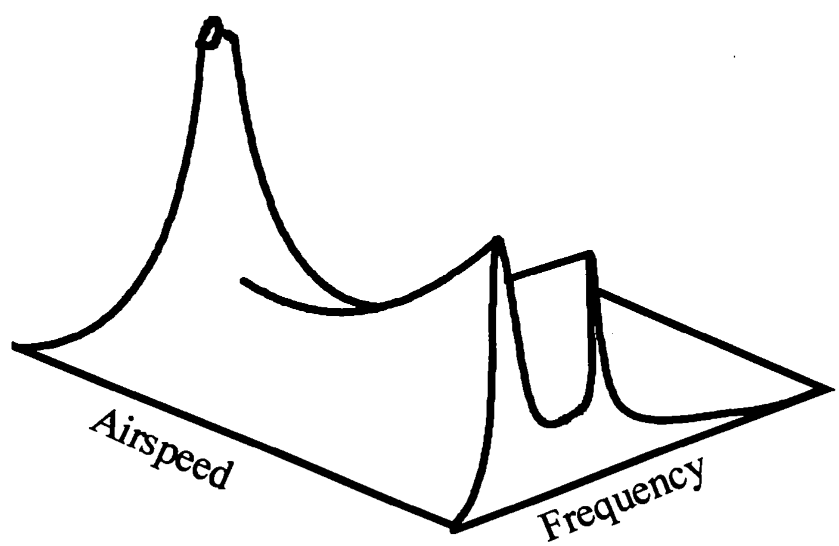
Flutter and Aeroelastic Stability

A Self-Study Video Course



Developed and Presented by

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Transport Airplane Directorate

Aircraft Certification Division

Federal Aviation Administration

Adapted from the September 16 & 17, 1997, IVT Satellite Broadcast

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Table of Contents

How Do I Use This Self-Study Package?

This self-study package consists of a VHS videotape (approximately 6 hours) and the accompanying self-study guide. This self-study guide provides you with the position of this course in the Airframe Engineering Curriculum, an orientation to the self-study video course, support materials for use with the videotape, a self-assessment, and the course evaluation.

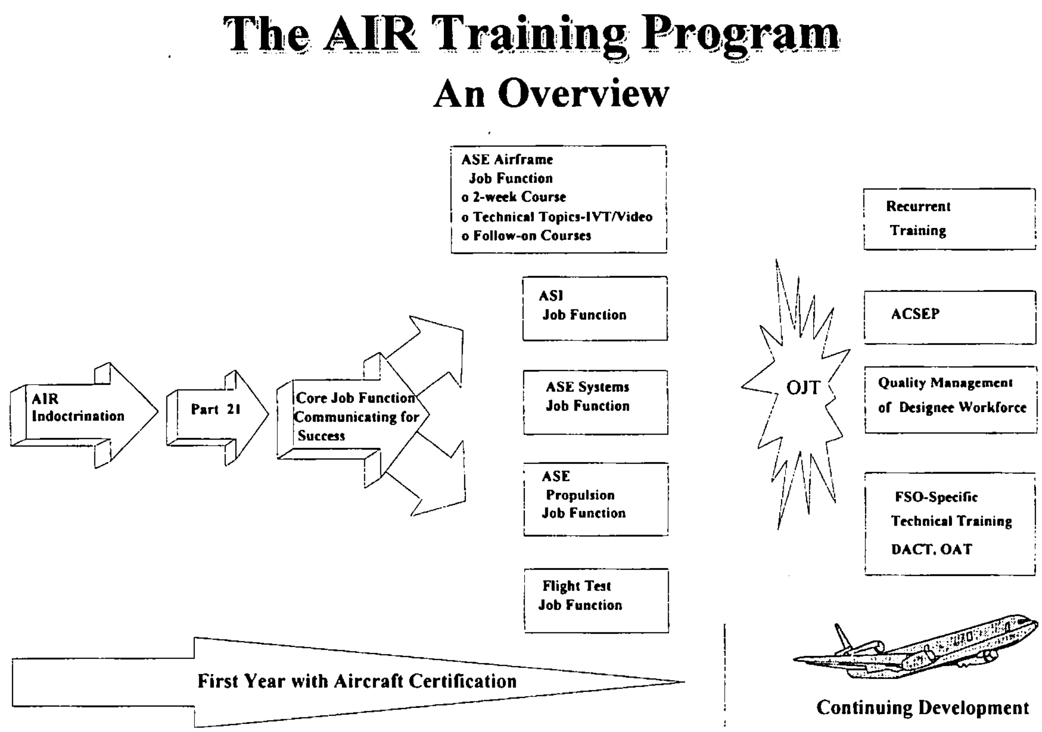
Follow these steps to complete your study.

1. Read Section I, *Airframe Engineering Curriculum*, to familiarize yourself with the the overall scope and format of the curriculum.
2. Read Section II, *Self-Study Video Course Orientation*, before viewing the videotape to get an overview of the purpose of the course, the target audience, the instructor(s), what you will learn, how this course will help you on-the-job, the topics covered in the course, and some good references.
3. Answer the pre-course self-assessment questions in Section III, *Self-Assessment.*
4. Turn to Appendix A, *Flutter/Aeroelastic Stability Video Presentation Visuals*, and start the videotape.
5. Refer to Appendix B, *FAR Parts for Flutter/Aeroelastic Stability,* as needed during the broadcast and as a reference tool.
6. Appendices C and D are reference materials compiled by the instructors. Appendix C provides the definitions of instability terms. Appendix D presents information on developing the flutter stability equation and on solving and interpreting equation results.
7. Complete the post-course self-assessment in Section III, *Self-Assessment.*
8. Complete the *Self-Study Video Course Evaluation Form* in Appendix E and send it to your Directorate/Division Training Manager (ATM).

I. Airframe Engineering Curriculum

What Does the Curriculum Cover?

The Airframe Engineering Curriculum fits into the broader AIR Training Program that is summarized in the following figure.



Within the context of the AIR Training Program, the Airframe Engineering Curriculum is designed to effectively meet the critical safety mission of the FAA by addressing the following Service goals:

Standardization

- Promote standardization throughout the organization in task accomplishment and application of airworthiness regulations in order to achieve uniform compliance.

Job Performance Proficiency

- Reduce significantly the time required for newly hired engineers to attain full job performance proficiency.

Customer Service

- Establish and maintain appropriate, effective, and responsive communication, collaboration, leadership, and teamwork with both internal and external customers.

In addition to the Service goals, the Airframe Engineering Curriculum is designed to provide ASEs with job function training in three domains:

- Tasks and procedures governing the work of engineers in design approval, technical project management, certificate management, and designee management.
- FAR airworthiness requirements that are the purview of airframe engineers. Generally they are subparts C and D of FAR Parts 23, 25, 27, and 29.
- Technical subjects essential for all new engineers to meet both introductory requirements and, later, minimum technical proficiency level requirements.

The resulting Airframe Engineering Curriculum structure consists of three main types of training opportunities:

1. Two-Week Job Function Course
2. Overviews of Technical Subjects
3. Follow-on Core Technical Subjects Courses.

Two-Week Job Function Course

The Two-Week Job Function Course uses an instructor-led, classroom-based format with lecture, discussion, and individual and group activities. Supporting materials used in the course include print, overhead transparencies, videotapes, job aids, and documents and sample reports.

The course is divided into the following two major sections:

Week 1

- **Certification Tasks** — includes design approval, technical project management, certification management, and DER management.

Week 2

- **FAR Requirements and Key FAR Sections** — includes training in the subparts of the FAR that apply to airframe engineers (subparts C and D) at two levels: an overview of those subparts across FARs 23, 25, 27, and 29; and in-depth discussion of significant sections of the FAR that are important to the Service. The importance of these sections may stem from problems in interpretation and application of requirements, technical complexity of a design, "high visibility" projects, or safety considerations that are paramount.

Overviews of Technical Subjects

High-level overviews of ten technical subjects are presented by NRSs or other senior engineers. These overviews will be available in two modes:

- An initial live three- to four-hour IVT satellite broadcast with accompanying course material will be received at each Directorate and other downlink sites.
- A Video/Self-Study Training Package adapted from the initial IVT presentation and accompanying course material will be available through the Directorate Training Manager.

Basic concepts and FAA-specific applications and examples are provided for each of the following ten technical subjects:

- Aircraft Loads
- Fatigue/Fracture Mechanics/Damage Tolerance
- Composite Materials

- Crashworthiness/Occupant Protection
- Material Properties/Manufacturing Processes of Metal
- Stress Analysis
- Flutter/Aeroelastic Stability
- Structural Test Methods
- Design and Construction
- Repairs and Modifications.

Each technical subject overview is designed to not only provide ASEs with the FAA perspective on the topic, but also serve as an indicator of what further training may be needed.

Core Technical Subjects Courses

As a follow-on to the Overviews of Technical Subjects, the curriculum will provide more in-depth training on the following three subject areas:

- Basic Loads
- Stress Analysis and Structural Test Methods
- Repairs and Modifications.

These core technical subjects are essential to the technical work of the airframe engineer in a regulatory environment regardless of product or technology. Training in each of the core subjects will be designed to bring airframe engineers to a minimum level of technical proficiency and to help promote proficiency in the application of the technical knowledge in an office work environment.

Additional technical training for engineers beyond these core subjects will depend largely on ACO organizational needs stemming from customer requirements, products certified, emerging technology, and the number of staff requiring more specialized training. In short, the more advanced the technical training required, the more individualized it becomes.

II. Self-Study Video Course Orientation

About This Self-Study Video Course

Flutter and Aeroelastic Stability is one in a series of ten "Overviews of Technical Topics" in the Airframe Engineering Curriculum designed to prepare you to meet the critical safety mission of the FAA. *[For more information on the Airframe Curriculum, refer back to Section I of this guide.]*

This self-study video course is based on the original eight-hour Interactive Video Teletraining (IVT) broadcast on September 16 and 17, 1997. The broadcst was televised from the IVT studio at the FAA Academy in Oklahoma City to various sites around the country. James R. Haynes and Gerald C. Lakin, senior engineers in the Transport Airplane Directorate Standards Staff, are the instructors. They will provide you with basic aircraft flutter concepts, criteria, regulations, and examples. During the broadcast, participants were able to communicate with the instructor either through a microphone and/or simple-to-use Viewer Response System keypads.

- Appendix A contains the actual visual support material used by the instructors during the broadcast. You can use these visuals to follow along with the videotape and record notes directly on the pages.
- Appendix B is a listing of relevant FAR Parts.
- Appendices C (*Aeroelastic Instability Definitions*) and D (*Flutter Analysis*) is information pulled together by the instructors as additional reference materials.
- Appendix E contains the Self-Study Video Course Evaluation Form. Please fill out this form after completing this course and send the form to your Directorate/Division Training Manager (ATM).

Who Is the Target Audience?

This course is designed for:

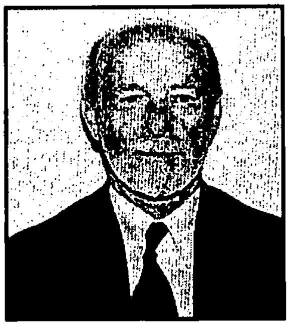
- New and experienced FAA airframe engineers who are not proficient or expert in flutter/aeroelastic stability, related FAA regulations, and/or the application of this knowledge to ensuring aircraft safety.
- Others with interest, such as multidisciplinary engineers or flight test pilots.

Who Are the Instructors?

Jim Haynes

James (Jim) R. Haynes received a BS in Aeronautical Engineering(1967) and an MS in Systems Engineering(1973), and has performed additional post-graduate studies in aeroelasticity and flutter at Renssalaer Polytechnic and the University of Oklahoma. He is a Registered Professional (Mechanical) Engineer. He has 28 years of experience as an aeronautical engineer and has worked as an FAA airframe engineer for the last 26 years.

Jim was an FAA Academy instructor from 1974-77 where he taught certification and engineering courses, including the Airplane Flutter and Aircraft Vibration courses. He has been the principle technical specialist for flutter for the FAA Transport Airplane Directorate since 1980. He was responsible for the development of Advisory Circular 25.629-1, "Flutter Substantiation of Transport Category Airplanes" and the principle author of the current version of FAR section 25.629, "Aeroelastic Stability Requirements." Jim is the FAA representative of the Aviation Rulemaking Advisory Committee (ARAC) working group for the development of regulations and advisory material concerning structures, loads, and flutter.



Gerry Lakin

Gerald (Gerry) C. Lakin received a BS (1961) and MS (1965) in Engineering Mechanics and did post-graduate work in Aeronautics and Astronautics (1966 and 1970). He is a Registered Professional Engineer and Senior Member of AIAA. He worked as an engineer and manager in structural dynamics (primarily flutter and vibration) for 36 years, including 30 years at the Boeing Company where he was involved in many commercial, military and space programs. He was an FAA DER at Boeing and consulted as an independent DER in the general aviation industry. He has published papers in the AIAA and ASME technical journals and taught the introductory course in Flutter and Vibration at Boeing.

Gerry joined the FAA in 1995 as a Project Officer in the Transport Airplane Directorate Standards Staff where he shares Part 25 oversight responsibilities for the Los Angeles and Atlanta ACOs. Some of the projects he is associated with are the civil certification of the McDonnell Douglas C-17 and Blended Wing Body airplanes, and the China Bilateral Airworthiness Assessment. He has provided training on certification projects and consulted on continued airworthiness issues involving flutter and vibration.

What Will You Learn?

After completing this course, you will have a basic understanding of the concepts and principles of Flutter and Aeroelastic Suitability, including:

- What aeroelastic instabilities are and how they differ from forced vibration response. In addition you will be able to visualize common aircraft flutter modes.
- Regulatory requirements, advisory material and policy for small and transport category airplanes.
- Analytical and experimental means of demonstrating compliance.
- Factors that influence aeroelastic stability and detail design considerations.
- Further reading material and studies, including analytical tools and additional training.

How Will This Course Help You On-the-Job?

After completing this course, you should be able to:

- Understand and recognize the characteristics of the different types of aeroelastic instabilities.
- List the FAR requirements, guidance, and policy that deal with aeroelastic stability.
- Review applicant's flutter certification plan and understand the general approach to demonstrate compliance.
- Describe parameters that can effect aeroelastic stability and relate this to detail design features and design changes.
- Understand that a great deal of education, training, and experience are necessary to make journeyman findings of compliance.

What Topics Does the Course Cover?

The following topic outline is intended to give you an overview of the course content.

I Introduction

II. Background and Review

A. Basic definitions

1. What is and isn't instability
2. Instability vs. forced vibration
3. Definition of flutter

B. Vibration modes

1. Single degree of freedom
2. Two degrees of freedom
3. Multi-degrees (continuous) of freedom
4. Free-free vibration modes
5. Coupled modes
6. Full airplane structural dynamic model

C. The mechanism of classical flutter

III. The Aeroelastic Stability Requirements

A. Transport airplanes

B. Small airplanes

IV. Demonstration of Compliance

A. General

1. Methods of compliance
2. Compliance philosophy
3. Flutter certification plan

B. Flutter analyses
   1. Flutter stability equation
   2. Solving
   3. Interpreting results
   4. Analytical investigations
   5. Reporting the results

C. Ground vibration tests
   1. Objectives
   2. Test plan and conformity
   3. Test article and support system
   4. Test results
   5. Other ground tests

D. Wind tunnel tests
   1. Purposes
   2. Dynamic similarity
   3. Instrumentation and testing techniques
   4. Tunnel investigations and parametric variations
   5. Flutter model video

E. Flight Flutter Tests
   1. Purpose
   2. Test article (configurations and conformity)
   3. Instrumentation and testing techniques
   4. Flight investigations and test conditions
   5. How results are used in the compliance program

V. What Effects Aeroelastic Stability
   A. Changes, modifications and repairs
   B. Assessing changes

VI. Flutter Prevention
   A. Detail design and service information

VII. Further Study, Analytical Tools, and Training
   A. Main referenced texts
   B. Standard analytical tools
   C. Recommended training courses
   D. Recommended training activities

VIII. Summary

What Are Some Good References?

