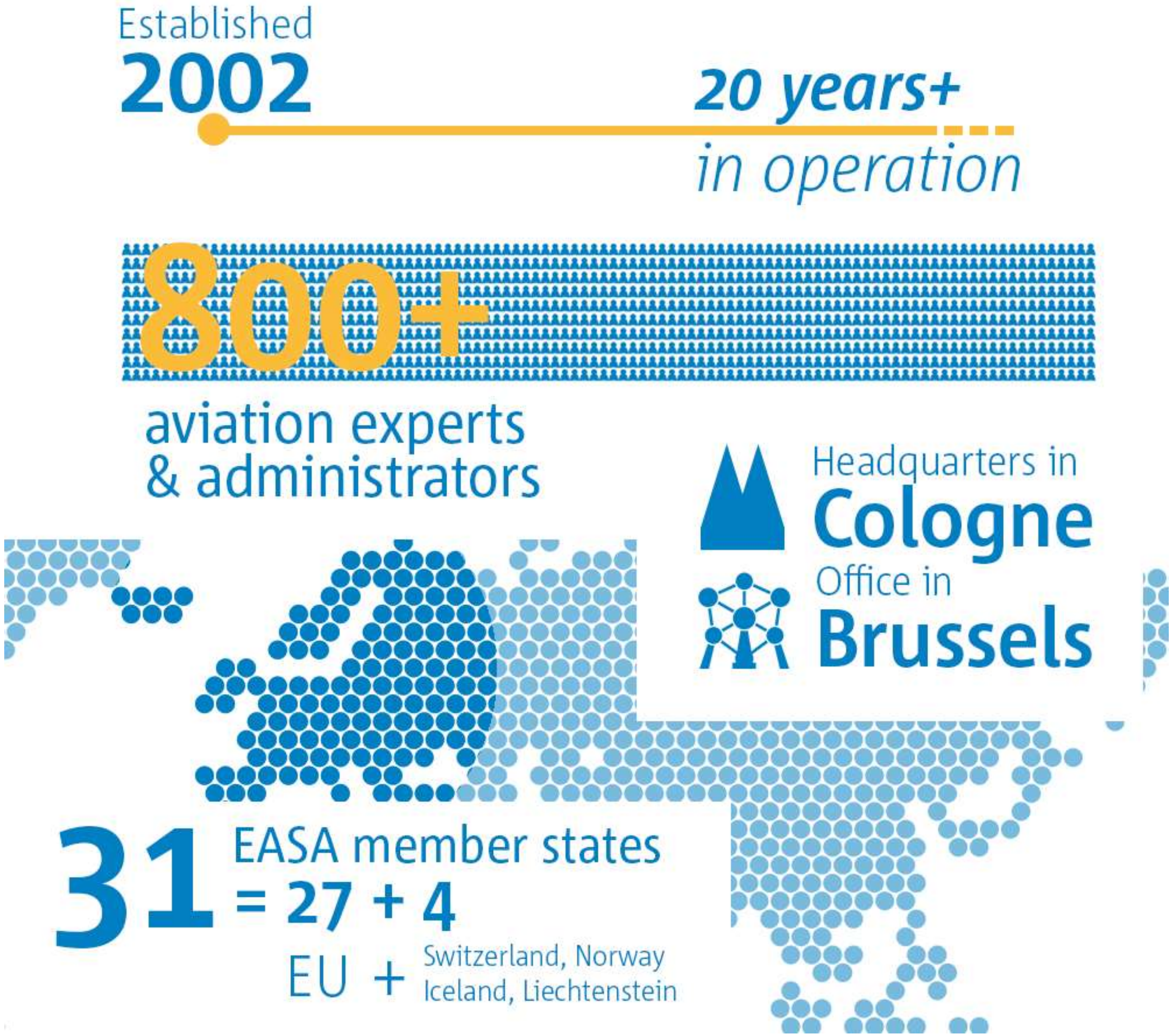
Contents

European Union Aviation Safety Agency

Part I: About EASA

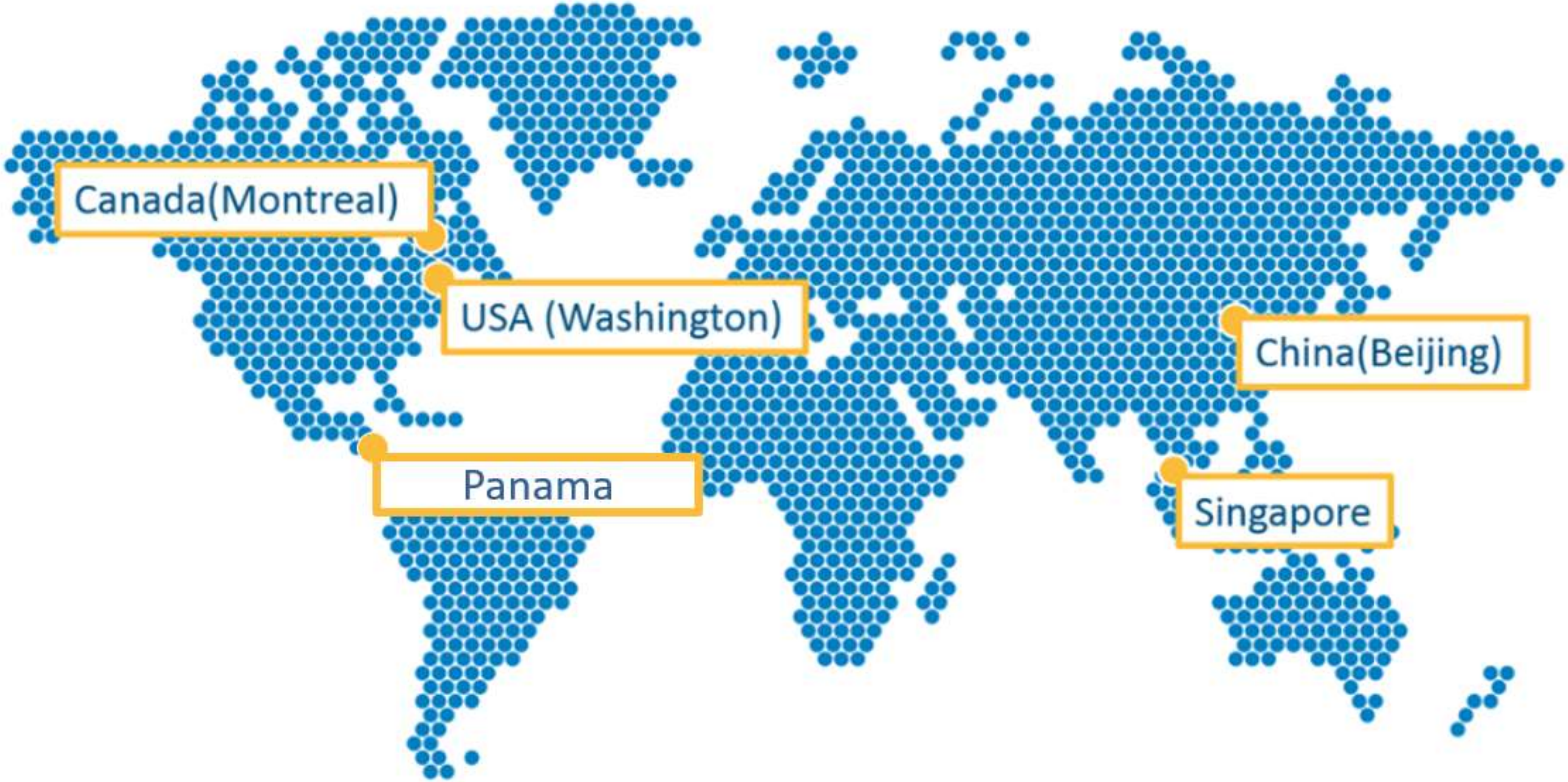
(more at our website: www.easa.europa.eu)

Facts and figures



EASA

5 international permanent representations



Mission

→ Ensure the highest common level of **safety protection** for EU citizens

→ Ensure the highest common level of **environmental protection**

→ **Single** regulatory and certification process among Member States

→ Facilitate the internal aviation **single market** & create a **level playing field**