The following are good published references for flutter/aeroelastic stability information:

Garrick, I.E. and Reed, W.H. III, *Historical Development of Flutter*, AIAA-81-0591-CP, 1981.

Theodorsen, T.; *General Theory of Aerodynamic Instability and the Mechanism of Flutter*, NACA Report 496, 1935.

Theodorsen, T. and Garrick, I.E.; *Mechanism of Flutter -- A Theoretical and Experimental Investigation of the Flutter Problem*, NACA Report 685, 1940.

Theodorsen, T. and Garrick, I.E.; *Nonstationary Flow about a Wing-Aileron-Tab Combination Including Aerodynamic Balance*, NACA Report 736, 1942.

Theodorsen, T. and Garrick, I.E.; *Flutter Calculations in Three Degrees of Freedom*, NACA Report 741, 1942.

Fung, Y.C.; Fung, Y.C.; *An Introduction to the Theory of Aeroelasticity*, Dover Publications, Inc. 1969.

Scanlan, R.H. and Rosenbaum, R; *Introduction to the Study of Aircraft Vibration and Flutter*, The MacMillan Co., 1962.

Bisplinhoff, R.L. and Ashley, H.; *Principles of Aeroelasticity*, Dover Publications, Inc., 1962.

Langley Research Center, *Flutter Testing Techniques*, NASA SP-415, October 9-10, 1976.

Pope, Alan and Rae, William, *Low Speed Wind Tunnel Testing*, Wiley-Interscience, Inc., 1984.

Advisory Group For Aerospace Research and Development (AGARD); *Manual on Aeroelasticity*, October 1968.

III. Self-Assessment

Pre- & Post-Course Self-Assessment Questions

During the IVT broadcast, the instructor asked participants to respond at the beginning and end of the presentation to the following questions about flutter certification and analysis.

Rate your level of understanding for each of the following statements before and after completing the course.

1. I understand what constitutes an aeroelastic instability.

	Very Confident	Moderately Confident	Not Confident
BEFORE THE COURSE:	☐	☐	☐
AFTER THE COURSE:	☐	☐	☐

2. I understand the regulatory requirements related to aircraft flutter.

	Very Confident	Moderately Confident	Not Confident
BEFORE THE COURSE:	☐	☐	☐
AFTER THE COURSE:	☐	☐	☐

3. I understand the analytical and experimental means of compliance for flutter requirements.

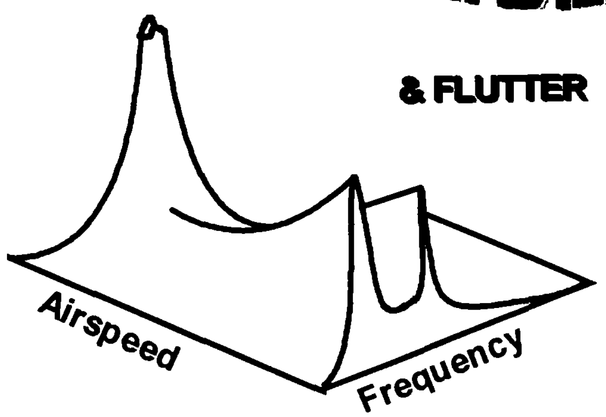
	Very Confident	Moderately Confident	Not Confident
BEFORE THE COURSE:	☐	☐	☐
AFTER THE COURSE:	☐	☐	☐

Flutter/Aeroelastic Stability
Video Presentation Visuals

Appendix A

AEROELASTIC STABILITY

& FLUTTER



1

What you will learn

- What aeroelastic instabilities are
- Regulatory requirements
- Acceptable means of compliance
- What affects flutter and flutter prevention
- Avenues of further study and development

2

Why aeroelastic stability has been (and is) important

- Flutter can be catastrophic and it can occur without warning.
- It is a historic as well as current problem:
  - It was responsible for one of the first catastrophic accidents in aviation history.
  - As recently as 1991, a large transport airplane was lost due to flutter with 50 fatalities (Accident Board finding).

3

Why aeroelastic stability is becoming more important

- Airplanes are larger, more flexible.
- Airplanes use advanced flight control systems that couple directly with the structural modes of the airplane.
- There are an increasing number of major modifications being accomplished that have a significant affect on aeroelastic stability.

4

Affect on design

- Aeroelastic stability concerns dictate the design of a significant amount of structure on a transport airplane:
  - Location of nacelles
  - Wing box stiffness
  - Vertical fin stiffness
  - Pylon stiffness and engine mount fail-safe structure
  - Control surface rigidity, geometry, and inertial properties.

5

Aeroelastic Instability

6

What is and isn't instability

Instabilities

- Flutter
- Whirl Flutter
- Divergence
- Control Reversal
- Deformation instability
- Aileron buzz??

Not Instabilities

- Forced Vibration
  - Oscillatory failures
  - Prop wash excitation
- Buffeting
  - Flow separation
  - Mach buffet

7

Instability vs. forced vibration

- Forced vibration: A system that has an external forcing function that is ***independent*** of the motion of the system.
- Stability phenomena are ***not*** forced vibration because the forcing function is ***dependent*** on the motion of the system.

8

Flutter

An unstable, self-excited structural oscillation at a definite frequency where energy is extracted from the airstream by the motion of the structure.

The deformation and motion of the structure result in forces on the structure that tend to ***maintain or augment*** the motion.

9

Vibration modes

1

Session overview

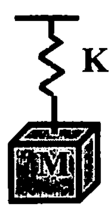
- Single degree of freedom
- Two degrees of freedom
- Multi-degree (continuous)
- Free-free vibration modes
- Coupled modes
- Full airplane structural dynamic model

11

Single degree of freedom

- Fa = Ma
- -Kx = Ma
- but $a = -\omega^2 x$
- $-Kx = -\omega^2 Mx$
- $[K/M-\omega^2]x=0$

This is the basic form of the stability equation no matter how complex the system.



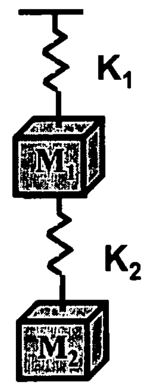
harmonic motion

$a = -\omega^2 x$

12

Two degrees of freedom

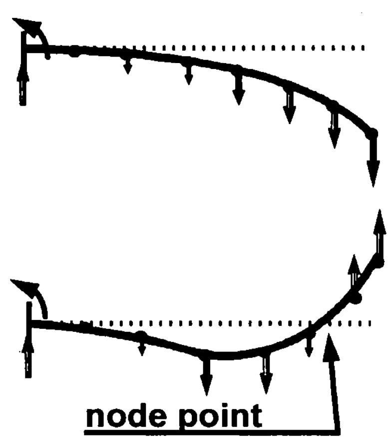
- $F_1 = M_1 a_1$ and $F_2 = M_2 a_2$
- $[F] = [M]\{a\}$
- $-[K]\{x\}=[M]\{a\}$
- $-\omega^2[M]\{x\}+[K]\{x\}=0$
- $[M^{-1}K - \omega^2 I]\{x\}=\{0\}$
- Two frequencies and two mode shapes. This is a two degree of freedom system.



13

Continuous structures

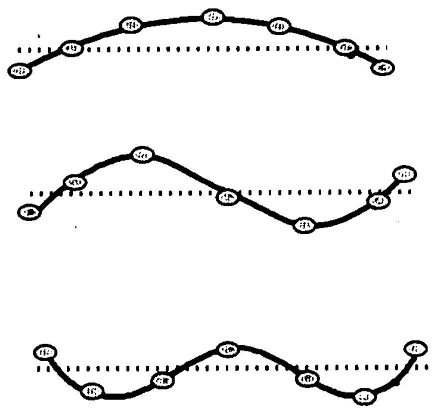
- Inertial forces proportional to displacement
- Infinite degrees of freedom
- Modeled with lumped masses and massless connecting beams



14

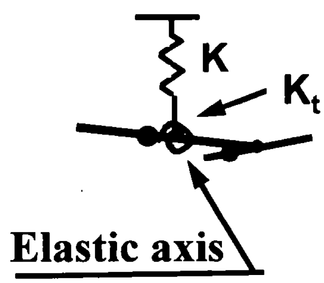
Free-free modes

- All inertial forces and moments balanced
- ***Symmetric*** and ***anti-symmetric*** modes if there is a plane of symmetry
- Otherwise; ***asymmetric modes***



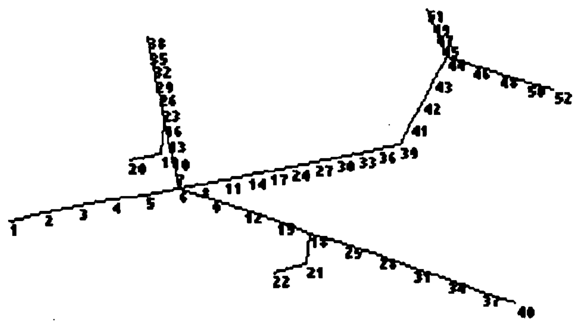
15

Coupled modes



16

Structural dynamic model



Lumped mass beam model ("stick model") is commonly used, even for complex airplanes.

17

Summary

- **Single degree of freedom**
- **Two degrees of freedom**
- **Multi-degree (continuous)**
- **Free-free vibration modes**
- **Coupled modes**
- **Full airplane structural dynamic model**

18

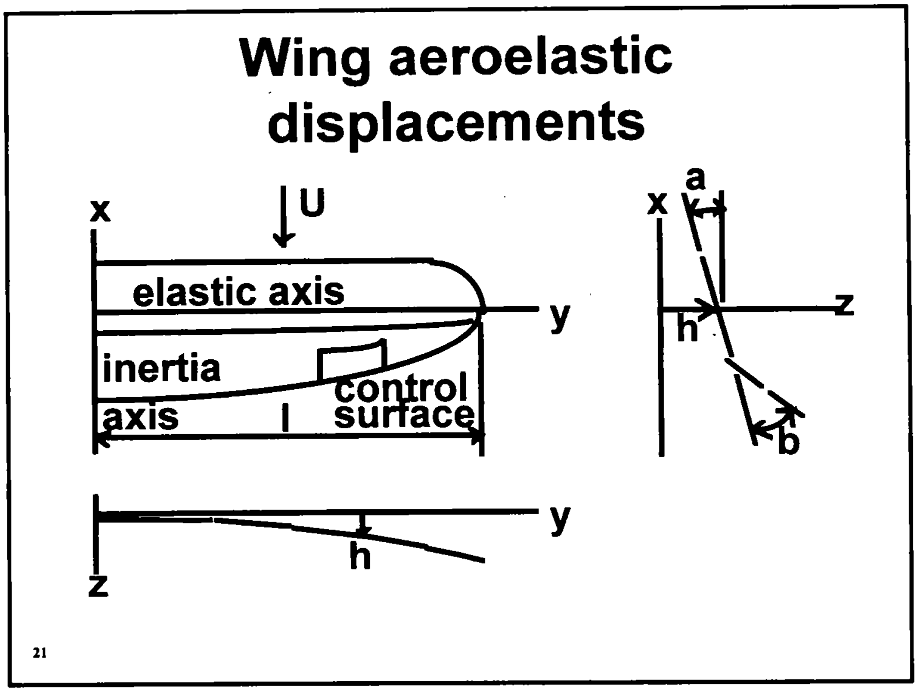
THE MECHANISM OF CLASSICAL FLUTTER

19

Session overview

- A control surface mechanism
- A main surface mechanism
- Other mechanisms involving main and control surfaces

20


Wing aeroelastic displacements
x
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elastic axis
y
inertia
axis
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control
surface
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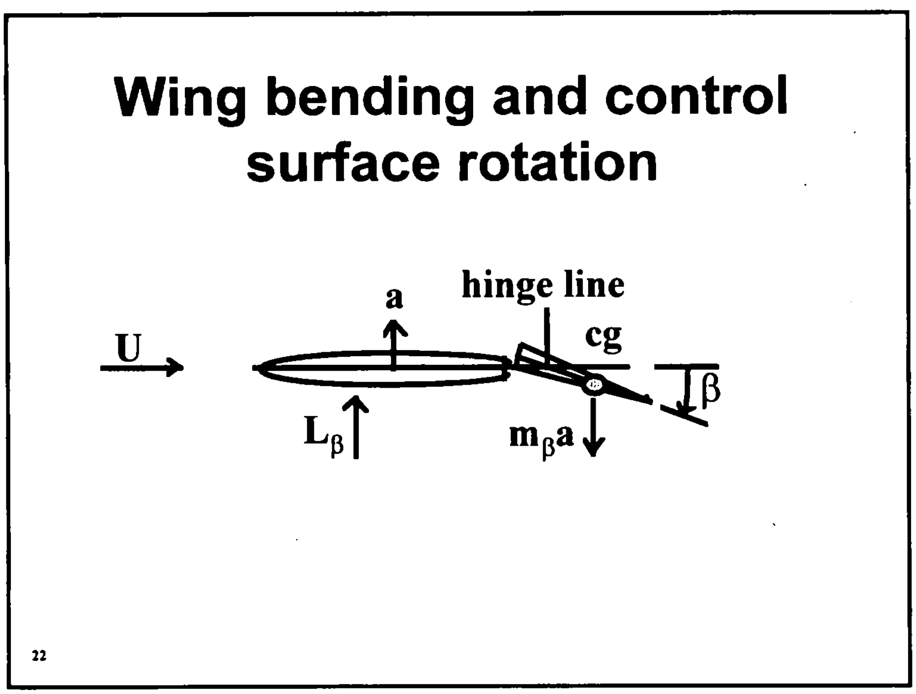
z
21

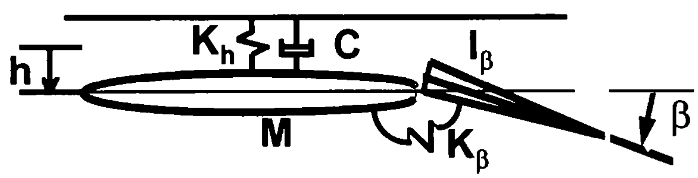

Wing bending and control surface rotation
a
hinge line
cg
U
β
Lβ
mβa
22

Flutter

An unstable, self-excited ***structural oscillation at a definite frequency*** where energy is extracted from the airstream by the motion of the structure.

23

Wing bending and control surface rotation

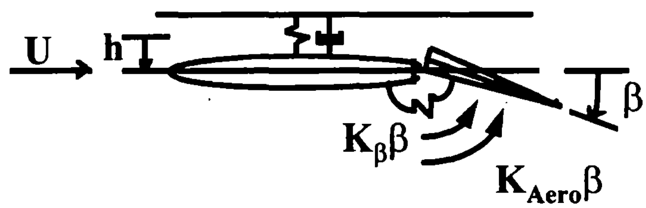


$\omega_h^2 = K_h / M$, **bending frequency**

$\omega_\beta^2 = K_\beta / I_\beta$, **control surface frequency**

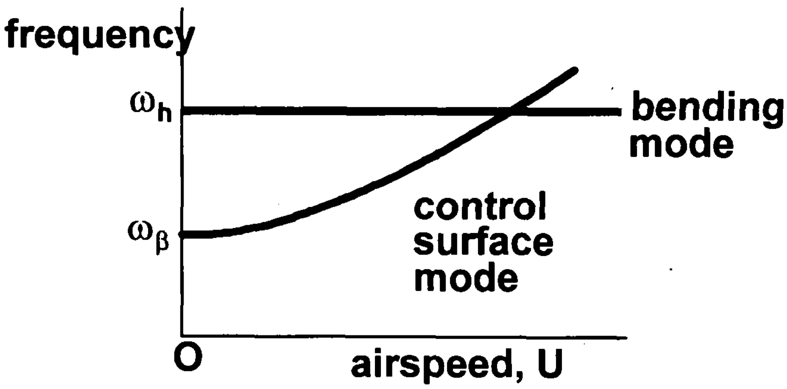
24

Aerodynamic stiffness



25

Structural mode frequency versus airspeed



26

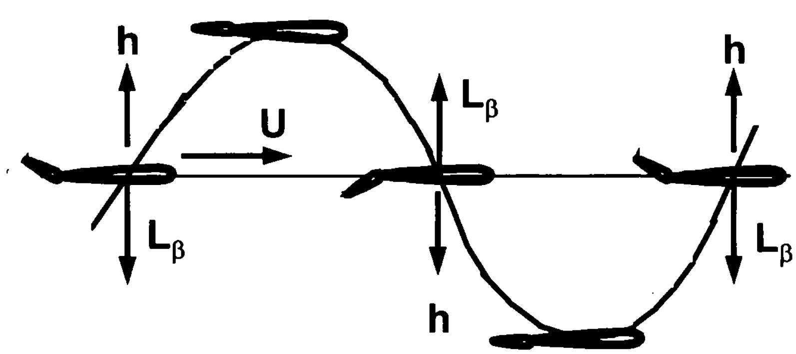
Flutter

An unstable, self-excited structural oscillation at a definite frequency where energy is extracted from the airstream by the motion of the structure.

The deformation and motion of the structure result in ***forces*** on the structure ***that tend to maintain or augment the motion.***

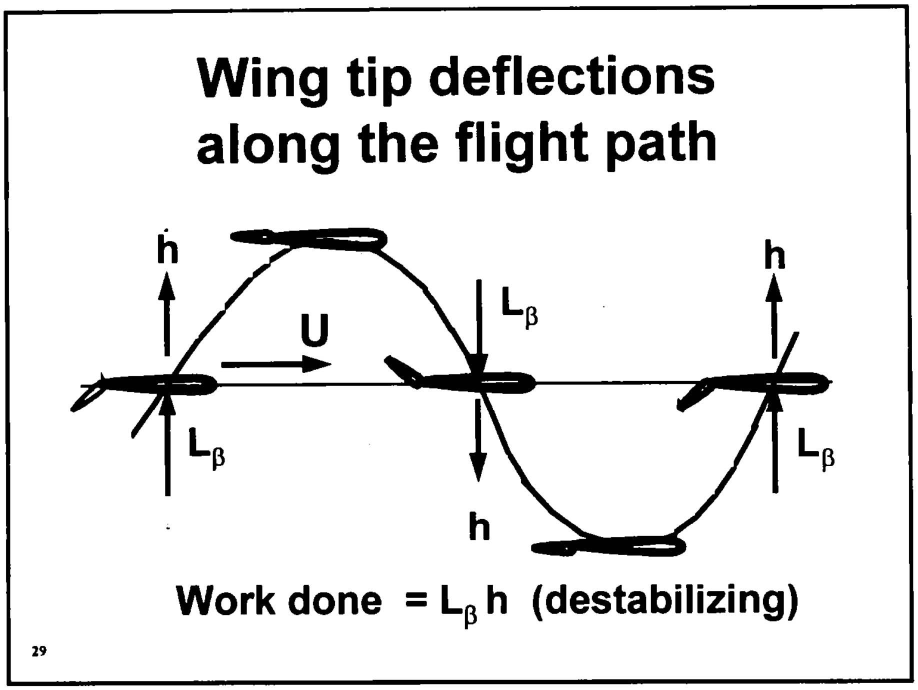
27

Wing tip deflections along the flight path



Work done $= -L_\beta h$ (stabilizing)

28


Wing tip deflections along the flight path
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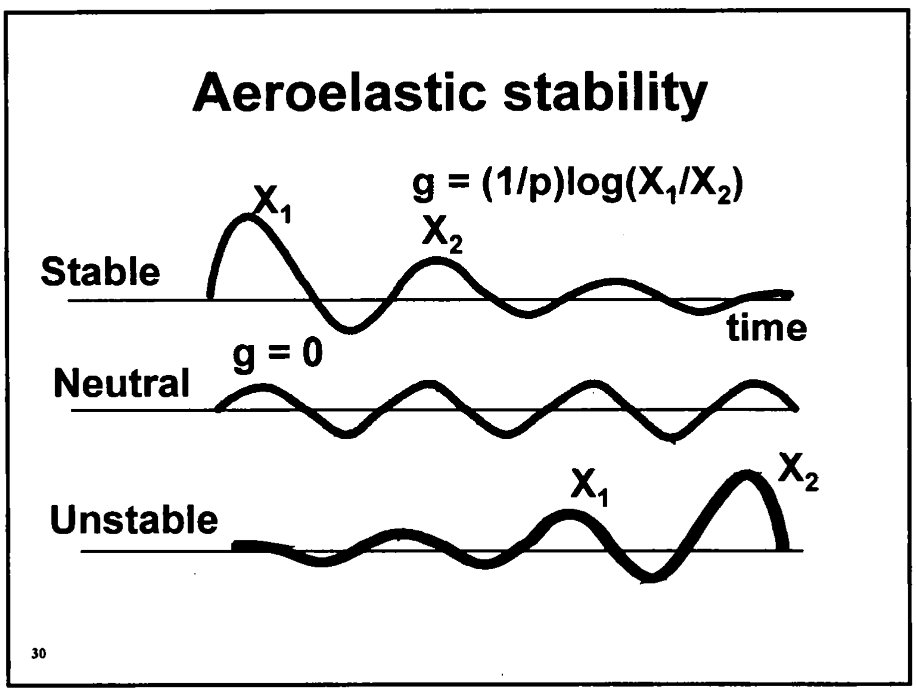
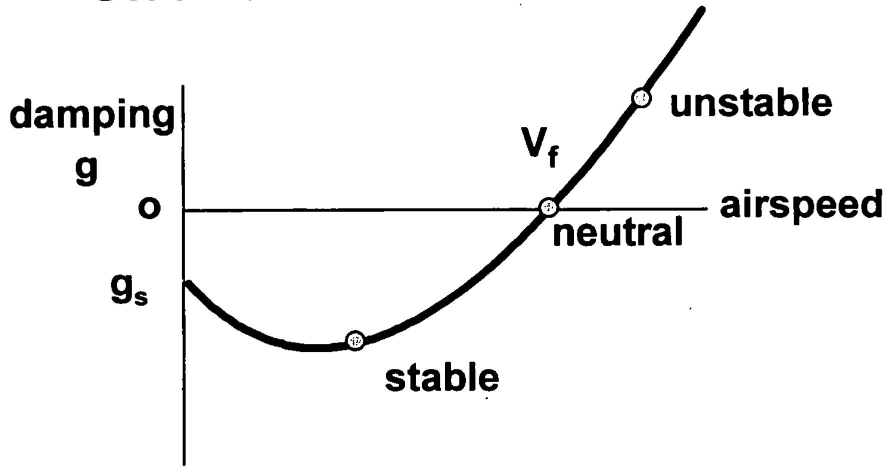
L_β
L_β
L_β
h
Work done = L_β h (destabilizing)
29


Aeroelastic stability
X_1
g = (1/p)log(X_1/X_2)
X_2
Stable
time
g = 0
Neutral
X_1
X_2
Unstable
30

Unbalanced control surface



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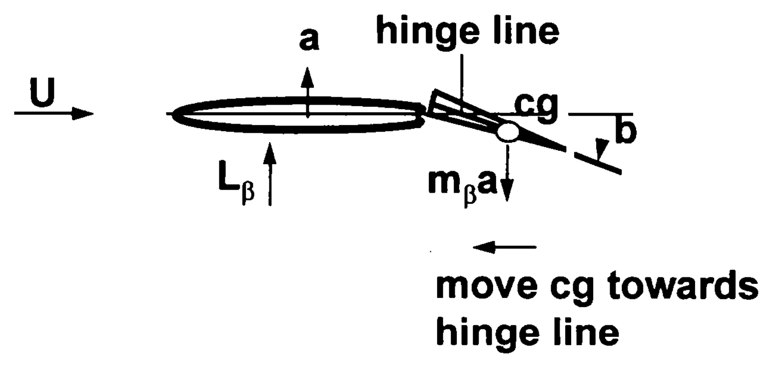
Partially balanced control surface



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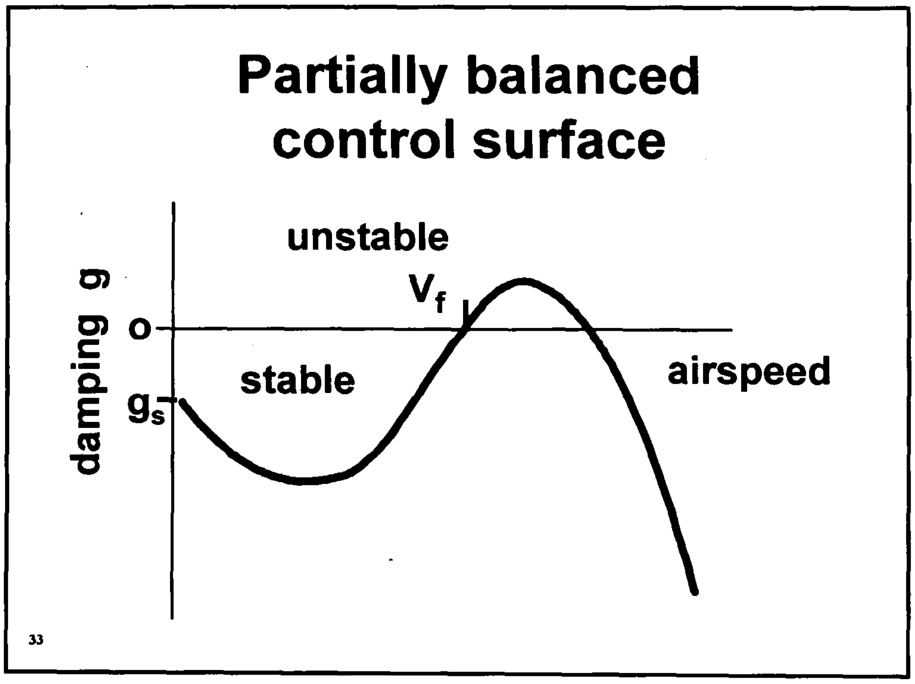
Partially balanced control surface
unstable
damping g
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stable
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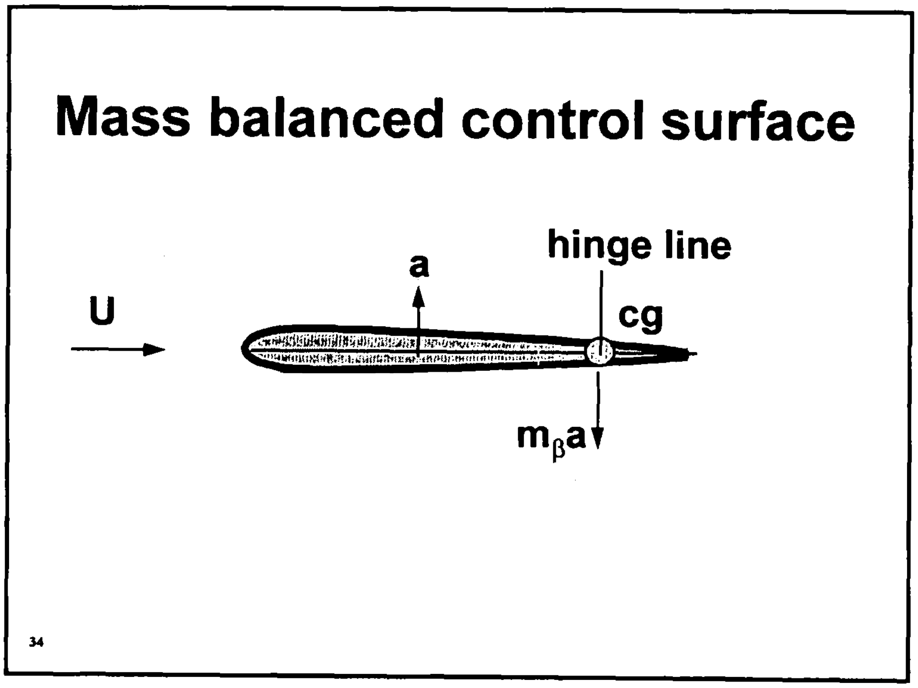
g_s
33


Mass balanced control surface
hinge line
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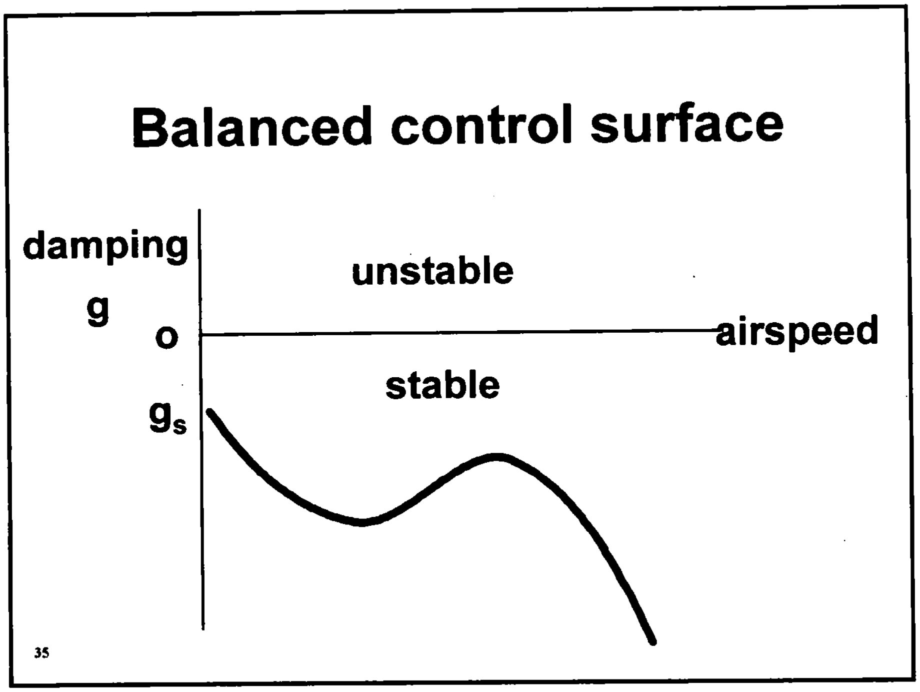
$m_\beta a$
34


Balanced control surface
damping
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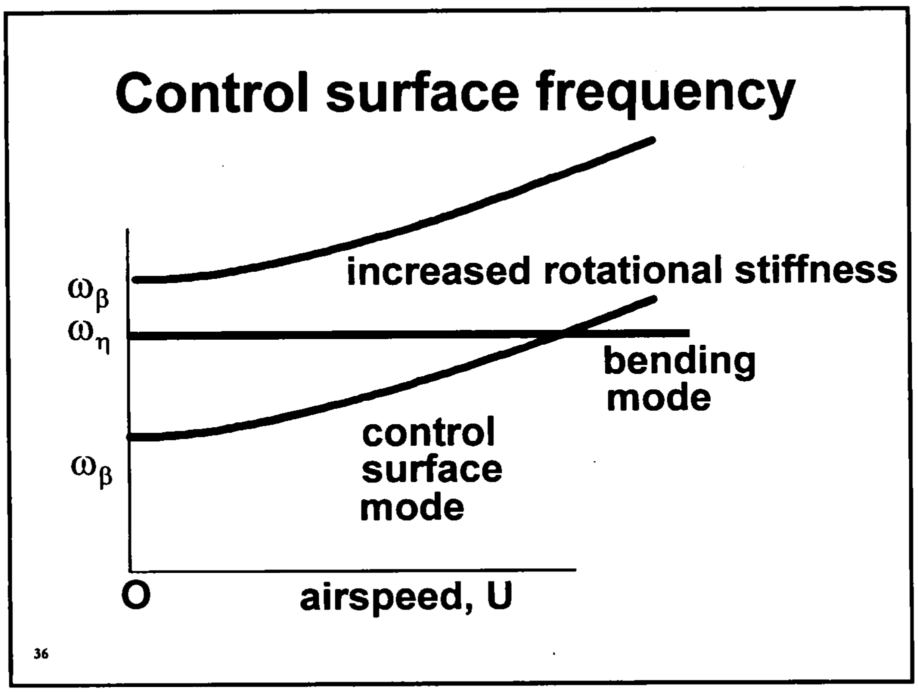
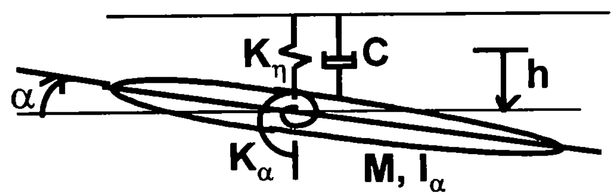
g_s
unstable
airspeed
stable
35