→ Work with other **international** aviation organisations & regulators

Scope of competences link

Aerodromes

Air Operations

Air Traffic Management

Aircraft & products

Aircrew & Medical

Drones & Air Mobility

Cybersecurity

General Aviation

Environment

REACH and Aviation

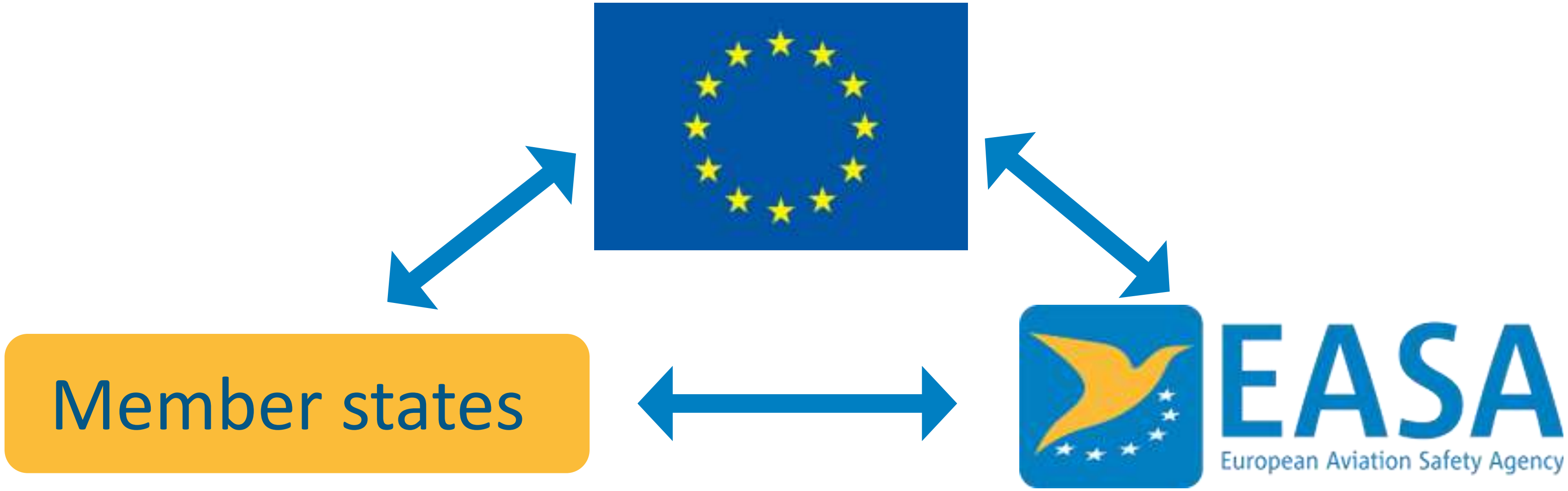
International cooperation

Safety Management & Promotion

Research & Innovation

Rotorcraft & VTOL

Partnership with EU Member States



- Implementing EU Legislation
- Oversight of national organisations
  - Production
  - Maintenance
  - OPs/Licencing
  - Training
  - ATM
  - Aerodromes

- Implementing rules
- Oversight of Member States
- Aircraft and products certification
- Safety of non-EU operations
- Approval of non-EU organisations
  - Production
  - Maintenance
  - Training
  - ATM

Part II: Design Approval process

Design Approval Process

- One of the main tasks (Product Certification) of EASA is to issue **design approvals**, including:
  - Type Certificate (**TC)** for Products (Aircraft, Engine, Propeller)
  - Supplemental Type Certificates (**STC**'s)
  - Design **changes**
  - **ETSO**'s for Parts & Appliances (e.g. seats)
  - **Repair** approvals
  - **CAW** (Continued Airworthiness) considerations
- [Initial and Continuing Airworthiness Regulations]

EASA

TYPE CERTIFICATE

EASA.A.647

FLIGHT DESIGN general aviation GmbH

TC image source: [Flight Design]

Design Approval Process

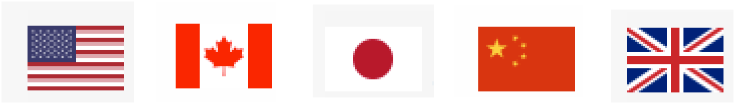
- Except for ELA1 (<1200 kg MTOM) and lower risk General Aviation aircraft (Part 21 Light), a Design Organization Approval (DOA) or APDOA is needed.
  - CVE (Compliance Verification Engineer) competent for complex subject

- For example, to issue a TC for a large aircraft (only main steps are shown here):
  - Application
  - EASA Team of Experts
    - Disciplines, like Structures, Flight Test, Avionics, etc. (some 19 disciplines in total)
    - Headed by Program Certification Manager (PCM)
  - TC Basis is defined
    - E.g. CS-25 Am. xx (for a Large Aeroplane like Airbus A350)
    - Special Conditions, Equivalent Safety Findings, etc.

Design Approval Process

(continued)

- Certification Plans
- Document delivery for familiarisation or agreement.
  - Level of Involvement : risk of non compliance, considering: novelty, complexity, DOA performance
  - Bilateral Agreements



- When compliance to the TC Basis has been shown, design approval (TC)

EASA

Design Approval Process

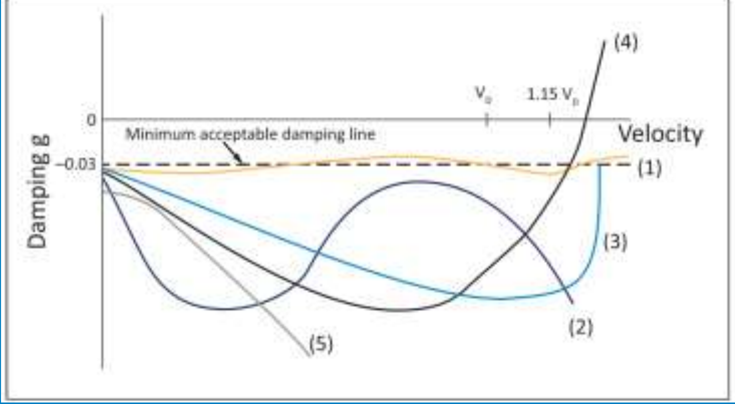
Some key points:

- → For a Large Aeroplane this process typically takes 5 years, for General Aviation 3 years (between application and issuance of TC)
- → It may involve 20-25 meetings (of several days) per discipline
- → The Applicant may define about 1500 certification documents, of which (depending on LoI) 40-70% may be reviewed by EASA
- → EASA Experts work on multiple programs at the same time
- → The Applicant is charged for the EASA activities

EASA

EASA
European Union Aviation Safety Agency

Part III: Aeroelastic Stability Requirements and Means of Compliance (MoC)



CS 25.629 Aeroelastic stability requirements

(See AMC 25.629)

(a) *General*. The aeroelastic stability evaluations required under this paragraph include flutter, divergence, control reversal and any undue loss of stability and control as a result of structural deformation. The aeroelastic evaluation must include whirl modes associated with any propeller or rotating device that contributes significant dynamic forces. Compliance with this paragraph must be shown by analyses, tests, or some combination thereof as found necessary by the Agency.

(b) *Aeroelastic stability envelopes*. The aeroplane must be designed to be free from aeroelastic instability for all configurations and design conditions within the aeroelastic stability envelopes as follows:

(1) For normal conditions without failures, malfunctions, or adverse conditions, all combinations of altitudes and speeds encompassed by the V_D/M_D versus altitude envelope enlarged at all points by an increase of 15 percent in equivalent airspeed at constant Mach number and constant altitude. In addition, a proper margin of stability

CAW:some Airworthiness Directives with impact on flutter

- Examples of design-related aeroelastc incidents
  - Outer fuel tank installation: airspeed limitations.
  - Speed limitation to prevent horizontal tailplane flutter, except if mod changing trailing edge contour.
  - Inspect and ensure an aileron cotter pin isn’t missing.
  - Missing bush, low cable tension.
  - Wear, poor lubrication,
  - Excessive free-play: Balance weight inspection.
  - Drain holes to avoid water accumulation.
  - Fittings damage.
  - Damper damages.
  - Replacement of rudder trim spring to prevent HTP flutter.
  - …

Aeroelastic Stability Certification Specifications

		
CS-25	CS-23	CS-27/29

Large Aeroplanes CS 25.629 and AMC

→ The Easy Access Rules have the AMC (aceptable Means of Compliance) right after the requirement

CS 25.629 Aeroelastic stability requirements

(See AMC 25.629)

(a) *General*. The aeroelastic stability evaluations required under this paragraph include flutter, divergence, control reversal and any undue loss of stability and control as a result of structural deformation. The aeroelastic evaluation must include whirl modes associated with any propeller or rotating device that contributes significant dynamic forces. Compliance with this paragraph must be shown by analyses, tests, or some combination thereof as found necessary by the Agency.

(b) *Aeroelastic stability envelopes*. The aeroelastic stability envelopes. The aeroplane must be designed to be free from aeroelastic instability for all configurations and design conditions within the aeroelastic stability envelopes as follows:

(1) For normal conditions without failures, malfunctions, or adverse conditions, all combinations of altitudes and speeds encompassed by the V_D/M_D versus altitude envelope enlarged at all points by an increase of 15 percent in equivalent airspeed at constant Mach number and constant altitude. In addition, a proper margin of stability

....

AMC 25.629 Aeroelastic stability requirements

1. *General*.

The general requirement for demonstrating freedom from aeroelastic instability is contained in CS 25.629, which also sets forth specific requirements for the investigation of these aeroelastic phenomena for various aeroplane configurations and flight conditions. Additionally, there are other conditions defined by the CS-25 paragraphs listed below to be investigated for aeroelastic stability to assure safe flight. Many of the conditions contained in this AMC pertain only to the current amendment of CS-25. Type design changes to aeroplanes certified to an earlier CS-25 amendment must meet the certification basis established for the modified aeroplane.