Control surface frequency
ω_β
ω_η
ω_β
increased rotational stiffness
bending
mode
control
surface
mode
O
airspeed, U
36

Wing bending and torsion

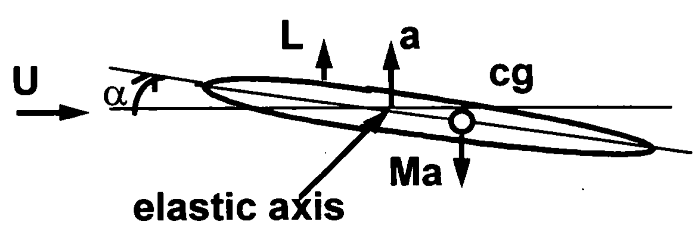


$\omega_h^2 = K_h/M$, **bending frequency**

$\omega_\alpha^2 = K_\alpha/I_\alpha$, **torsion frequency**

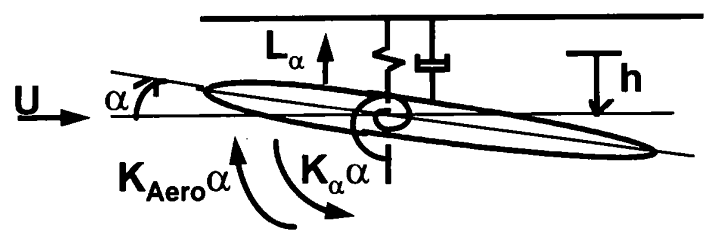
37

Wing bending and torsion



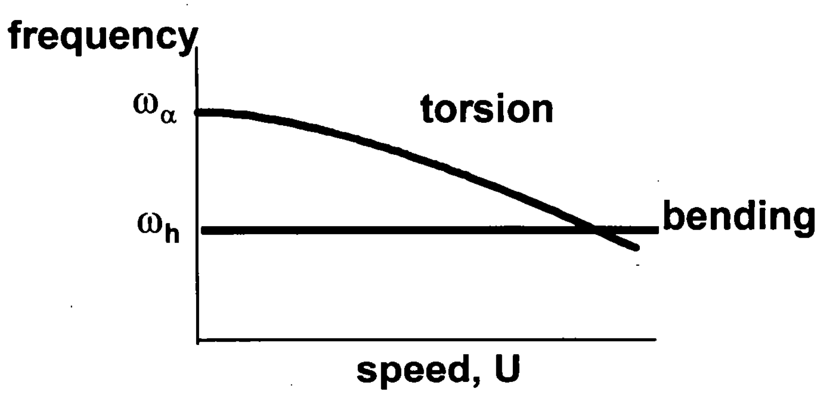
38

Aerodynamic stiffness

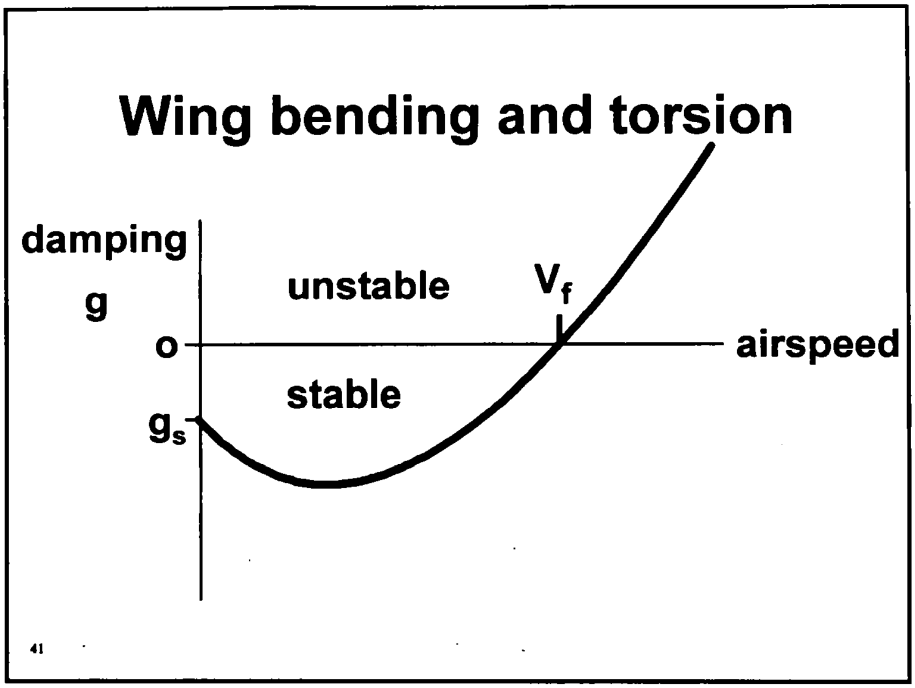


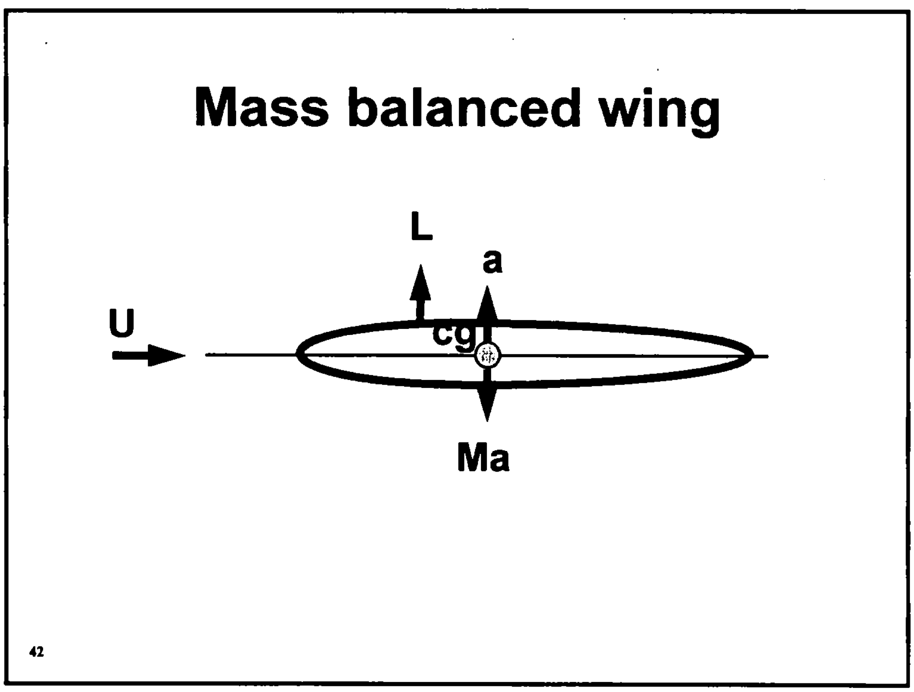
39

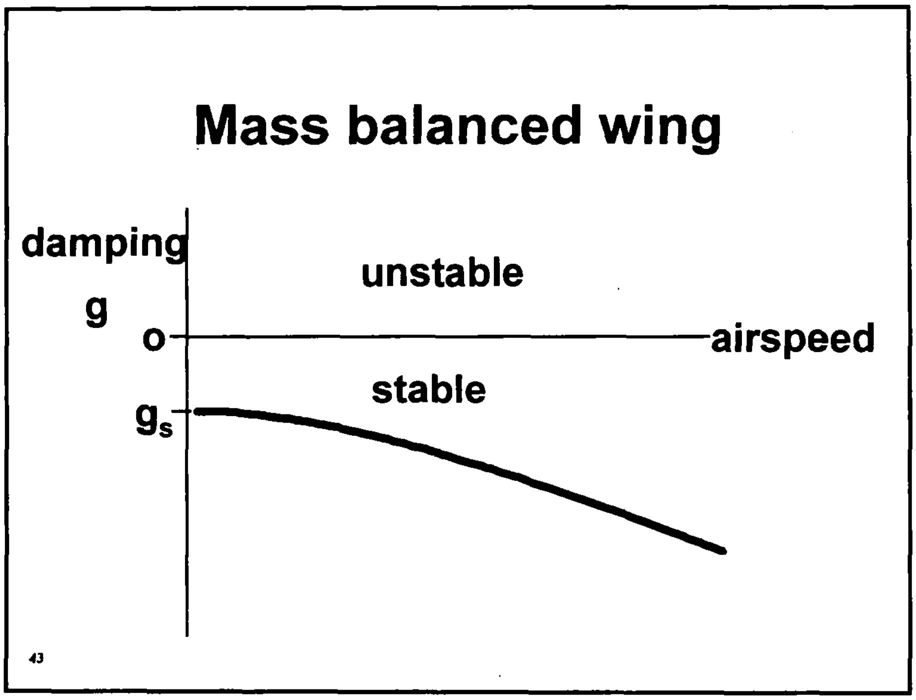
Structural mode frequency versus airspeed

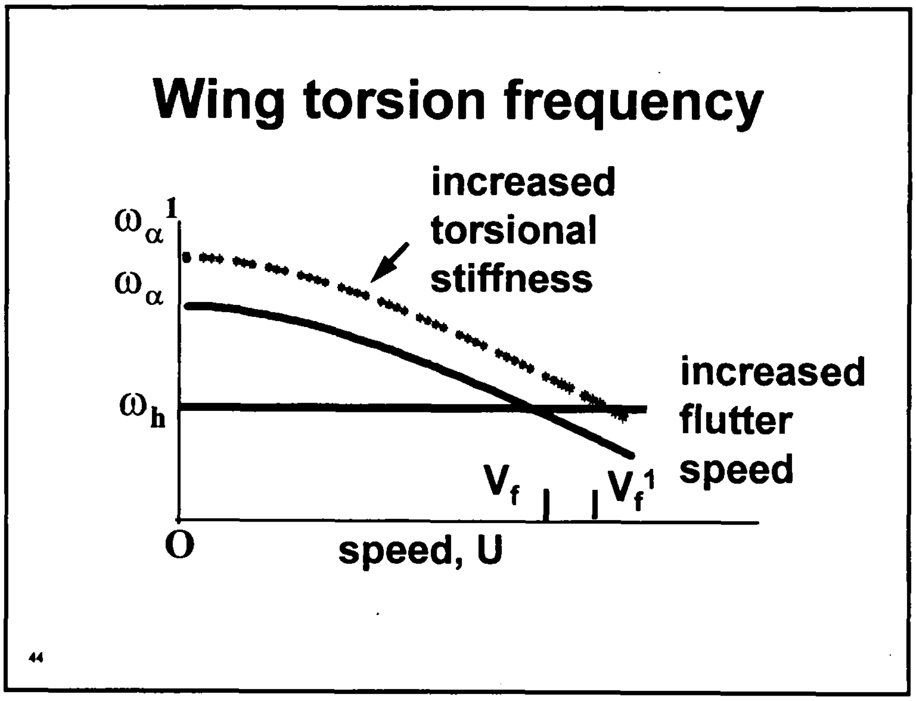


40

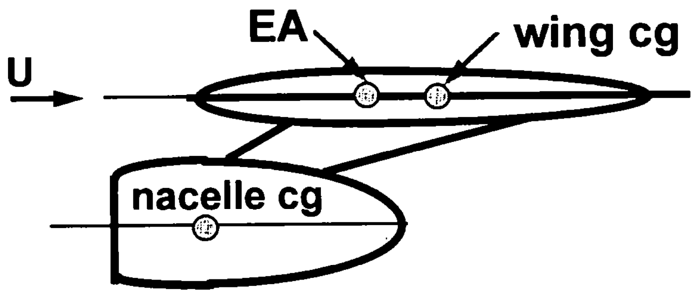

Wing bending and torsion
damping
g
unstable
V_f
o
airspeed
stable
g_s
41


Mass balanced wing
L
a
U
cg
Ma
42


Mass balanced wing
damping
g
o
airspeed
unstable
stable
g_s
43


Wing torsion frequency
ω_α^1
ω_α
ω_h
increased
torsional
stiffness
increased
flutter
speed
V_f
V_f^1
O
speed, U
44

Wing mounted engine



reduced torsion frequency - unfavorable
cg moved forward - favorable

45

Mass matrix

$$\begin{array}{l} \left[\begin{array}{cccc} W & S_\alpha & S_\beta & S_\delta \\ S_\alpha & I_\alpha & P_{\alpha\beta} & P_{\alpha\delta} \\ S_\beta & P_{\alpha\beta} & I_\beta & P_{\beta\delta} \\ S_\delta & P_{\alpha\delta} & P_{\beta\delta} & I_\delta \end{array}\right] \end{array} \begin{array}{l} \text{bending} \\ \text{torsion} \\ \text{control surface} \\ \text{tab} \end{array}$$

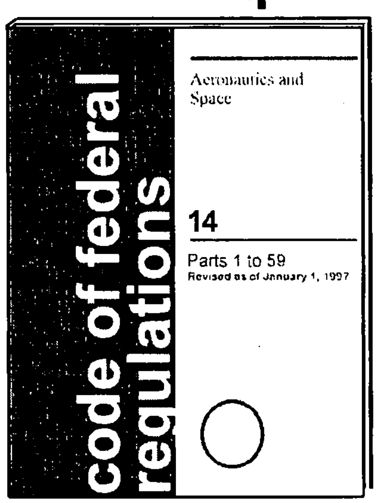
46

Session summary

- A control surface mechanism
- A main surface mechanism
- Other mechanisms involving main and control surfaces

47

Aeroelastic Stability Requirements



Part 25
Transport Airplanes

48

Session overview

- Principle references
- Instability phenomena
- Means of compliance
- Flutter clearance envelopes
  - Normal envelope and normal conditions
  - Failure envelope and failure conditions
- Mass balance criteria
- Flight flutter test requirement

49

Principle references

- FAR 25.629 "Aeroelastic stability requirements"
- Advisory Circular AC25.629-1 "Flutter Substantiation of Transport Category Airplanes"
- Military Specification, Mil-A-8870

50

Instability phenomena

- Flutter
- Divergence
- Control Reversal
- Loss of stability and control due to structural deformation
- Whirl flutter

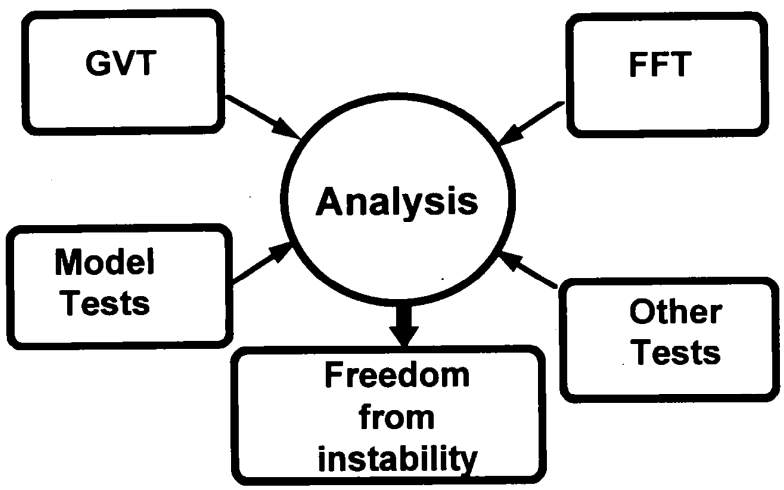
51

Means of compliance

- Aeroelastic analysis,
- Wind tunnel tests,
- Ground vibration tests,
- Flight flutter tests, or
- Any other tests found necessary by the administrator.

52

Compliance philosophy



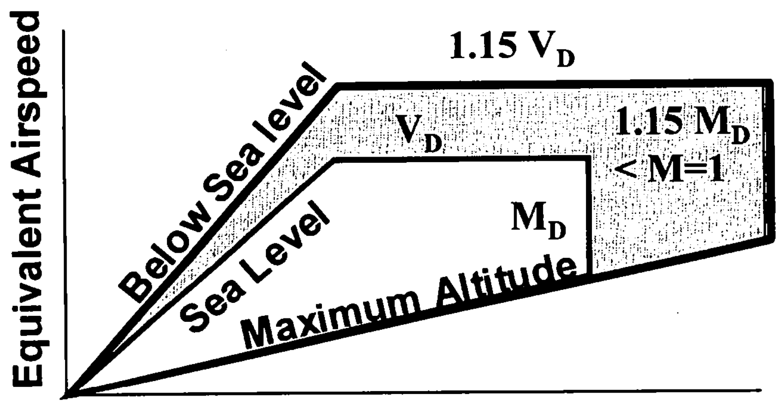
53

Stability envelopes

- Envelope for normal configurations and conditions.
- Envelope for failures, malfunctions and adverse conditions.

54

Normal envelope



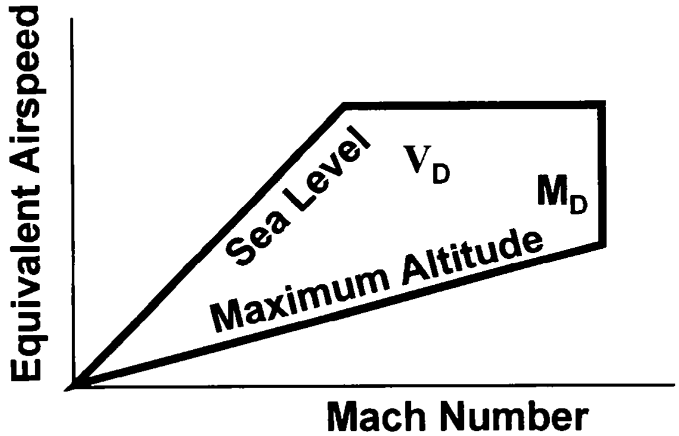
55

Normal conditions

- Fuel and payload capacities and distributions.
- For airplanes approved for icing: ice masses under normal flight in icing conditions.
- Pressurized and unpressurized.
- Any other configuration or condition approved for operation. (MMEL)

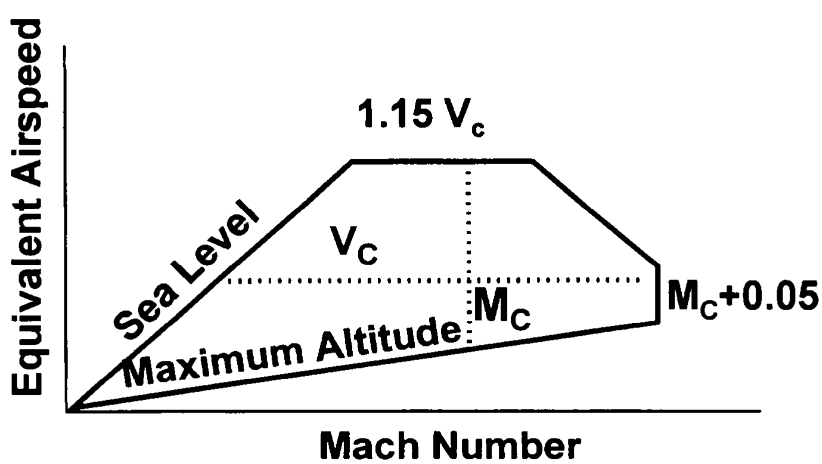
56

Failure envelope

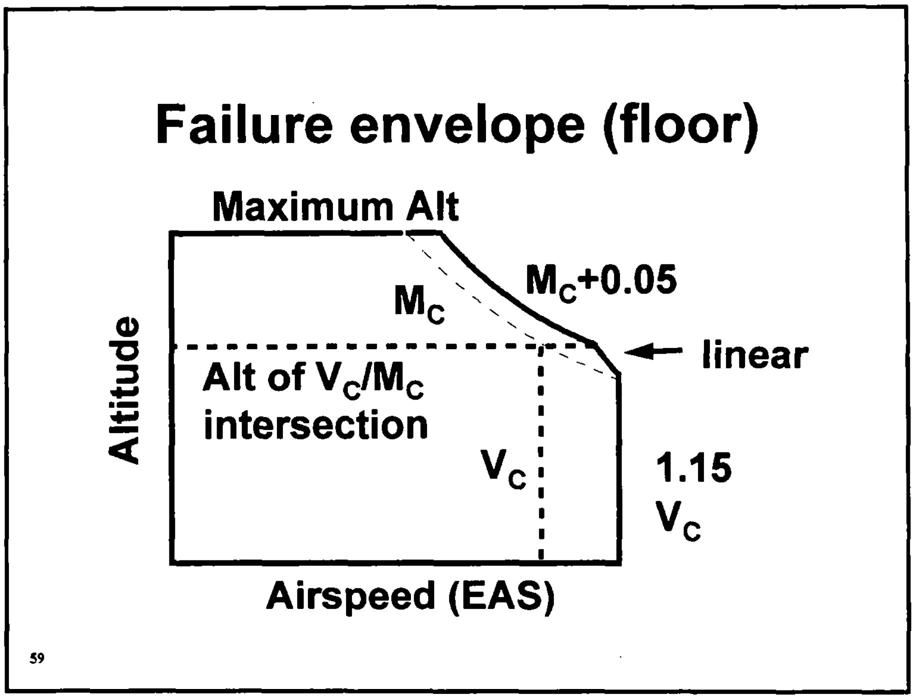


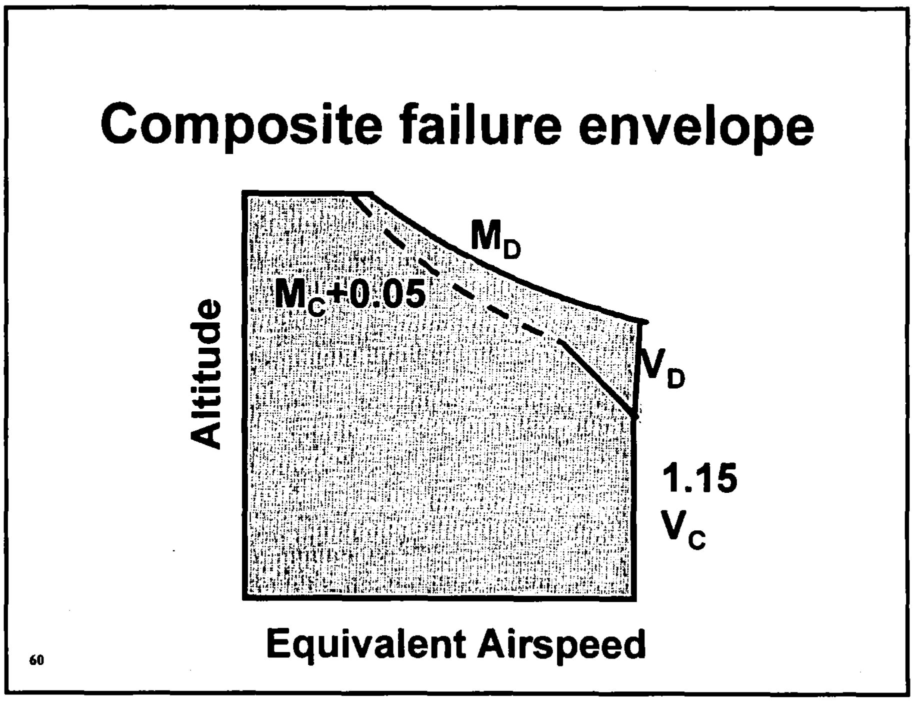
57

Failure envelope (floor)



58


Failure envelope (floor)
Maximum Alt
M_C
M_C+0.05
linear
Altitude
Alt of V_C/M_C intersection
V_C
1.15 V_C
Airspeed (EAS)
59


Composite failure envelope
M_D
M_C+0.05
Altitude
V_D
1.15 V_C
Equivalent Airspeed
60

Failure conditions

- Damage or failure conditions considered under 25.671, 25.672 or 25.1309.
  - Hinge failures, tab controls, actuator failures and combinations of control system failures.
- Single failures of independent flutter damper systems.
- Damage tolerance, discrete source, and bird strikes.

61

Failure conditions

- Single failures in supports of large mass items (engines, external fuel tanks, etc.).
- Single failures of supports of large rotating masses (propellers and turbofans).
- Mismanagement of fuel (and zero fuel).
- Inadvertent encounters with icing.
- Any other combination of failures not shown to be extremely improbable.

62

Concentrated mass balance

- Rigidity: 2 times the frequency of the mode likely to flutter (Mil-A-8870).
- Limit load factors (per AC 25.629-1):
  - 100g normal to the plane of the surface
  - 30g parallel to the hinge line
  - 30g in the plane of the surface perpendicular to the hinge line.
- Adequate for repair, re-painting, and the accumulation of ice and water.

63

Flight flutter tests

- Flight flutter tests to V_{DF} mandatory for all new transports (Amendment 25-77).
- Flight flutter tests to V_{DF} mandatory for changes that have a significant effect on aeroelastic modes (Amendment 25-77).
- Prior to Amendment 25-77 flight flutter tests were mandatory if the Mach number exceeded 0.8.

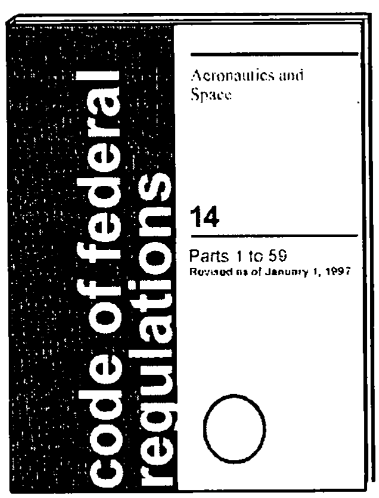
64

Session summary

- Principle references
- Instability phenomena
- Means of compliance
- Flutter clearance envelopes
  - Normal envelope and normal conditions
  - Failure envelope and failure conditions
- Mass balance criteria
- Flight flutter test requirement

65

Aeroelastic Stability Requirements



Part 23

Small Airplanes

66

Session overview

- Principle references
- What is covered by the rule
- Means of compliance
- Simplified criteria

67

Principle references

- FAR 23.629 "Flutter"
- FAR 23.659 "Mass balance"
- Advisory Circular 23.629-1A "Means of compliance with section 23.629, "Flutter"
- FAA Report 45 "Simplified Flutter Prevention Criteria"
- NACA Technical Report 685

68

Session overview

- Main references
- What is covered by the rule
- Means of compliance
- Simplified criteria

69

Categories of airplanes

- General small airplanes
  - Less than 260 knots and less than Mach 0.5.
  - Fixed stabilizers and no "T" or boom tails.
  - No unusual mass distributions.
- Special small airplanes
  - Airplanes not meeting the "General" definition.

70

Small airplane instabilities

- Flutter
- Divergence
- Control Reversal
- Whirl flutter (turbopropeller airplanes)

71

Substantiation envelope

- Must be free from instability within the design V-n envelope at speeds up to $1.2V_D$ if shown by analysis.
- If other methods are used, then the speed depends on the method.
- Adequate tolerances must be established for speed, damping, mass balance, and control system stiffness throughout the envelope.

72

Fail-safe requirements

- For "General" airplanes: single failures in tab systems.
- For "Special" airplanes: single failures in primary flight control systems, flutter dampers, or tab systems.
- For any airplane electing the fail-safe or damage tolerance approach: Freedom from flutter after the failure condition.

73

Session overview

- Main references
- What is covered by the rule
- Means of compliance
- Simplified criteria

74

Means of compliance

- Rational analysis
- Analysis and flight tests
- Ground vibration tests
- Simplified Criteria (Report 45)

75

2D analyses

- Two dimensional analysis is sometimes acceptable for small conventional airplanes with large aspect ratio. Ref - AC 23.629-1A, Appendix 2.
- NACA Report 685 contains a very useful collection of parametric charts that are based on 2-D flutter solutions.

76

3D analyses

- Current methods are full airplane 3D modal analyses.
- The traditional approach described in AC 23.629-1A, Appendix 2, will be described in more detail later.

77

Whirlmode analysis

- Whirlmode substantiation for turbopropeller airplanes (both single and multiple engines).
- Must include stiffness and damping variations (deteriorated or failed engine mounts).
- Appendix 2 of AC 23.629-1A contains a detailed explanation of the analytical method for whirlmode analysis.

78

Analysis plus flight tests

- Although § 23.629 seems to allow flight tests alone as substantiation, this is not normally practical.
- Critical configurations and critical flight conditions must be established by analysis before flight testing.
- Special category airplanes require fail safe substantiation which is difficult to do by flight.

79

Ground vibration tests

- Part 23.629 <u>requires</u> that the natural frequencies be determined by tests, irrespective of the method of substantiation.
- <u>Necessary</u> for use in simplified criteria.
- <u>Necessary</u> for validation of analyses.
- In some cases, <u>may help</u> determine critical configurations for flight testing.

80

Session overview

- Main references
- What is covered by the rule
- Means of compliance
- Simplified criteria

81

Report 45 criteria

- Wing torsional stiffness
- Aileron balance and free play
- Elevator & rudder mass balance
- Tab balance, free play, and rigidity
- Balance weight attachments - stiffness and strength

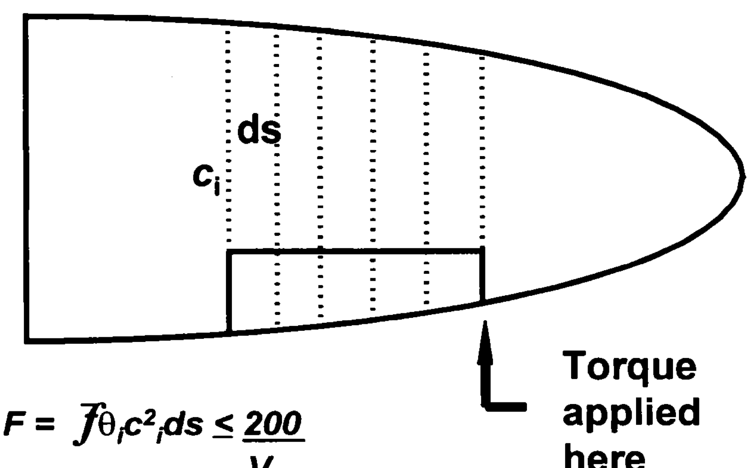
82

Report 45 limitations

- Simplified criteria is limited to use only with airplanes meeting the "General" definition.
- The wing and aileron criteria of Report 45 are more restricted.
  - No large mass distributions on the wing.