Related CS-25 paragraphs:

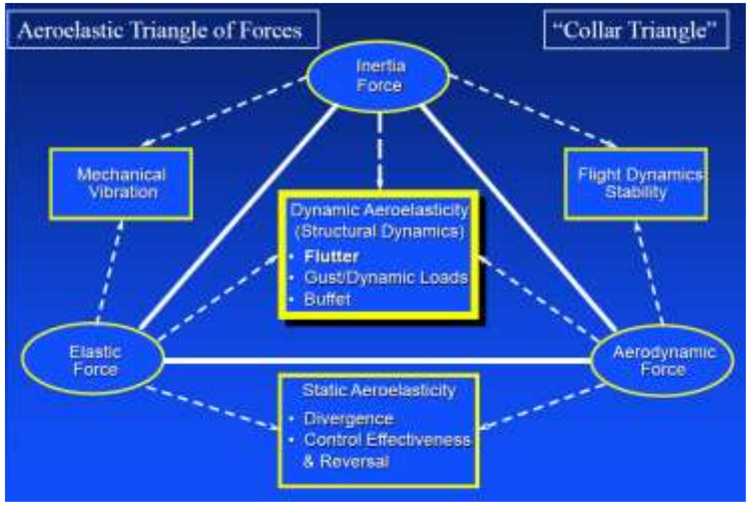
CS 25.251 - Vibration and buffeting

CS 25.305 - Strength and deformation

LA Aeroelastic Stability Requirements

- → Main airworthiness requirement for aeroelastic stability: CS/FAR **25.629**

- → Requires freedom from (whirl) flutter, divergence and control reversal (aeroservoelasticity, LCO included)



(plus aeroservoelasticity…)

Aeroelastic Stability Requirements CS-25

- → CS **25.629** is harmonised with FAR **25.629**
- → Extensive guidance material in AMC 25.629 (FAA AC 25.629-1B)
- → Revised in CS-25 in 2005
  - → Main change: 1.2 Vd/Md –> 1.15 Vd/Md for normal conditions
  - → Amdt 18 AMC ice accumulation link to AMC **25.1420**
- → Since Amdt 24 (2020), addressing (single and combinations of) structures & systems failure conditions to be considered
- → Related requirements: **25.251** (vibration) **25.343** (0 fuel). Failures: **25.302**, **25.571**, **25.631, 25.671(c), 25.672, 25.903, 25.1309**

General Aviation Regulations

- → CS 23 Amdt 5 and later (performance-based) + ASTM
- → The regulation is higher level to allow flexibility
- → AMC1 has content similar to CS 23 amdt 4

CS 23.2245 Aeroelasticity

(a) The aeroplane must be free from flutter, control reversal, and divergence:

(1) at all speeds within and sufficiently beyond the structural design envelope;

(2) for any configuration and condition of operation;

(3) accounting for critical degrees of freedom; and

(4) accounting for any critical failures or malfunctions.

(b) The applicants' design must account for tolerances for all quantities that affect flutter.

AMC1 23.2245 Aeroelasticity

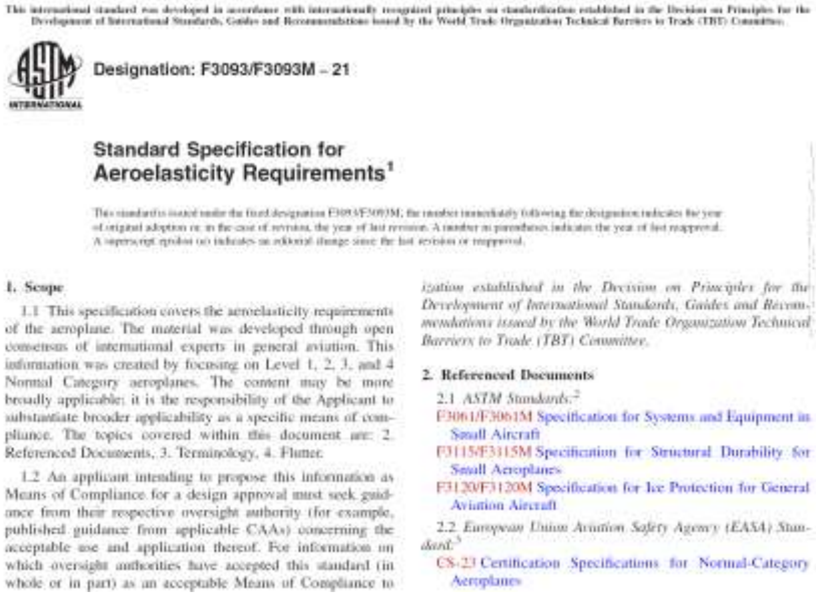
ASTM F44 F3264-21 Standard Specification for Normal Category Aeroplanes Certification

6.10 Aeroelasticity

F3061/F3061M-20 Standard Specification for Systems and Equipment in Small Aircraft

F3093/F3093M-21 Standard Specification for Aeroelasticity Requirements

[AMC&GM to CS-23: Issue 4]



This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

ASTM INTERNATIONAL

Designation: F3093/F3093M – 21

Standard Specification for Aeroelasticity Requirements[1]

This standard is issued under the fixed designation F3093/F3093M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers the aeroelasticity requirements of the aeroplane. The material was developed through open consensus of international experts in general aviation. This information was created by focusing on Level 1, 2, 3, and 4 Normal Category aeroplanes. The content may be more broadly applicable; it is the responsibility of the Applicant to substantiate broader applicability as a specific means of compliance. The topics covered within this document are: 2. Referenced Documents, 3. Terminology, 4. Flutter.

1.2 An applicant intending to propose this information as Means of Compliance for a design approval must seek guidance from their respective oversight authority (for example, published guidance from applicable CAAs) concerning the acceptable use and application thereof. For information on which oversight authorities have accepted this standard (in whole or in part) as an acceptable Means of Compliance to

ization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

F3061/F3061M Specification for Systems and Equipment in Small Aircraft

F3115/F3115M Specification for Structural Durability for Small Aeroplanes

F3120/F3120M Specification for Ice Protection for General Aviation Aircraft

2.2 *European Union Aviation Safety Agency (EASA) Standard:*[3]

CS-23 Certification Specifications for Normal-Category Aeroplanes

EASA

Rotorcraft flutter and vibration requirements

- CS **27/29.629** (and AC) Flutter
  - *Each aerodynamic surface of the rotorcraft must be free from flutter under each appropriate speed and power condition.*
- CS **27/29.251** Vibration
- CS **27/29.241** and **.663**, Ground Resonance
  - *…analysis and tests, …or reliable service experience, or … analysis or tests that malfunction or failure of a single means will not cause ground resonance.*
- CS **27/29.603** (environmental characteristics)
- CS **27/29.610** (lightning damages)

Rotorcraft flutter and vibration MoC

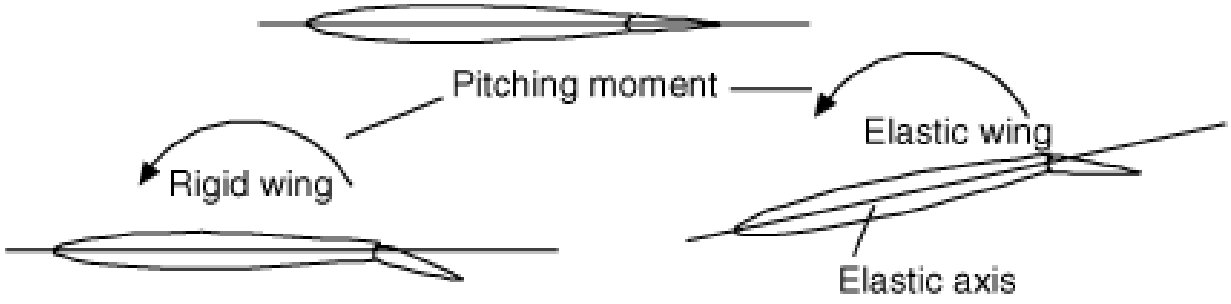
- Ground resonance:
  - analysis and test,
  - or reliable service experience,
  - or analysis or test with malfunction or failure (e.g. damper)

- Flutter and divergence: Typically combination of analysis and flight test
  - Example of focus: Main and tail rotor systems, and the horizontal stabiliser. Tail resonance.

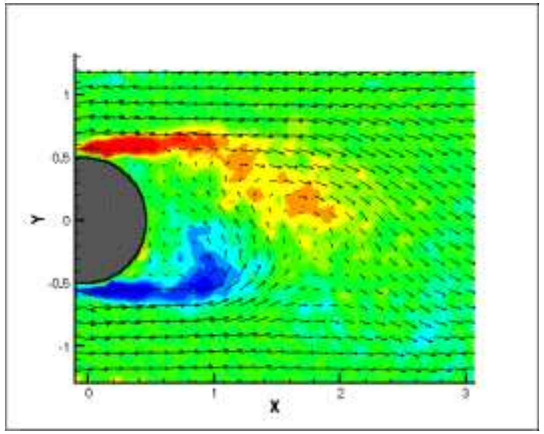
- Vibration: stable. Related to rotors frequencies

Non-flutter phenomena

- → Static aeroelasticity (zero frequency)
  - → Divergence
  - → Control reversal



- → Buffeting (**2*.251**)

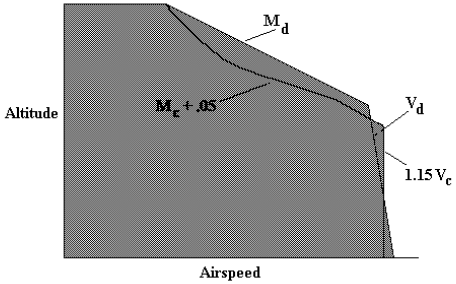


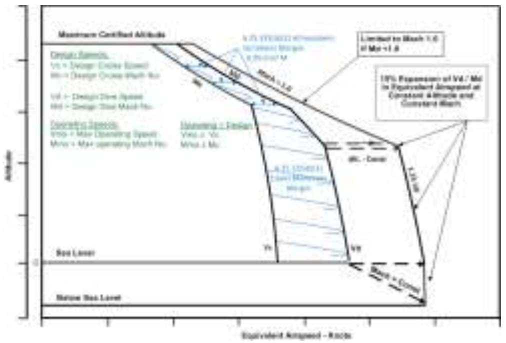
→ Image credit: [Aviation dictionary](), [FAMU-FSU College of Engineering]()

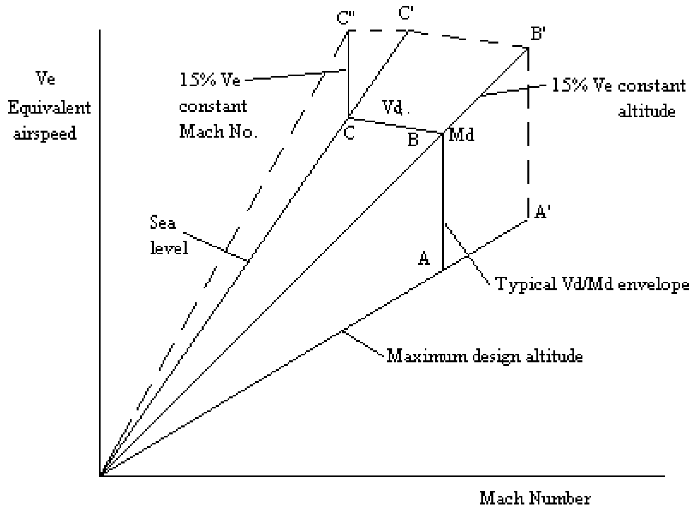
EASA

Aeroelastic Stability Requirements

- Aeroelastic stability to be shown for:
  - Normal conditions (up to 1.15 Vd/Md for LA, 1.2 factor for GA)
    - Weight, speed, altitude, payload, fuel,..







  - Failures (structural and system), malfunctions and adverse conditions

Aeroelastic Stability MoC

- Compliance with requirements
  - By analysis, supported by test evidence
- Analysis
  - Structural model (FEM, Beam)
    - Mass, stiffness, damping
  - Aerodynamic model (DLM, CFD)
  - Flight control systems model
- Test evidence
  - GVT / Windtunnel / Flight Test
  - A380 flight test

Aeroelastic Stability Requirements

- Analysis
  - Solving a (large) set of second order differential equations of motion

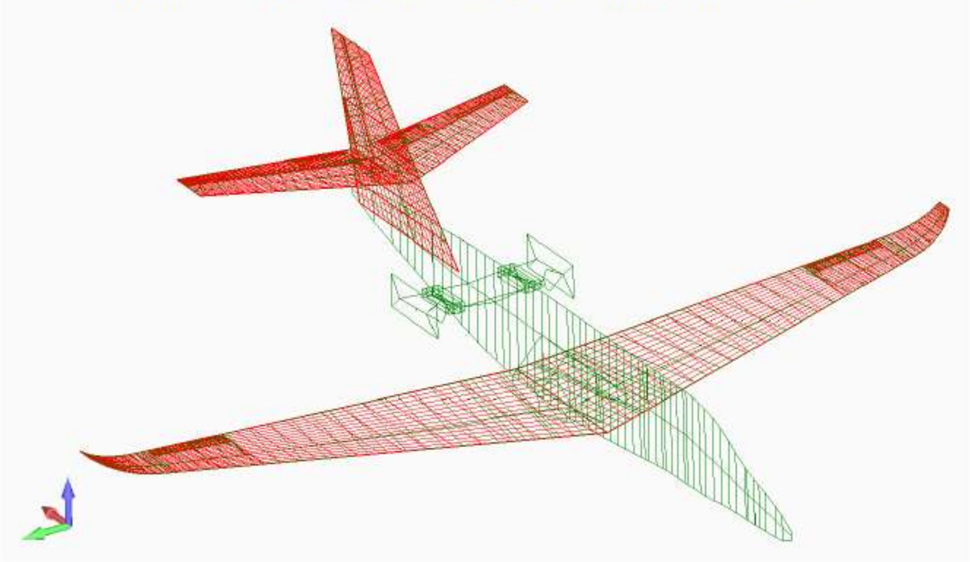
$$\left(\mathbf{A}+\rho\mathbf{B}\right)\ddot{\mathbf{q}}+\left(\mathbf{C}+\rho U\mathbf{D}\right)\dot{\mathbf{q}}+\left(\mathbf{E}+\rho U^{2}\mathbf{F}\right)\mathbf{q}=\mathbf{0}$$

  - Methods: modal analysis, PK method,…
  - Structural damping
    - Assumed value of g=0.03 (1.5% viscous damping)
    - Measured during GVT (per mode)
  - Parametric variation (mass, stiffness, flight control system)

Airflow excitation

- Navier-Stokes CFD too heavy.
- Certification standard:
  Doublet-Lattice model.
  Subsonic unsteady oscillatory
  solution

FIGURE 2.2-1 – General View of the Doublet-Lattice Model

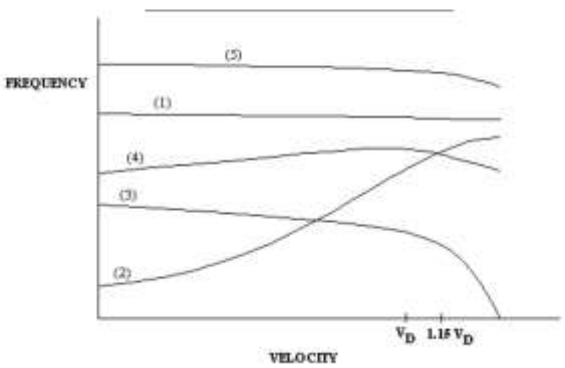


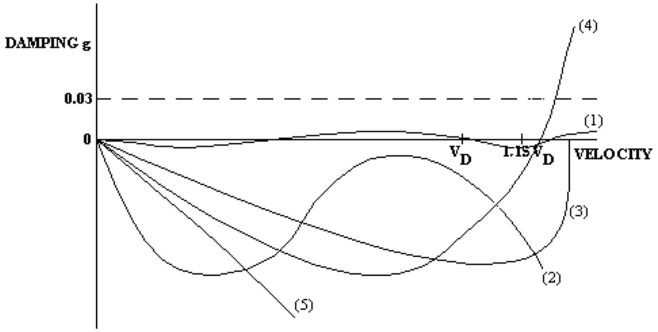
→Superposition elementary solutions (Panel horseshoe) Relation matrix: forces vs. modal displacements.

→Corrected with validated shape, compressibility and viscosity effects.

Aeroelastic Stability Requirements

- Analysis
  - V-f plots
  - V-g plots
  - Mode shape plc





Aeroelastic Stability Requirements

- Test evidence
  - Wind tunnel model
  - GVT (component or full scale)
  - Flight test

Flight test safety

- Sufficient analytical understanding: Representativeness, correlation and margins.
- Gradual envelope increase.
- It is safer to sufficiently excite modes since this may allow to measure damping progression.

Accepted MoC general aviation

- Usual practice: GVT+ Analysis + flight test
- Analysis
  - Mode validation usually GVT
  - Analysis only : for modifications or for flight condition approval with reduced envelope. Could be based on comparison with previous models and may be supported by measured stiffness of components or FEM models. Inaccurate for higher modes.
  - Report 45 rarely used, sometimes partially.
- GVT
  - Tested configurations (full/ empty fuel or ballast tanks, variation in mass especially for control surfaces)
  - Simulation of the pilot in the control system (free/blocked stick or mass simulation)
  - Elastic suspension of the aircraft
  - Consideration of material damping
  - Tested and analysed frequency range
  - Conformity. Tolerances, paint, wear in service.
- Flight test normally not reliable as only MoC

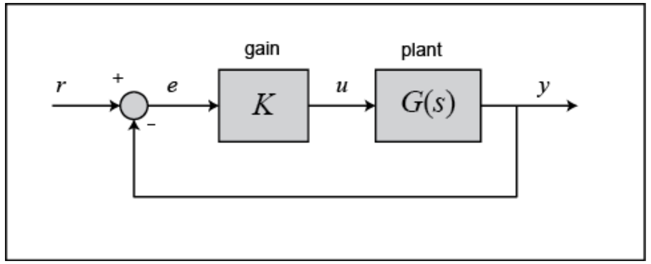
General Aviation Regulations and MoC comparison

	CS 22 (gliders) Amdt 2	LSA-ASTM F2245-12d +	CS-VLA Amdt 1	CS23 Amdt 4	CS23.2245 Amdt 5/6 ASTM F3093
GVT + analysis	GVT + analysis or other demonstration 1.2 Vd	Vne >200 km/h GVT or report 45 conventional	- 1.2 Vd -GVT+ analysis Or GVT+ FT Or flight test+ rep 45+VD <259 km/h -Tab control irreversible, spring devices reliability	-1.2 Vd -GVT or other Analysis or rep. 45 -No GVT for Mods -Tab control irreversible, spring devices reliability -ice protection AC 23.14192 -Turboprop whirl mode	-1.2 Vd/Md -GVT or other exc Level 1 <750kg -Analysis or, With limitations, R 45 -Tab control irreversible, spring devices reliability -Ice protection AC 23.14192 -Propeller flutter -Turboprop whirl mode
Flight test	Y, Vdf No rapid reduction of damping. No divergence or control reversal	Y . No flutter or control divergence, from VSO to VDF	See options above. Margin and no rapid damping reduction up to vd	Y Margin and no rapid damping reduction up to Vd Not for Mods	Always (4.2) Not for mods
Tolerances	N	N	speed, damping, mass balance, and control system stiffness	speed, damping, mass balance, and control system stiffness Turboprop variations	Speed, damping, mass balance, and control system stiffness Turboprop variations
Failure, malfunction, or disconnection	N	N	Any single element in tab system	any single element in the primary flight control system, any tab control system, or any flutter damper PSE residual	VD/MD < 480 kph/ M0.5, Any single element in tab system Other, like CS23 Amdt 4