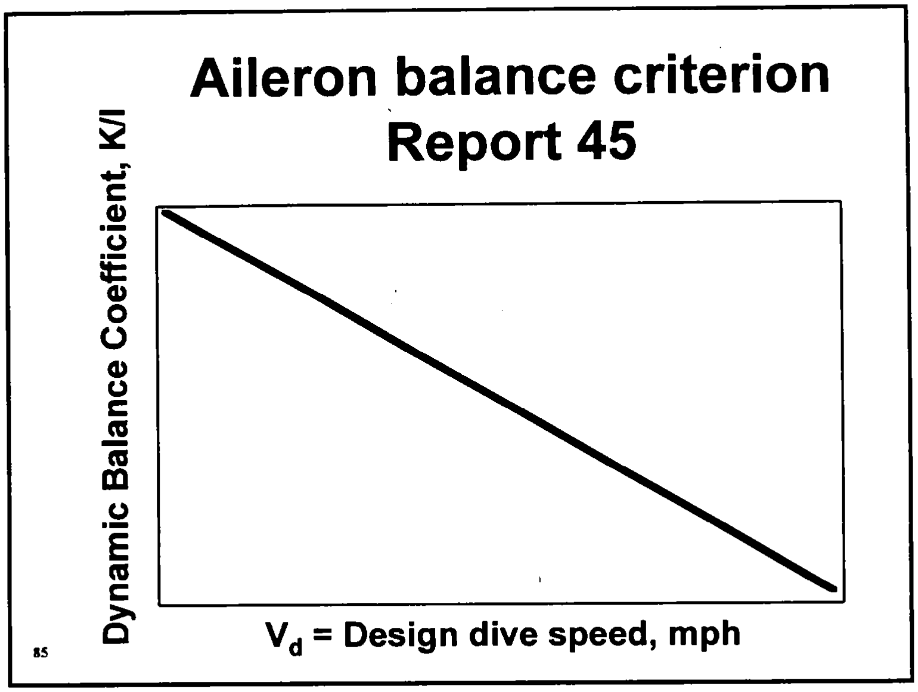
83

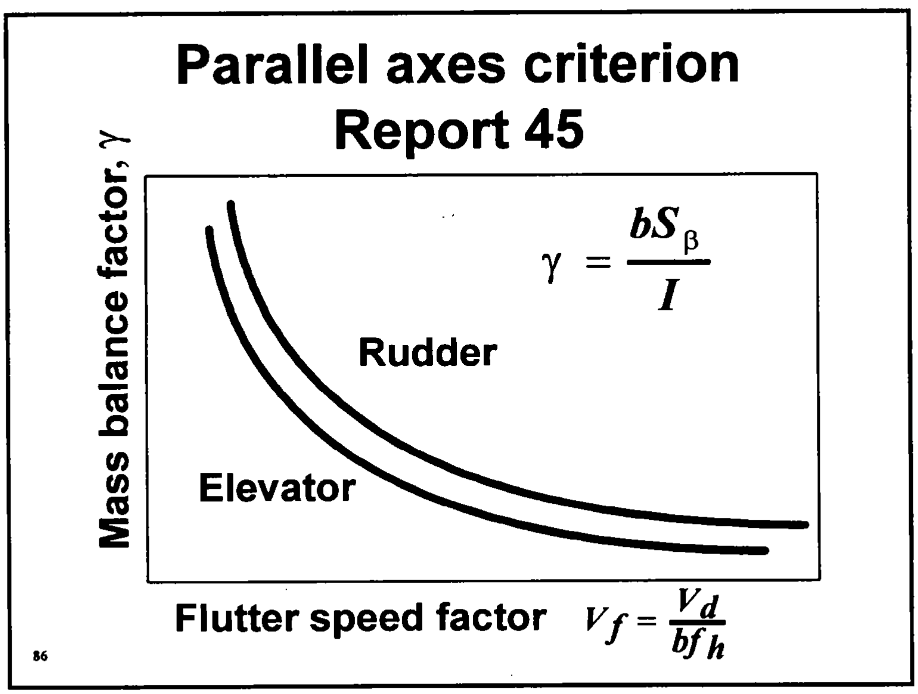
Wing torsional stiffness Report 45



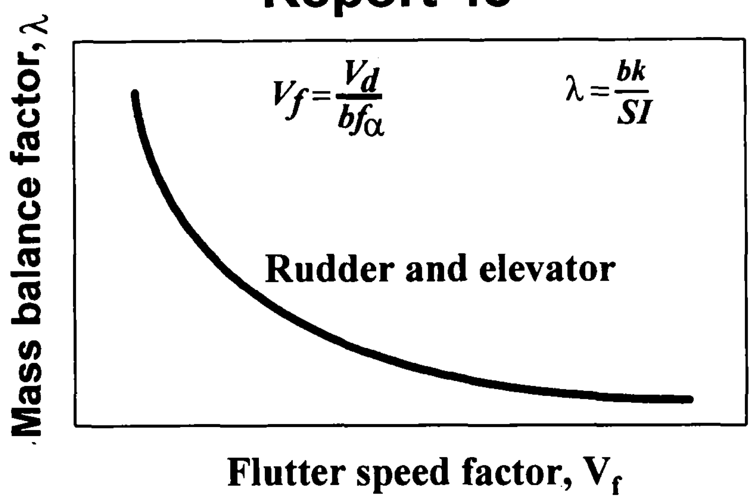
$$F = \int \theta_i c_i^2 ds \leq \frac{200}{V_d}$$

84


Aileron balance criterion
Report 45
Dynamic Balance Coefficient, K/I
V_d = Design dive speed, mph
85


Parallel axes criterion
Report 45
Mass balance factor, γ
$\gamma = \frac{bS_\beta}{I}$
Rudder
Elevator
Flutter speed factor $V_f = \frac{V_d}{bf_h}$
86

Perpendicular axes criterion
Report 45



87

Irreversible tab criteria
Report 45

- No appreciable deflection by means of a moment applied directly to the tab when the control surface is held fixed.
- Free-play 2.5 percent of the tab chord aft of the hinge line. (Note: AC 23.629-1A is much more restrictive.)
- Tab minimum rotational or torsional frequency are provided by a formula.

88

Balance weight design criteria per Report 45

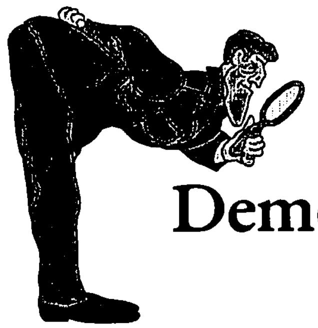
- Attachment frequency > 1.5 times the highest frequency with which the control surface could couple in flutter.
- Limit load factors; 24g normal to the surface and 12g in the other two directions. (Same as Part 23 and AC 23.629-1A.)

89

Session summary

- Principle references
- What is covered by the rule
- Means of compliance
- Simplified criteria

90



Demonstration of Compliance

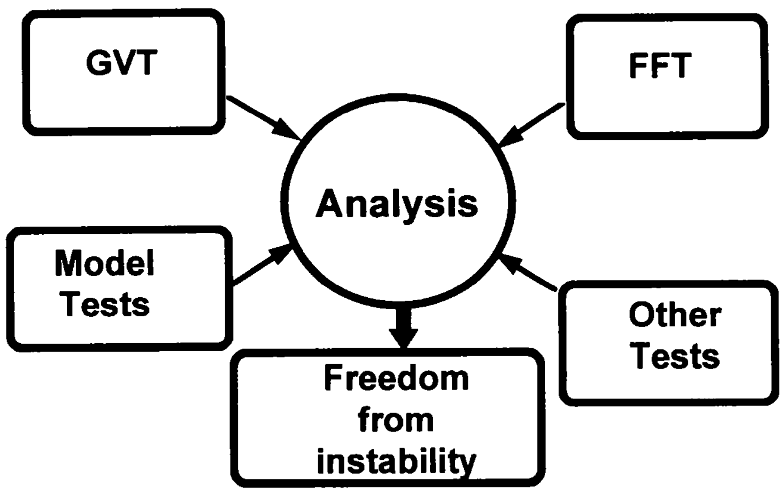
91

Means of compliance

- Analyses
- Ground vibration tests (GVT)
- Wind tunnel model tests
- Flight flutter tests (FFT)
- Any other tests found necessary

92

Compliance philosophy



93

Flutter certification plan

- Description of the airplane project.
- Means of showing compliance.
- Schedule of accomplishment.
- Data approval and test witnessing responsibilities.

94

FLUTTER ANALYSIS
&
ANALYTICAL INVESTIGATIONS

95

Flutter analyses overview

- Flutter stability equation
- Solving
- Interpreting results
- Analytical investigations
- Reporting the results

96

The mathematical model

$$[M]\{\ddot{x}\} + [K]\{x\} = \{F\}$$

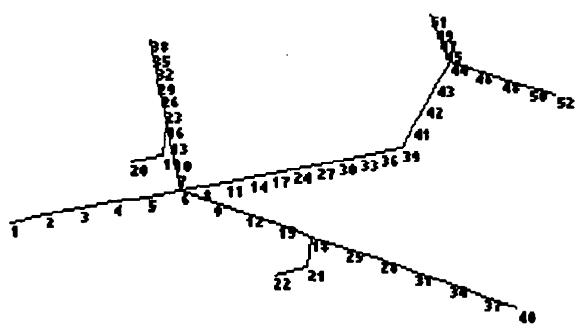
Assume that the vibration is constant amplitude and sinusoidal.

$$\{\ddot{x}\} = -\omega^2\{x\}$$

$$-\omega^2[M]\{x\} + [K]\{x\} = \{F\}$$

97

Structural dynamic model



Lumped mass beam model ("stick model") is commonly used, even for complex airplanes.

98

Selecting structural modes

First solve the structural model without any aerodynamic forces.

$$-\omega^2 [M] \{x\} + [K] \{x\} = \{0\}$$

Select a set of these frequencies and mode shapes (usually the first 20-30 modes or up to 35-40 Hz).

99

Superposition of modes

The flutter modes in air (at an airspeed) are considered to consist of a linear superposition of the selected structural modes.

$$\{x\} = q_1\{\phi_1\} + q_2\{\phi_2\} + \ldots q_n\{\phi_n\}$$

$$\{x\} = [\Phi]\{q\}$$

100

Generalized coordinates

The new unknown variables, "q", which are the proportions of each structural mode contained in the flutter mode, are called the <u>generalized coordinates</u>.

$$-\omega^2 [M] [\Phi] \{q\} + [K] [\Phi] \{q\} = \{F\}$$

101

The generalized equation

Multiply through on the left by the transpose of the matrix [F]

$$-\omega^2 [\Phi]^T [M] [\Phi] \{q\} + [\Phi]^T [K] [\Phi] \{q\} = [\Phi]^T [F]$$

$$[\phi]^T [M] [\phi] = \text{generalized mass} = \overline{M}$$

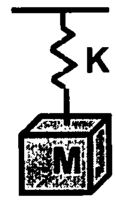
$$[\phi]^T [M] [\phi] = \text{generalized stiffness} = \overline{K}$$

$$-\omega^2 \overline{M} \{q\} + \overline{K} \{q\} = [\Phi]^T [F]$$

102

Structural damping

Structural damping is proportional to the spring force but 90 degrees out of phase.



$$M\ddot{x} + igKx + Kx = 0$$

$$M\ddot{x} + (1 + ig)Kx = 0$$

$M\ddot{x} + K_1x = 0$ where K_1 is complex

103

Handling damping

- Structural damping can be ignored for now and a <u>global structural damping</u> considered when plotting the results. (AC23.629-1A or Method 1 of AC25.629-1) or.....
- The structural damping measured for each mode in the ground vibration test can be included directly in the generalized stiffness matrix. (Method 2, AC25.629-1).
- In the later case, the stiffness matrix is complex.

104

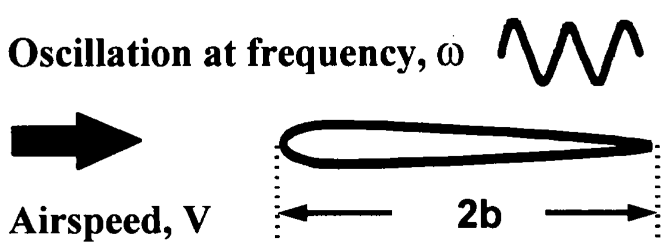
Handling damping

- Structural damping can be ignored for now and a global structural damping considered when plotting the results. (AC23.629-1A or Method 1 of AC25.629-1) or.....
- The structural damping measured for each mode in the ground vibration test can be included directly in the generalized stiffness matrix. (Method 2, AC25.629-1).
- In the later case the stiffness matrix is complex.

$$-\omega^2 \overline{M}\{q\} + \overline{K}\{q\} = [\Phi]^T [F]$$

105

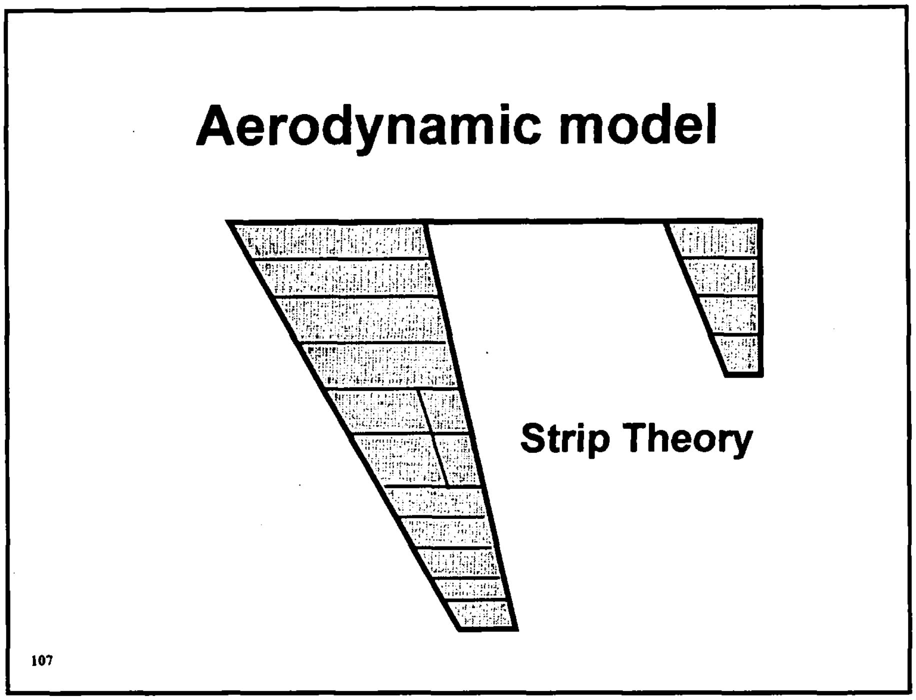
Unsteady aerodynamics

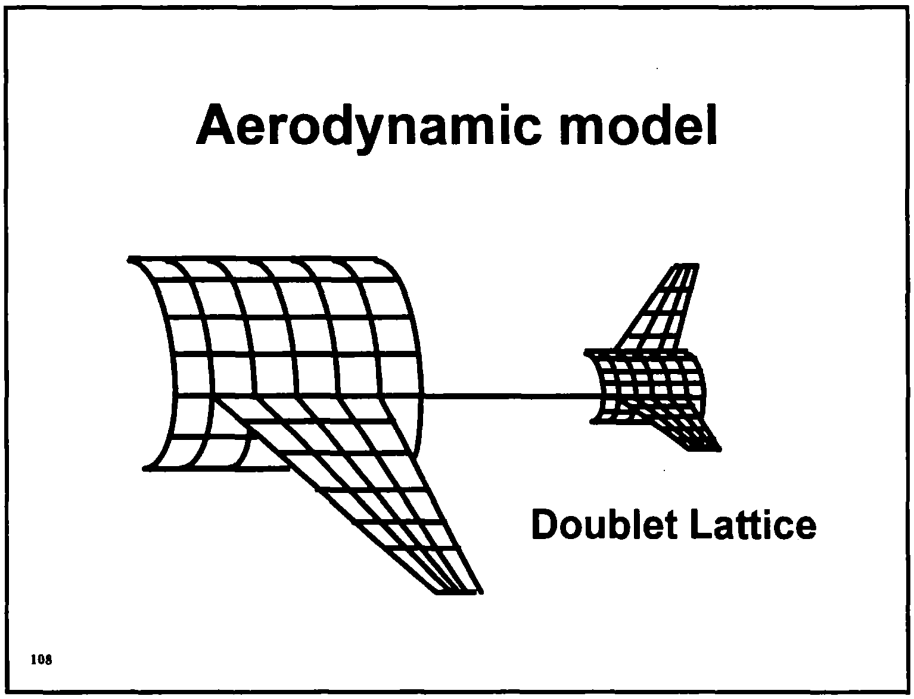


Aerodynamic force coefficients depend on the reduced frequency, k

$$k = \frac{b\,\omega}{V}$$

106


Aerodynamic model
Strip Theory
107


Aerodynamic model
Doublet Lattice
108

Aerodynamic forces

AIC = Aerodynamic Influence Coefficients

$$F = -\omega^2 Q[AIC]\{x\} \quad \text{or} \quad -\omega^2 Q[AIC][\phi]\{q\}$$

so:

$$[\phi]^T F = -\omega^2 Q\, [\phi]^T\, [AIC]\, [\phi]\{q\}$$

$$[\phi]^T [AIC][\phi] = \bar{A}$$

$\bar{A}$ **= generalized aerodynamic matrix**

109

Flutter stability equation

$$-\omega^2 \bar{M}\{q\} + \bar{K}\{q\} = -\omega^2 Q\bar{A}\{q\}$$

$$[-\omega^2 \bar{M} + \omega^2 Q\bar{A} + \bar{K}]\{q\} = 0$$

$$[\bar{K}^{-1}\bar{M} - Q\bar{K}^{-1}\bar{A} - \frac{1}{\omega^2} I]\{q\} = 0$$

110

Flutter analyses overview

- Flutter stability equation
- Solving
- Interpreting results
- Analytical investigations
- Reporting the results

111

Solution difficulties

- Equation is inconsistent since it is only solvable for neutral stability, yet it has damping (aero and maybe structural).
- AIC depends on reduced frequency, k, and k depends on the flutter frequency which is unknown.