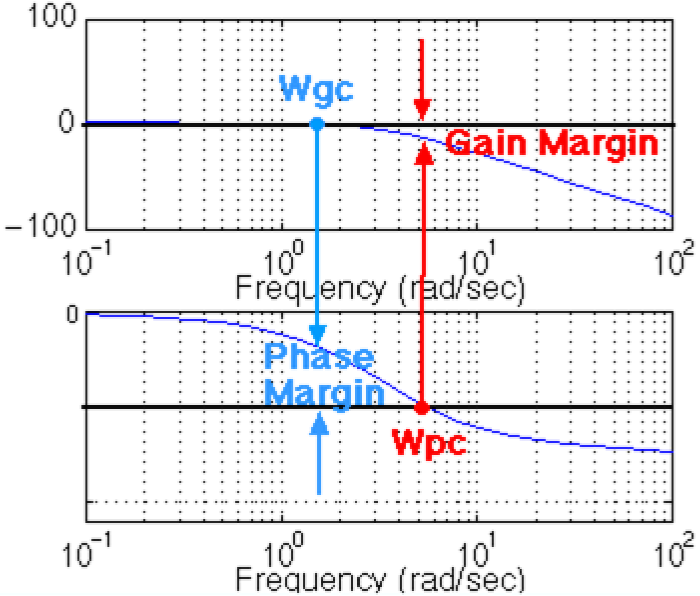
EASA

Compliance issues (1)

- Aeroservoelasticity (ASE)
  - Phase and gain margins of +/- 60 degrees & 6 dB are required (CRI)



- High Lift Devices (= flaps, slats) extended
  - Generic CRI (Certification Review Item)



- Increased load factor
  - Can be an issue for aircraft with MLA (Maneuver Load Alleviation) systems

Image source: University of Michigan

Compliance issues (2)

- Flight control systems failure cases
  - Required to be considered:

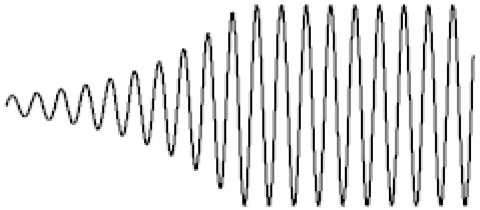
(9) Any damage, failure or malfunction, considered under CS 25.631, CS 25.671, CS 25.672, and CS 25.1309.

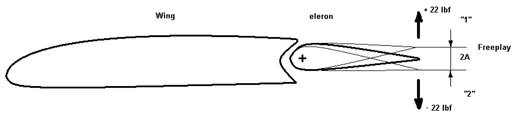
(10)Any other combination of failures, malfunctions, or adverse conditions not shown to be extremely improbable.

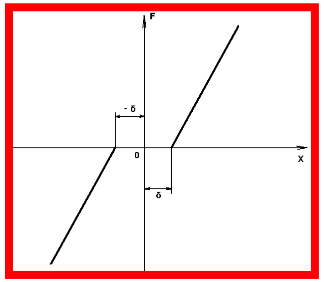
Image source: aviation exchange, from Airbus Training Manual

Compliance issues (3)

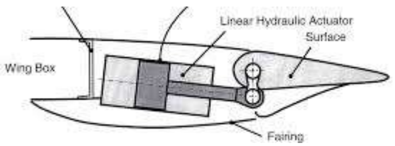
- Limit Cycle Oscillations (LCO)
  - Sustained vibration
  - Usually related to free-play in flight control system
    - Adherence to MIL-A-8870 / JSSG-2006 free-play limits is encouraged







  - Actuators in bypass mode: CATA policy in development



  - LCO is allowed under certain conditions
    - FAA have published guidance material , EASA generic CRI.
    - May require time-domain based analysis

Compliance issues (4)

- Non-linearities
  - Structural
    - Deflections & deformations (e.g. lateral bending mode of wing mounted engines)
    - Free-play (see previous slide)
  - Aerodynamic
    - E.g. due to transonic effects
  - Flight control systems
    - E.g. filters
    - Damping mode of actuators
- May require time-domain based analysis

Compliance issues (5)
Potential of non-linear dynamics tools?

→ Harmonic balance limitations?

→ Time domain analysis best standard, but could it depend on initial conditions (anlysis/test)?

→ Non-linear dynamics quite broader than LCO. Not usually employed in certification.

→ Useful/how to capture qualitative behaviours for typical non-linearities in aviation?
  - → Global stability, attractors and basins
  - → Bifurcation types
  - → Quasiperiodic solutions, chaos, beating…

→ Models which give some insight:
  - → Center manifold
  - → Lyapunov-Schmidt
  - → Multiple scales
  - → …

→ Useful plots

?

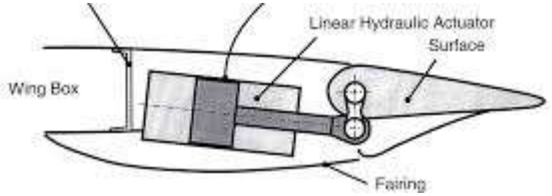
Compliance issues (6)

- Future developments
  - Active flutter suppression system (that suppresses a divergent flutter mode in the operational or design envelope of the aeroplane)
  - Novel designs, proactive evaluation of failure modes. Validation of complex models.
    - EASA CM-S-014 Modelling and Simulation
  - Use of AI (surrogate models)
    - EASA AI Concept Paper and related NPA (Note of Proposed Amendment to the regulation)
    - See ZHAW-EASA research project for the surrogate model of an eVTOL

Compliance issues (7)

→Future developments cont'd

- → Novel GVT and flight test techniques (e.g use of vibrometers)
- → Better visual presentation of results
- → RMT.0766 Safe Operation in SLD icing conditions (for flutter, accretion mass behind the leading edge). Difficult to model.
- → LA: LCO for actuators in passive mode: CATA policy in development



- → GA: ASTM working group WK70524 (more on this later)

Image source: G. K. Nikas, Researchgate

Changes / STC typically requiring flutter assessment:

- Installation or other large or concentrated masses on flexible structure: Fin Camera, large antennas, stores
- New Fuel Tank Installation
- Cargo Conversion
- Change the mass on a control surface (like painting)
- Change the stiffness of the control system
- Significant weight increases, extensive stiffness change
- Changes in aerodynamics: e,g, winglet or spade installation
- Envelope increase
- Change of flight control system standard, as affecting transfer between command and control surface deflection (e.g. logic changes, mode filters, gains…)
- Turboprop engine or propeller change (whirl flutter)
- …

Derivatives and changes considerations

- Local changes can affect a flutter mode of a distant structure

- For STCs, an arrangement with the TCH to support flutter demonstration may be necessary

- If baseline and new analysis available, focus on:
  - Baseline critical modes,
  - Those less accurate or conservative

Major/minor classification and LOI

- → Change classification affects DOA requirements and fees and charges.
- → In principle such installations are major, unless it is clear that there is a large flutter margin, and the change of mass, stiffness or aerodynamics is small
- → Level of Involvement (structures expert): such changes are complex and generally critical. Novelty case by case.

Step 1 — Likelihood of an unidentified non-compliance			
CDI / Performance level of the DOAH	No novel aspects, no complex aspects	No novel aspects, but complex ones; Novel aspects, but no complex ones	Novel and complex aspects
High	Very low	Low	Medium
Medium	Low	Medium	High
Low or unknown	Medium	High	High

EASA

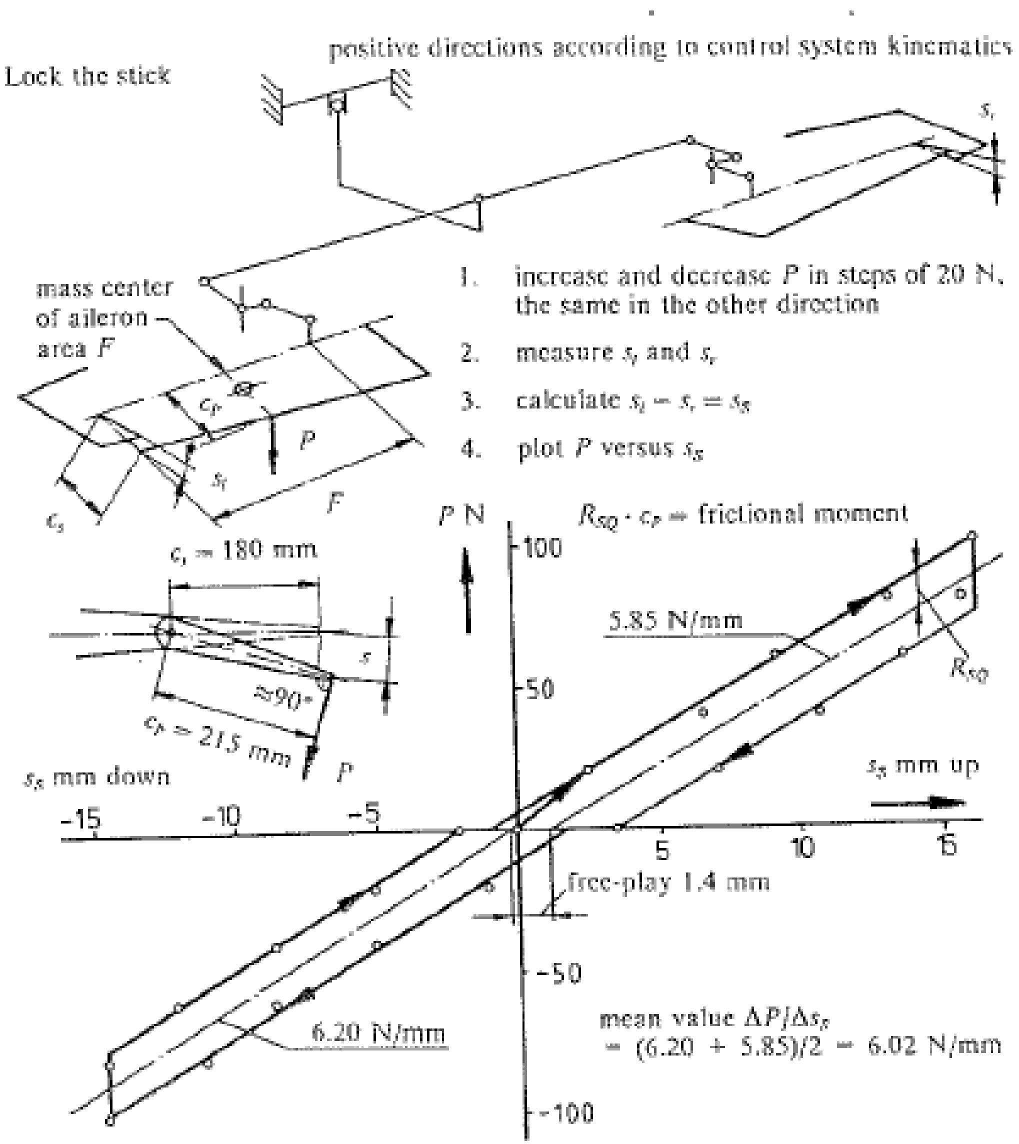
Maintenance precautions

→ Free-play control (CMR)

→ AMM Paint and SRM repair weight limits

→ Inspect stiffness, wear and complete attachment of control surfaces

Image source: Free-play measurement DLR Mitteilung 91-03



Innovative research and certification with EASA

→ Research and Innovation

→ For projects of a sufficient Technological Readiness, we can have a short meeting

→ For longer engagement, EASA offers pre-application innovation services:

EASA

Part IV: lessons learnt in GA.
ASTM WK70524

GA Airworthiness Directives related to flutter

- Overwhelmingly related to control surfaces/systems
  - Surface and tab balances loose or failed
  - Misbalance due to paint thickness
  - Loose or failed rods, bolts or pins/nuts
  - Control surface detachment or control system weakening due to cracks or delamination
  - Freeplay due to wear
  - Incorrect assembly

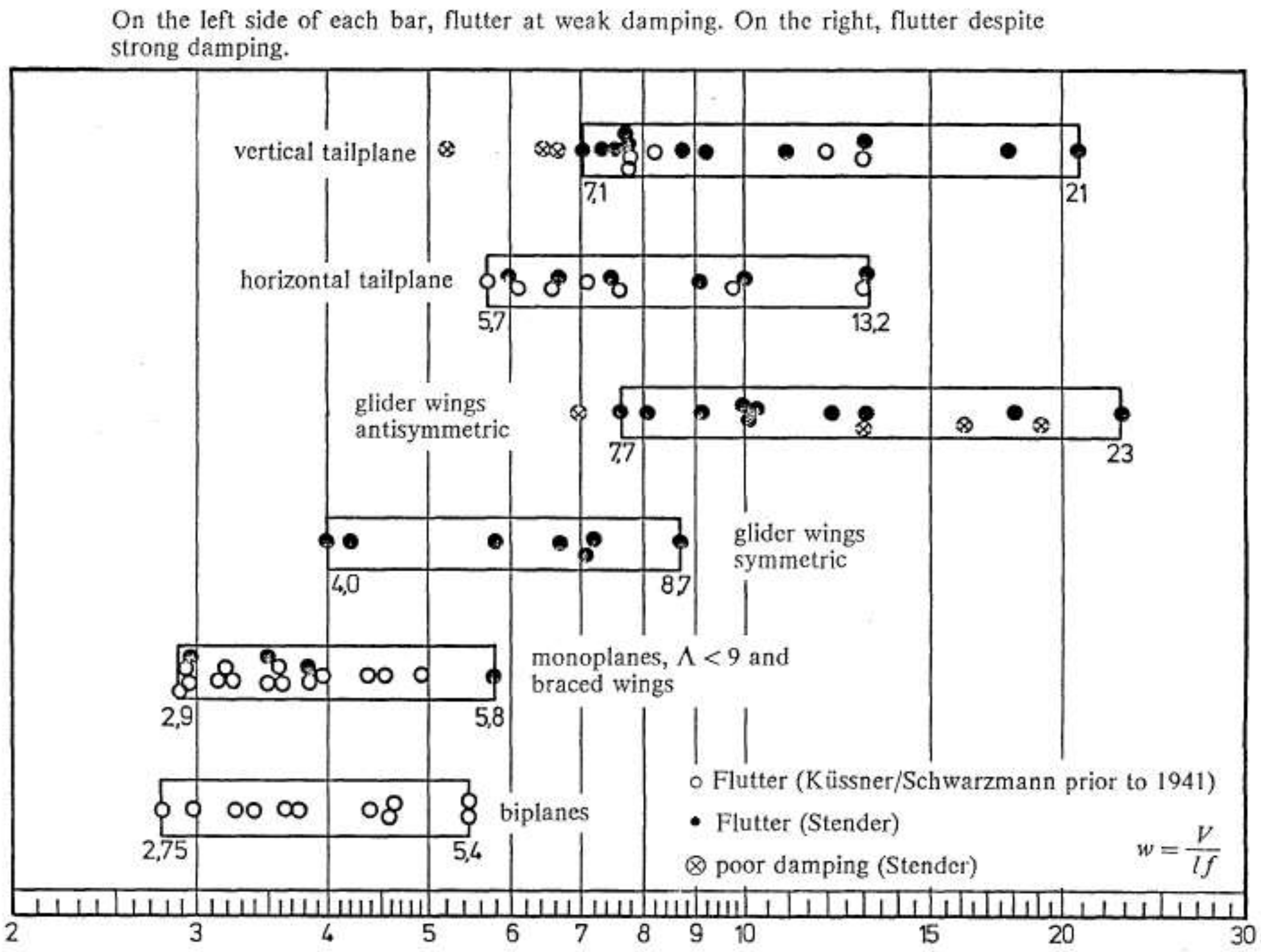
- Winglet modification

- Before certification: Test flight accidents

Flutter accidents

- → WonderMudry (design)
- → Grob (configuration control)
- → DG300 (glider) winglet flutter close to Vne and MTOW
- → DLR Mitteilung 91-03 Fig 7 →
- → Integral-R

Figure 7. Ranges of reduced wavelength w where flutter occurred (Evaluation of flutter incidents in German aircraft)



GVT and flutter analysis

- GVT quality
  - Process to ensure finding the critical resonance frequencies.
  - Check all first control surface modes have been found.
  - Ensure control surface friction doesn’t prevent identifying a mode
  - Quality checks
  - Recording of excitation
  - Possible measurement of non-linearity

- Analysis description and validation
- Existence of FEM, or if only GVT output modes how to address sensitivity/failure analysis and future modifications

- Identify and describe critical aeroelastic mechanisms from the flutter analysis. E.g.
  - ST: Wing symmetric torsion +
  - bSQ1= Aileron symmetric rotation

Flight test 1

- → Last safety net
- → Objective: to excite flutter mechanisms and measure their damping
  - → Appropriate damping margin
  - → No large and rapid reduction
- → Gradual opening of envelope, with excitation and damping measurement in between
  - → Close to Vne, steps of 5-10 kmh

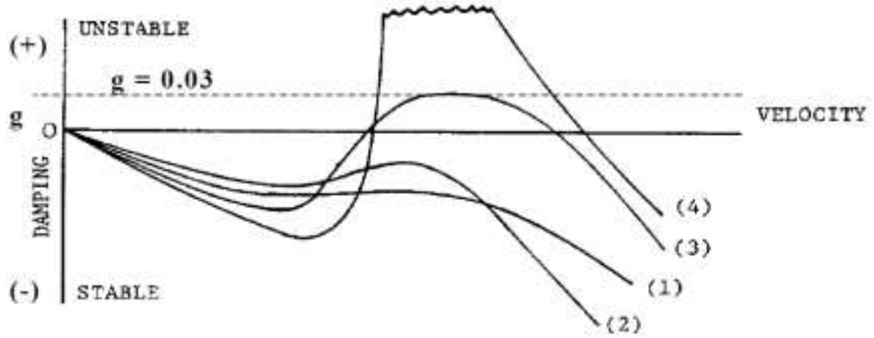


Figure 1-1. Flutter Analysis Evaluation

Flight test 2

- Induce flutter
  - Challenges of excitation, to achieve signal/noise ratio
  - Stick impact: good signal/noise ratio up to ~10 Hz
  - Turbulence excitation
  - Shakers/pyrothecnics - less usual

- Damping measurement
  - Accelerometer instrumentation
  - Signal post-process

- Instrumented flight test
  - Accelerometers placed away from nodes for critical modes
  - The GVT instrumentation could take into account to leave accelerometers for flight test