112

Artificial damping

Add some extra "artificial" structural damping. Artificial damping forces are:

$ig\overline{K}\{q\}$

The main idea is that we can solve for the "artificial" damping that results in neutral stability, then the total system damping must be the negative of this result.

$$-\omega^2\overline{M}\{q\}+(1+ig)\overline{K}\{q\}=-\omega^2 Q\overline{A}\{q\}$$

113

Final flutter equation

$$\left[\overline{K}^{-1}\overline{M}-Q\overline{K}^{-1}\overline{A}-\frac{(1+ig)}{\omega^2}I\right]\{q\}=\{0\}$$

This is the standard eigenvalue form:

$[D-\lambda I]\{q\}=\{0\}$

where:

$\lambda=(1+ig)/\omega^2$

114

Solving the flutter equation

- For the desired altitude, choose a value of k.
- Solve for λ's using an extraction algorithm.
- From λ (complex number) get g (artificial damping) and ω for each mode.
- Then from the assumed $k=b\omega/V$, find V
- Plot ω and g against V for each mode.
- Choose another k and repeat.

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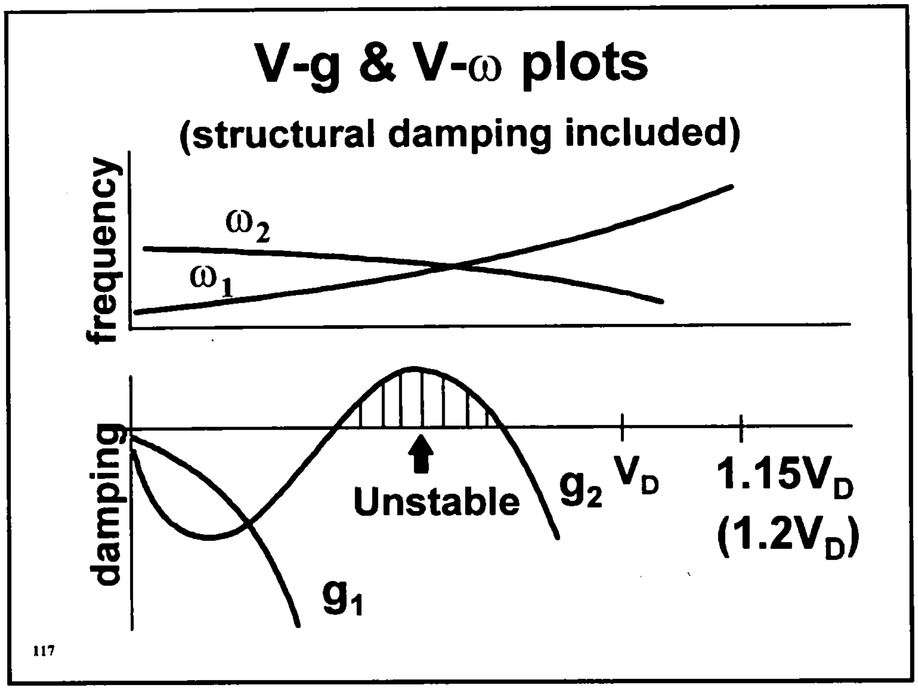
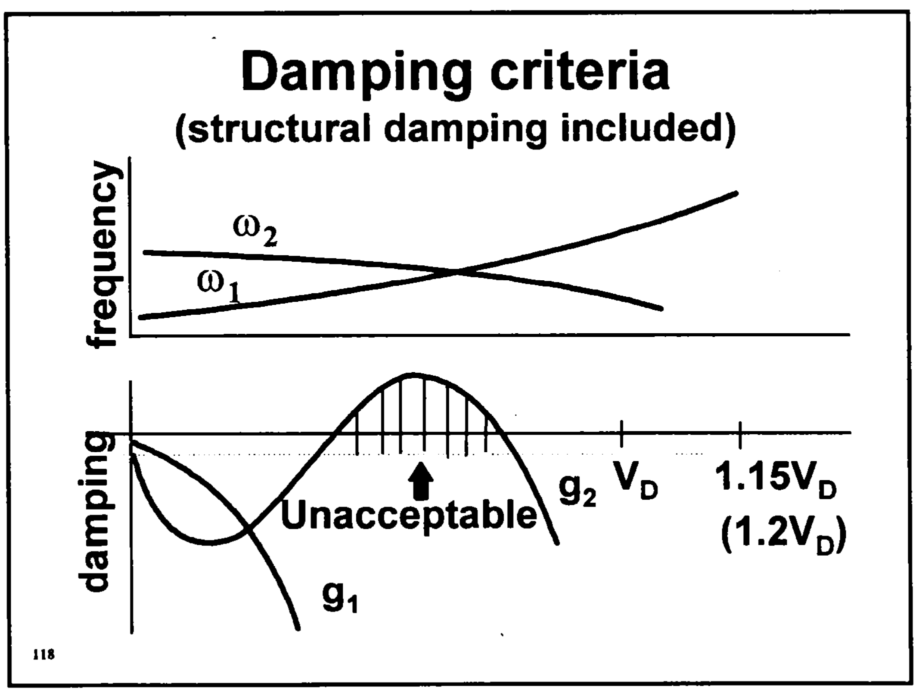
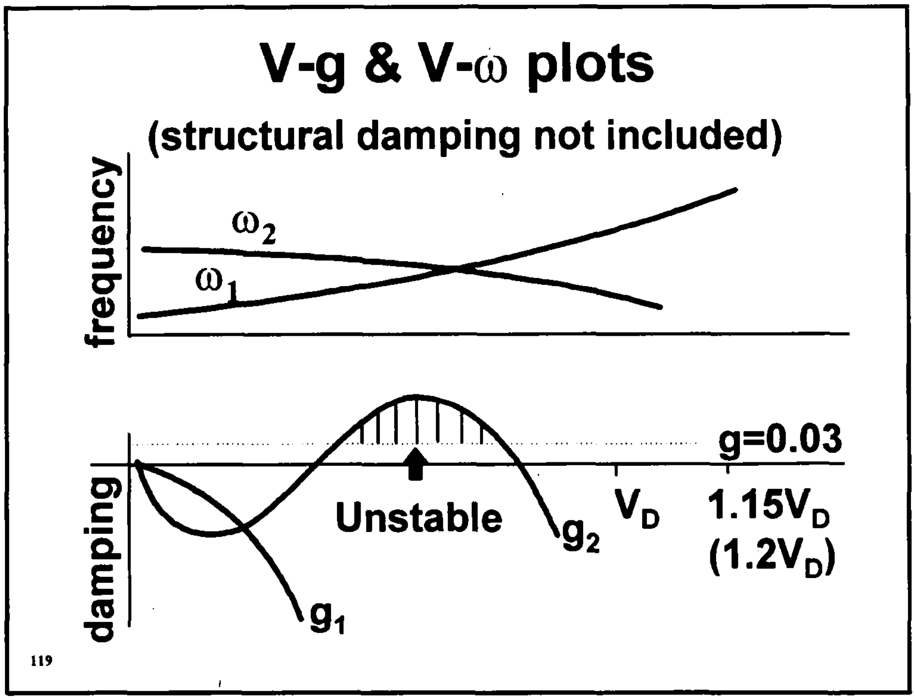
Flutter analyses overview

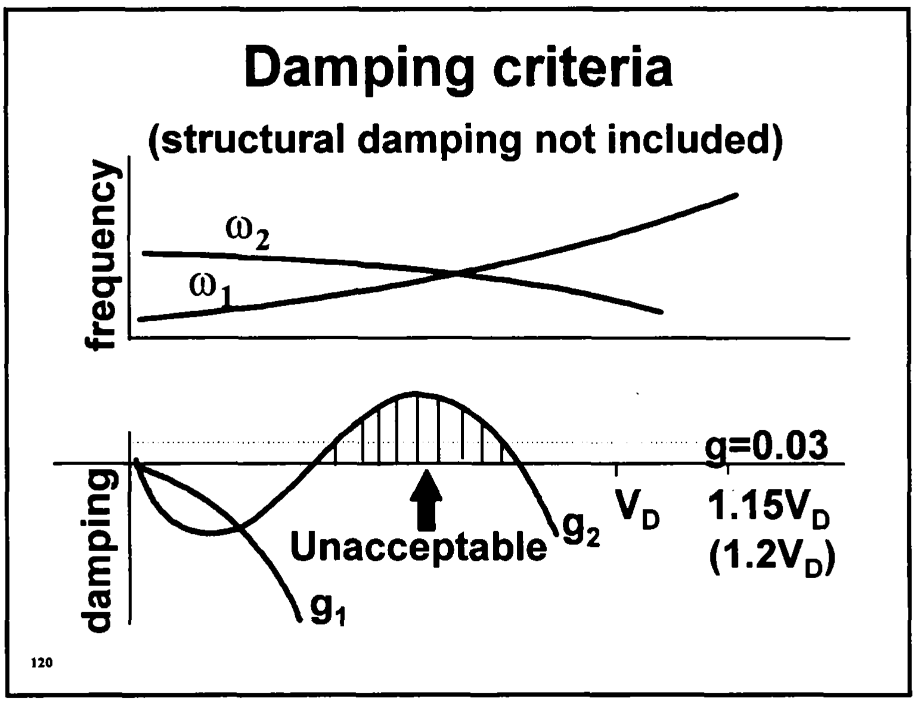
- Flutter stability equation
- Solving
- Interpreting results
- Analytical investigations
- Reporting the results

116


V-g & V-ω plots
(structural damping included)
frequency
ω2
ω1
damping
Unstable
g2
VD
1.15VD
(1.2VD)
g1
117


Damping criteria
(structural damping included)
frequency
ω2
ω1
damping
Unacceptable
g2
VD
1.15VD
(1.2VD)
g1
118


V-g & V-ω plots
(structural damping not included)
frequency
ω2
ω1
damping
g=0.03
Unstable
g2
VD
1.15VD
(1.2VD)
g1
119


Damping criteria
(structural damping not included)
frequency
ω2
ω1
damping
g=0.03
Unacceptable
g2
VD
1.15VD
(1.2VD)
g1
120

Flutter analyses overview

- Flutter stability equation
- Solving
- Interpreting results
- Analytical investigations
- Reporting the results

121

Analytical investigations

Flutter stability can be very sensitive to small changes is certain parameters.

Parametric investigations are necessary to understand the sensitivity of these parameters and ensure adequate margin for stability.

122

Analytical investigations

- Normal conditions
  - Conditions within the flutter clearance envelope
  - Parametric investigations of parameters about their nominal values.
- Failure conditions
  - Specific failure configurations
  - Parametric investigations to envelope failure conditions.

123

Parametric investigations

- Fuselage rigidity (pressurized and unpressurized).
- Wing & fuselage rigidity near limit load.
- Nacelle frequency and aerodynamic force variations.
- Stabilizer pitch stiffness variations.

124

Parametric investigations

- Control surface inertial properties (static balance, dynamic balance) to establish the service limitations.
- Control surface aerodynamic derivatives (normal practice is 75% to 125% nominal).
- Automatic flight controls variations
  - Double gains (+6 decibels)
  - Phase variation of +/- 60 degrees.

125

Parametric investigations

- Control surface rotation stiffness variations
  - For powered systems, hydraulic failures, actuator deterioration, disconnects, hinge failures, etc.
  - For conventional mechanical controls, all frequencies from 0 up to 1.5 times the fixed stick frequency should be investigated as normal conditions.

126

Flutter analyses overview

- Flutter stability equation
- Solving
- Interpreting results
- Analytical investigations
- Reporting the results

127

Analytical investigations report

- Airplane general arrangement
- Flutter clearance envelopes
- Weights, fuel and payload distributions
- Discussion of aerodynamic (math) model
- Discussion of structural (math) model
- Validation of integrated model

128

Analytical investigations report

- Discussion of important modes and frequencies
- V-g & V-ω plots for nominal configurations
- Parametric plots for important parameter investigations
- V-g & V-ω plots for significant failure conditions.

129

Flutter analyses summary

- Flutter stability equation
- Solving
- Interpreting results
- Analytical investigations
- Reporting the results

130

GROUND VIBRATION TESTS

Ground vibration tests

- Objectives
- Test plan and conformity
- Test article and support system
- Test results
- Other ground tests

132

Test objectives

- Define vibration mode frequencies, mode shapes and damping of aircraft.
- Validate mathematical model.
- Use data directly in simplified flutter criteria.
- Evaluate modifications to a certified design.
- Study characteristics such as nonlinearity.

133

Ground vibration tests

- Objectives
- Test plan and conformity
- Test article and support system
- Test results
- Other ground tests

134

Test plan and conformity

- FAA approved test plan.
- ACO engineer should witness as much of test as possible.
- Test conducted under supervision of DER.
- Test article must be in conformity
  - Structurally complete
  - Weight and mass distribution, not details.
- Equipment and setup usually not conformed.

135

Ground vibration tests

- Objectives
- Test plan and conformity
- Test article and support system
- Test results
- Other ground tests

136

Test support system

- Rigid body frequencies on support system 1/2 or less of lowest elastic mode frequency.
- Common methods of support
  - Deflated tires with blocked struts
  - Suspend from springs, e.g. bungee cords
  - Soft support such as air bags.

137

Test article

- Airplane configuration according to FAA-approved test plan.
- Include all equipment of mass.
- Control surfaces
  - Faired to primary surface
  - Fixed or free
  - Power on.
- Investigate flaps down configuration.