AC 23.629-1B

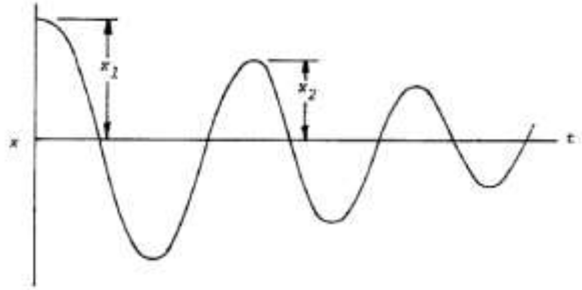
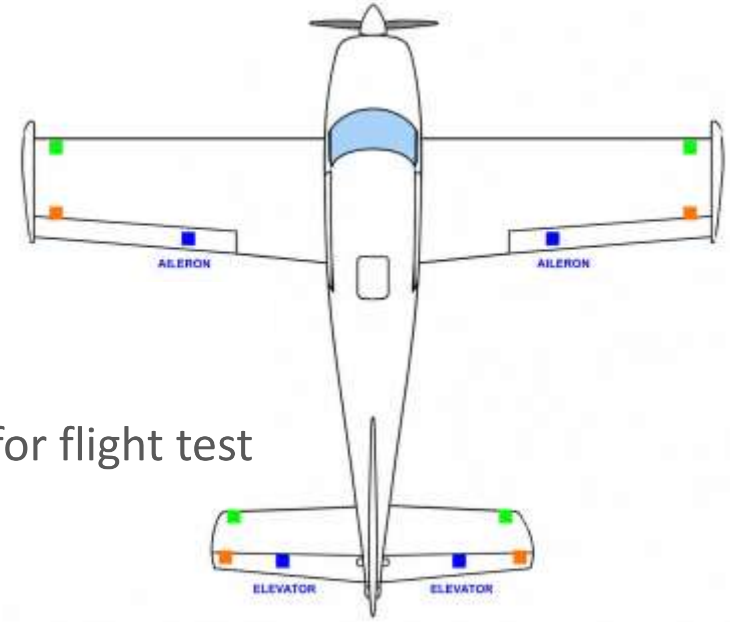


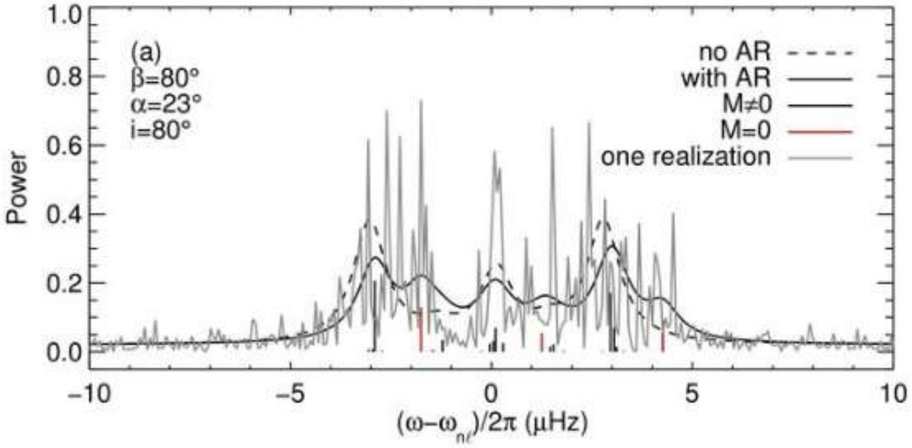
Figure A-3. Structural Damping Measurements
(X = Displacement, t = time)

The log decrement, δ, is then equal to ln (X_1/X_2); or as $\frac{0.693}{n}$
Where n=no. of cycles to ½ amplitude; i.e.: $X_1/X_2 = 2$.



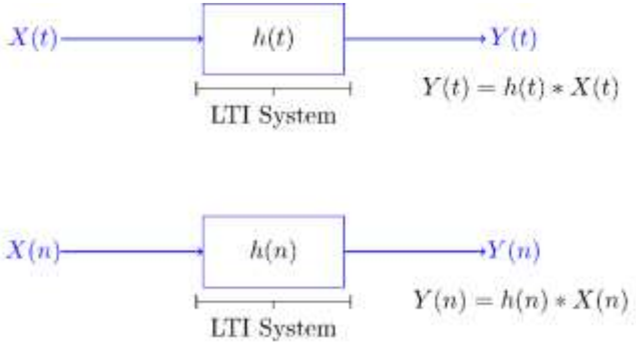
Excitation by turbulence

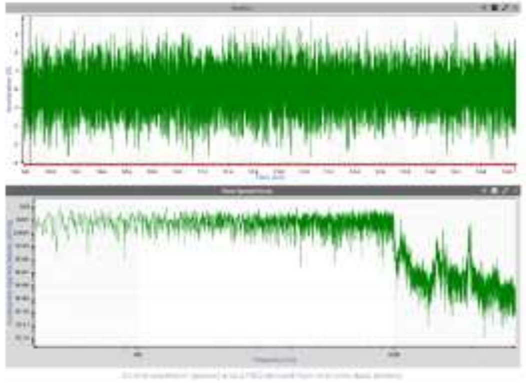
- A power spectrum reflects the average power or variance of a signal, per frequency. Although for random processes, the values change from one instant to the next, and its PSD over a short time will be very irregular, the power measured over a longer time converges to a power spectrum.



- Operational Modal Analysis: Input-only methods
  - Assumption of white or broadband input near the modes

- Output PSD





$$S_Y(f) = S_X(f)|H(f)|^2$$

- Image source: Papini, E., Gizon, (2019)

Excitation by turbulence 2

- Welch method implemented by Aura-Aero, novel for EASA
  - Able to capture critical modes of relatively high frequencies
  - Non-parametric, to assess the dominant peaks
  - Trade-off frequency resolution/variance reduction
    - Random data Bendat & Piersol table 8.1
  - Several minutes necessary to achieve sufficient precision in damping measurement
  -

- Research on parametric, dynamic models A
  - E.g. ARMA/SSI, Kalman filters.
  - E.g, Peeters & De Roeck, DLR research (see backup slides), TU Muenchen.
  - Able to collect data from several accelerometers
  - Stabilization diagram as a heuristic robustness check
  - Can achieve high accuracy in a short time, but only if assumptions are right
  - How to quantify uncertainty?

- OMA has limitations (precision, productivity, expected behaviour such as the absence of transonic excursion ...) that may disqualify the methodology for large airplanes.

Sensitivity and failure analyses, and design/certification consequences

- Sensitivity to the variation of main parameters
  - Covers for uncertainties in analysis and assumptions
- E.g. Sensitivity to Aileron balance and stiffness
  - Leads to the measurement of aileron balance, and reinforcement of the control system
  - Control system test
- Best design precautions:
  - Use balanced surfaces as far as possible, esp. for the first tests (statically, and dynamically for the main modes)
  - Attach balances safely
  - Robust control systems, and tabs
  - Connections easily inspectable
- Configuration control, including balances and free-play
  - Free-play should be measured before flight
- Ensure critical failures are considered
  - any single element in the primary flight control system,
  - any tab control system,
  - or any flutter damper.
  - Details of the concrete disconnection point can be decisive

Possible non-linear behaviours

→ Usually not considered for GA

→ Some possible non-linear effects for flutter:

- → Structural stiffness:
  - → Control surface plastic behaviour
  - → Geometric non-linearity
  - → Lifting surface deformation / large masses
  - → Free-play (covered if measured and values below DLR Mitt 91-03
- → Structural damping vs. viscous/hysteretic (expected small effect)
- → Friction of the control system
- → Aerodynamic:
  - → Damping. E.g. dependency on frequency
  - → High angle of attack (dynamic stall)
  - → High deflection of control surface
  - → Vortex-induced vibrations
  - → High Mach (not applicable)
- → Aeroservoelasticity (usually not applicable)
- → References: Report 45, DLR Mitteilung , BCAR K3-9

Feedback appreciated on which non-linearities can actually be critical in GA

?

EASA

Proposed CM/ASTM GA aeroelasticity demonstration

- CM and/or ASTM working group to modernize AC 23.629-1B
- Best design practices
- Ground tests
  - GVT
  - Surface balance
  - Free-play
- Flutter analysis
  - Sensitivity and failure analysis
- Flight Conditions, safety of the flight
  - GVT+ analysis
  - W&B surfaces
  - Free-play measurement
  - Configuration control and substantiation of changes with EASA
  - Compliance demonstration: Gradual opening of the envelope, with excitation and damping measurement in between

ASTM WK70524

New Practice for Aeroelastic Compliance Demonstration

- Initiative from Textron Aviation
- Replace traditional AC 23.629-1B with more complete and updated content
- 3 subjects
  - GVT
    - Practice
  - Flight flutter
    - Practice (Compliance demonstration)
    - Guide (Safety of the Flight)
  - Analysis
    - Practice

- **Practice:** An ASTM practice is "a set of instructions for performing one or more specific operations that does not produce a test result." *Id.* This is a document that can set out requirements.
- **Guides:** ASTM Guides are "compendium[s] of information or series of options that *do[] not recommend* a specific course of action." *Id.* (emphasis added).
- **Specification:** An ASTM specification is "an explicit set of requirements to be satisfied by a material, product, system, or service."

CS-23 other approaches/guidance

- CAP467 Section K, BCAR K3-9
  - Semi-empirical
- AC 23.629-1B
- DLR-Mitteilung 91-03
  - Semi-empirical
- DLR/LBA guidance : On the flutter clearance of sailplanes and powered sailplanes
- AGARD-CP-278_3

Thank you for your attention!

Any questions….?

Investigation focus at TC

- . Compliance with this paragraph must be shown by analyses, tests, or some combination thereof as found necessary by the Agency (see AMC 25.629).

5. *Compliance*. Demonstration of compliance with aeroelastic stability requirements for an aircraft configuration may be shown by analyses, tests, or some combination thereof. In most instances, analyses are required to determine aeroelastic stability margins for normal operations, as well as for possible failure conditions. Wind tunnel flutter model tests, where applicable, may be used to supplement flutter analyses. Ground testing may be used to collect stiffness or modal data for the aircraft or components. Flight testing may be used to demonstrate compliance of the aircraft design throughout the design speed envelope.

5.1. *Analytical Investigations*. Analyses should normally be used to investigate the aeroelastic stability of the aircraft throughout its design flight envelope and as expanded by the required speed margins. Analyses are used to evaluate aeroelastic stability sensitive parameters such as

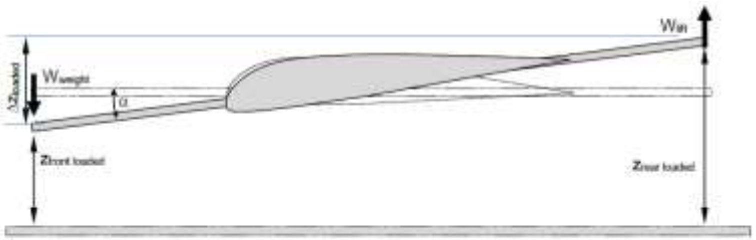
CS-23 Regulation and guidance

- Related requirements

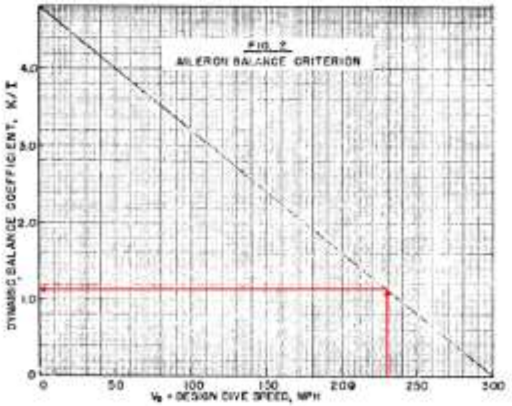
  - 23.343(c)(3)/F3116 Flutter with zero fuel
  - 23.677/F3061/F3232 Trim systems
  - 23.687/F3061/F3232 Spring devices
  - 23.1419 AMC /F3120 Flutter with ice accumulation
  - Amdt 5 and later: CS 23.2205 Interaction of systems and structures

Report 45

- → Only for conventional designs
- → Simple and conservative
- → No GVT: Wing torsional stiffness measurement and modal analysis



- → Control surface balance criteria



DOATL oversight

- Competences
  - Aeroelasticity CVE needs experience in a consolidated company before doing own analyses
    - CVE interview with structures expert very recommended
  - Should there be an internal CVE?
  - Software
    - Nastran
    - Neocass
  - Validation of the method
  - Training
    - TU Delft fundamentals of aeroelasticity
    - Kansas University training
    - Siemens GVT master class
  - GVT requires expensive and sophisticated equipment. New technologies
  - GVT and flutter analysis often subcontracted
  - Structural FEM is less complicated by comparison

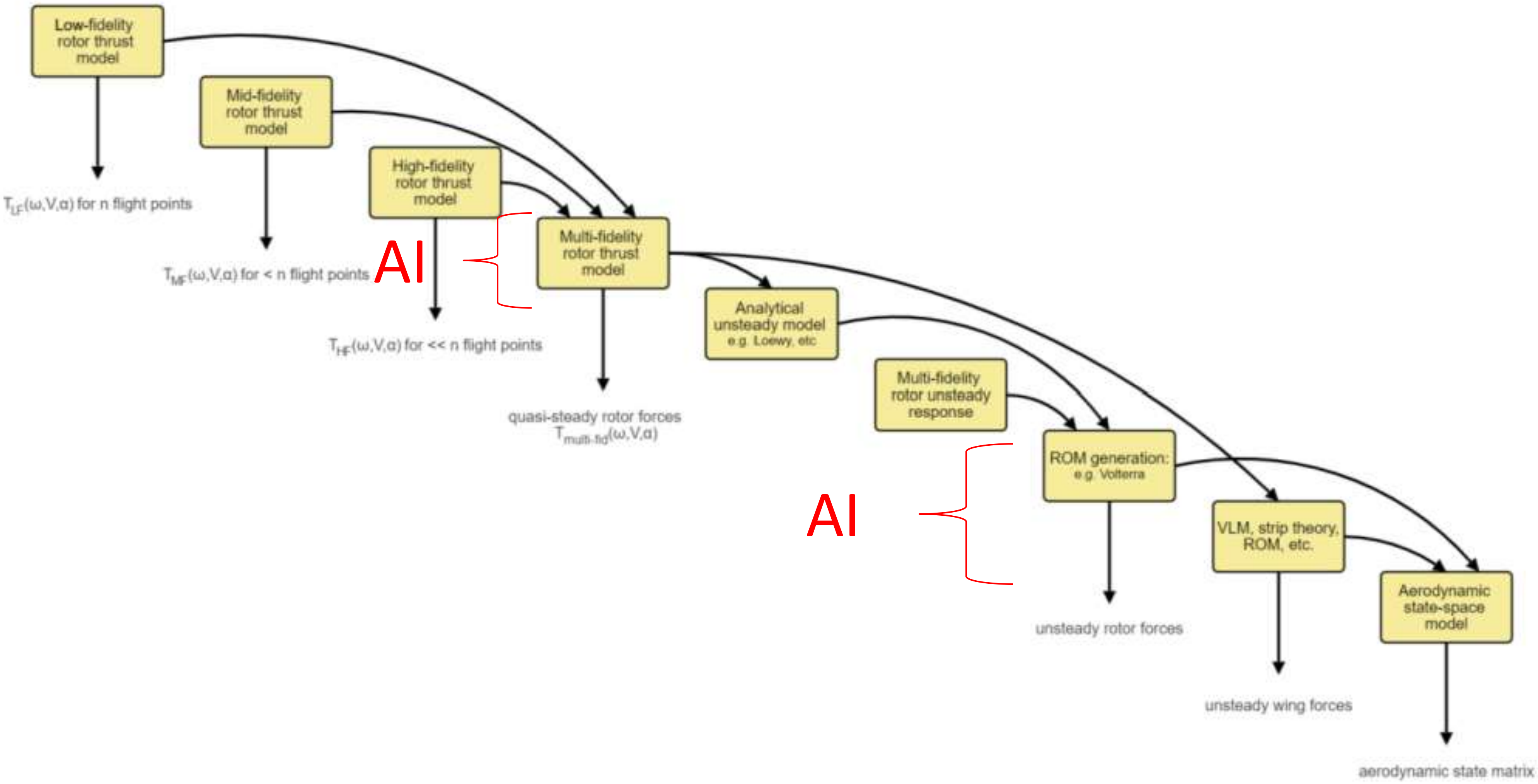
DOATL oversight

- FC process
  - Responsibilities
  - Process definition for configuration control, analysis of deviations, and classification and approval of changes.
  - Maintenance criteria (balance, correct assembly, freeplay measurement)
  - Gradual opening of the envelope
  - Role of FTOM

Changes / STC typically requiring flutter assessment:

- Fin Camera Installation or other concentrated masses on flexible structure
- New Fuel Tank Installation
- Cargo Conversion
- Winglet installation
- Significant weight increases, extensive stiffness change
- Envelope increase
- Change of flight control system standard, as affecting transfer between command and control surface deflection (e.g. logic changes, mode filters, gains…)

Future development
(EASA Research Model SI)



Excitation by turbulence, output-only modal analysis, some references

- Linear Time-Invariant (LTI) Systems with Random Inputs (probabilitycourse.com)
- Output-only measurement-based parameter identification of dynamic systems subjected to random load process. Katrin S Runtemund
- Random data . Analysis and measurement procedures. Julius S. Bendat & Allan G. Piersol
- Fundamentals of Statistical Signal processing. Estimation Theory. Steven M.Kay

- Peeters, B., De Roeck, G. (1999). Reference-based Stochastic Subspace Identification for Output-Only Modal Analysis. Mechanical Systems and Signal Processing, 13(6):
- HALO flight test with instrumented under-wing stores for aeroelastic and loads measurements in the DLR Project iLOADS, J. Sinske et al.
- Online Monitoring of Flutter Stability During Wind Tunnel Testing of n Elastic Wing with Pylon and Engine Nacelle Within the HMAE Project (M. Boeswald et al, DLR, IFASD 2019-070): Stochastic-Subspace-Identification (SSI)
- Flutter Flight testing: Using Operational Modal Analysis to identify, track and predict flutter for safe and efficient flight test campaigns. Soal et l, DLR IFASD 2024
- Experimental and operational modal analysis: automated system identification for safety-critical applications. Volkmar et al DLR
- Reliable monitoring of modal parameters during a flight vibration test using autonomous modal analysis and a Kalman filter. Volkmar et al IFASD 2024, DLR