138

Test equipment

- Electromagnetic exciter most common
  - Wide frequency range
  - Force applied through drive rod
  - Harmonic, transient or random force input
  - Force or amplitude feedback control
- Accelerometers used to measure amplitude
- Data system
  - Time history recorder
  - Frequency domain analysis

139

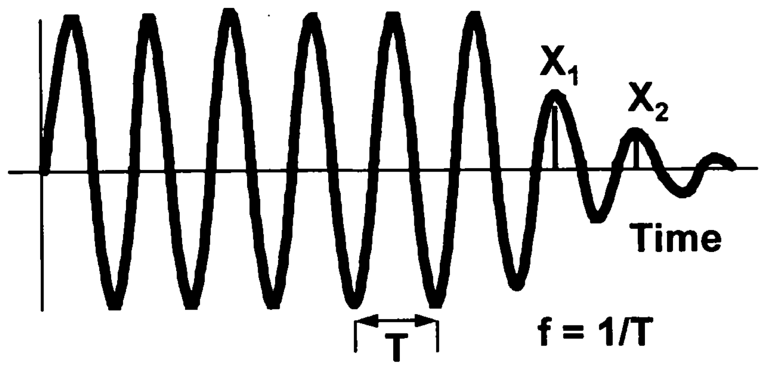
Test procedures

- Resonance dwell and damping decay
  - Hand shake
  - Sinusoidal exciting force with shaker
- Modes identified from frequency sweep
- Roving and/or distributed accelerometers map out mode shapes and node lines

140

Resonance dwell and decay

$$g=(1/\pi)\log(X_1/X_2)$$



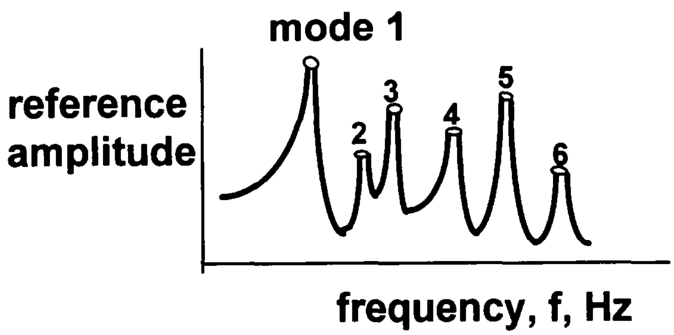
141

Test procedures

- Resonance dwell and damping decay
- Modes identified from frequency sweep
  - Force away from node line - at extremity
  - More than one shaker/position may be used
  - More than one reference acceleration may be used
- Roving and/or distributed accelerometers map out mode shapes and node lines

142

Vibration frequency sweep



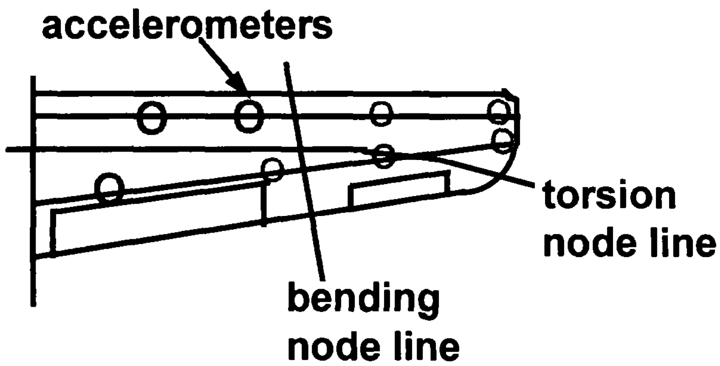
143

Test procedures

- Resonance dwell and damping decay
- Modes identified from frequency sweep
- **Roving and/or distributed accelerometers map out mode shapes and node lines**

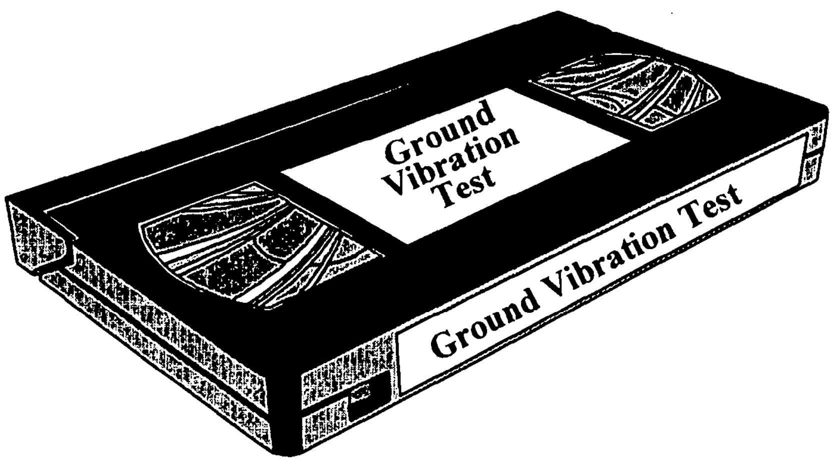
144

Wing vibration mode shapes



145

Ground vibration test video



146

Ground vibration tests

- Objectives
- Test plan and conformity
- Test article and support system
- Test results
- Other ground tests

147

Modes normally encountered

- Wing vertical and chordwise bending, torsion
- Fuselage torsion, stab antisymm bending
- Fuselage side bending, fin bending, torsion
- Fuselage vert bending, stab symm bending
- Stab pitch, yaw and torsion
- Nacelle, external store modes
- Control surface and system modes

148

Use of data to show compliance

- DER recommend approval
- Validation of vibration modes
- Directly with Report 45 criteria
- Directly in flutter analyses
- Demonstrate before and after modification (always accompanied with analyses)

149

Ground vibration tests

- Objectives
- Test plan and conformity
- Test article and support system
- Test results
- Other ground tests

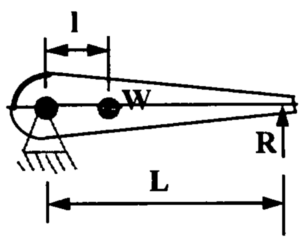
150

Other types of ground tests

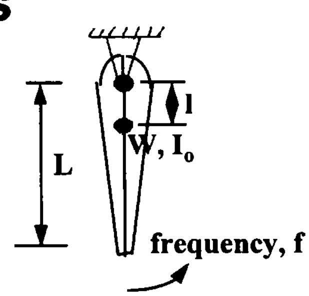
- Control surface and tab mass properties
- Control surface and tab freeplay
- Control system stiffness & damping test
- Stiffness test
- Other required by FAA

151

Control surface mass properties



CG: $l = (R/W)xL$

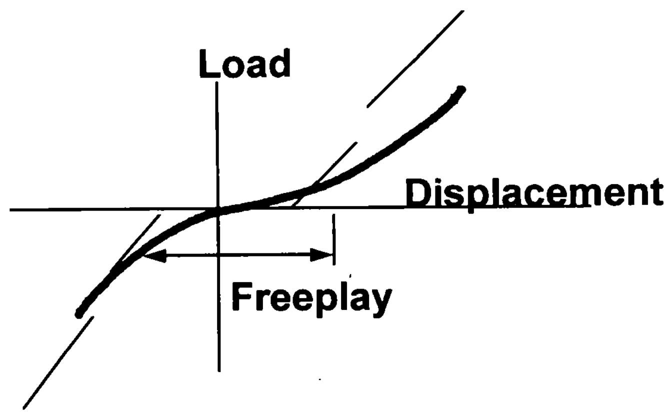


$I_o = WL^2[(g/4p^2f^2L)-1]$

Details given in Report 45

152

Control surface and tab freeplay



153

GVT Summary

- Objectives
- Test plan and conformity
- Test article and support system
- Test results
- Other ground tests

154

wind Tunnel Tests

155

Wind tunnel tests

- Purposes
- Dynamic similarity
- Instrumentation and testing techniques
- Tunnel investigations and parametric variations
- Flutter model video

156

Validation of flutter analyses

- Validate (or calibrate) analysis for a few configurations - compliance made by computer analysis.
- Confirm flutter speed boundary.
- Visual study of flutter modes - video.
- Compressibility effects.
- Damping trends with airspeed (flight test).

157

Support analyses in showing compliance

- Determine flutter margins
- Full span, asymmetric configurations such as failures and adverse conditions

158

Complex configurations & special effects

- Test configurations difficult to analyze, e.g. control surfaces, t-tails and whirl flutter
- Investigations, e.g. effect of angle of attack on flutter speed

159

Wind tunnel tests

- Purposes
- Dynamic similarity
- Instrumentation and testing techniques
- Tunnel investigations and parametric variations
- Flutter model video

160

Model scale factors

- Length (L_m/L_a)
  - Tunnel width / airplane wing span
- Velocity (V_m/V_a)
  - Tunnel speed / airplane design speed, or
  - $M_m/M_a = 1$ for high speed testing
- Density (ρ_m/ρ_a)
  - Wind tunnel / airplane altitude at critical speed and Mach No.

161

Dynamic similarity

- For similar aerodynamic loading, inertia, elastic, viscous and gravitational forces must act in same relationship in the tunnel...
- ...these quantities would have to be matched between airplane and model:
  - Mach number
  - Reynolds number
  - Froude number.

162

Wind tunnel tests

- Purpose
- Dynamic similarity
- Instrumentation and testing techniques
- Tunnel investigations and parametric variations
- Flutter model video

163

Instrumentation and testing techniques

- Model "flown" similar to flight flutter test
- Flutter speed approached slowly
- Model excited by various means
- Damping and frequency of various modes tracked using model instrumentation
- Flutter speeds are often reached, sometimes leading to catastrophic results

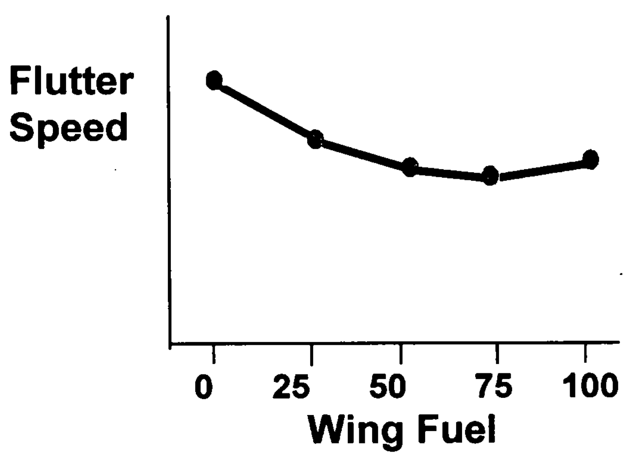
164

Wind tunnel tests

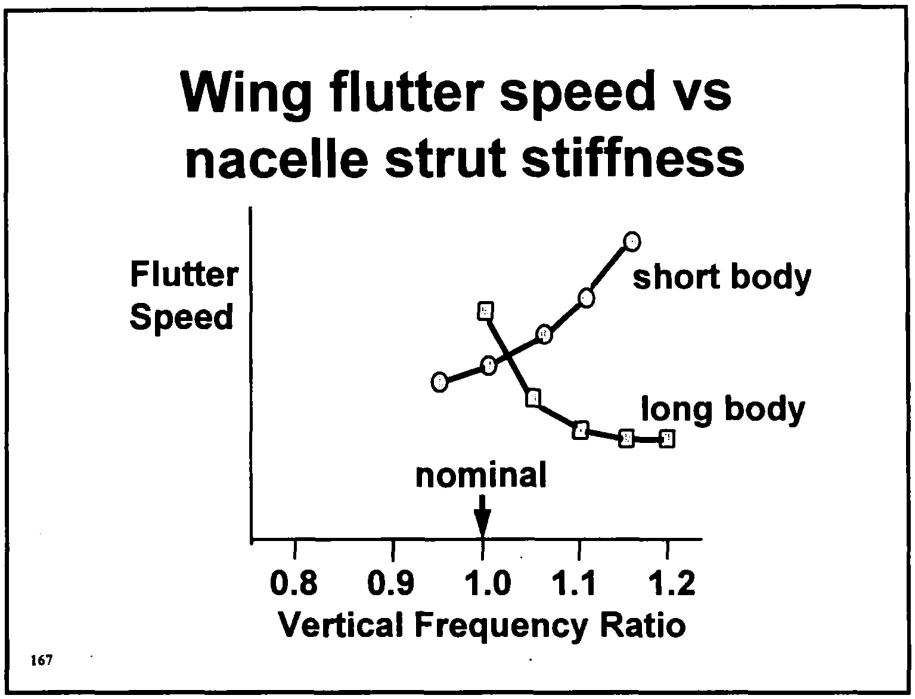
- Purpose
- Dynamic similarity
- Instrumentation and testing techniques
- Tunnel investigations and parametric variations
- Flutter model video

165

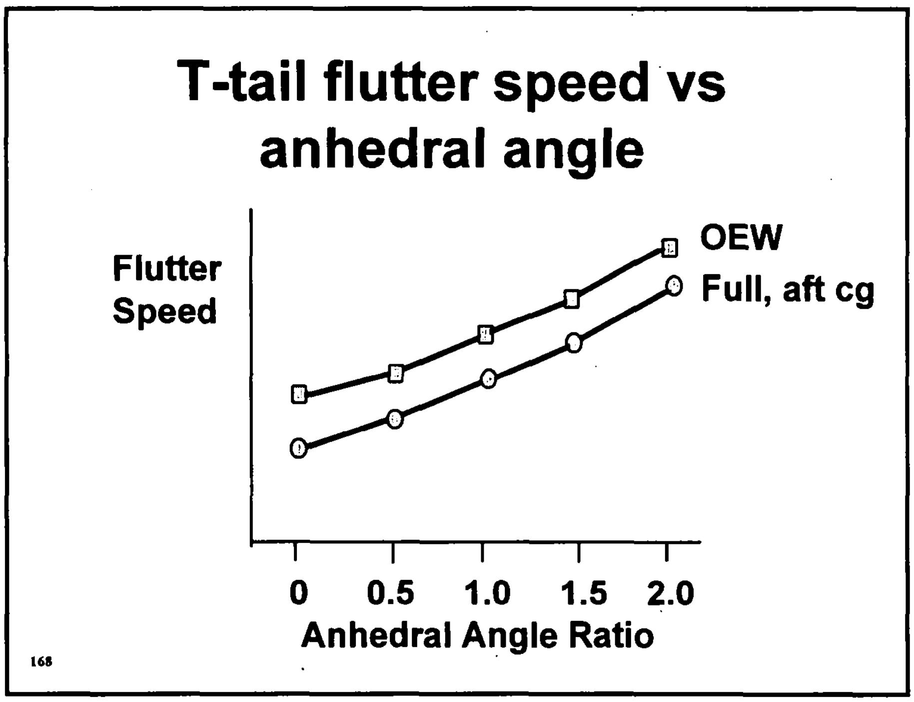
Wing flutter speed vs fuel



166



Wing flutter speed vs nacelle strut stiffness
Flutter Speed
short body
long body
nominal
0.8
0.9
1.0
1.1
1.2
Vertical Frequency Ratio
167



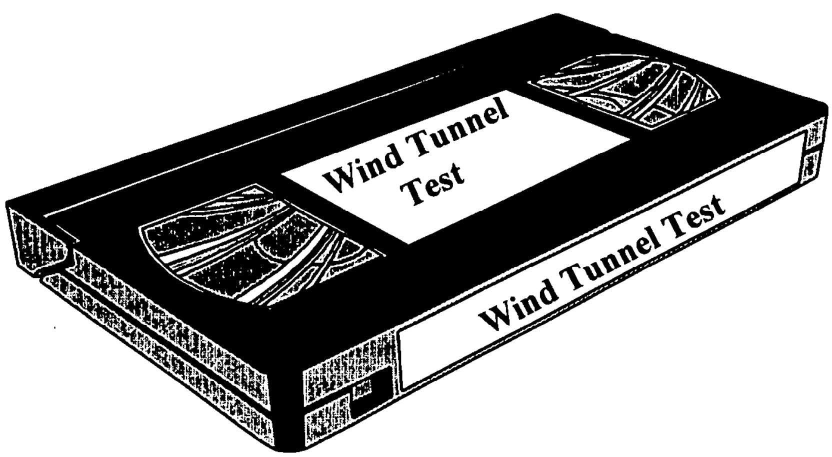
T-tail flutter speed vs anhedral angle
Flutter Speed
OEW
Full, aft cg
0
0.5
1.0
1.5
2.0
Anhedral Angle Ratio
168

Wind tunnel tests

- Purpose
- Dynamic similarity
- Instrumentation and testing techniques
- Tunnel investigations and parametric variations
- Flutter model video

169

Wind tunnel test video



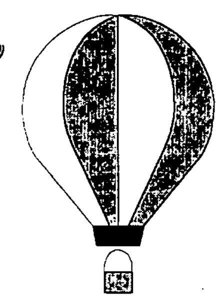
170

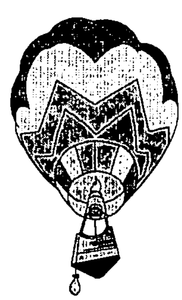
Wind tunnel tests summary

- Purposes
- Dynamic similarity
- Instrumentation and testing techniques
- Tunnel investigations and parametric variations
- Flutter model video

171

FLIGHT FLUTTER TESTS





172

Flight flutter tests

- Purpose
- Test Article (configurations and conformity)
- Instrumentation and testing techniques
- Flight investigations and test conditions
- How results are used for compliance

173

Flight flutter tests

- Purpose

174

Purpose

- Demonstrate airplane is free from flutter & vibration throughout V_{DF}/M_{DF} envelope
- Confirm flutter analyses
- Demonstrate failures/adverse conditions to V_{FC}/M_{FC}
- Investigate other phenomena
  - e.g. control surface buzz

175

Flight flutter tests

- Purpose
- Test article (configurations and conformity)

176

Configuration and conformity

- Airplane must be in conformity per FAA approved test plan
- Flutter critical payloads and fuel loading
- Automatic flight control systems
  - Autopilot, yaw damper, load alleviation device
- Other flutter critical parameters
  - Control surface mass balance and freeplay
- Minimum crew - hazardous test (No FAA pilots or engineers)

177

Flight flutter tests

- Purpose
- Test article (configurations and conformity)
- Instrumentation and testing techniques

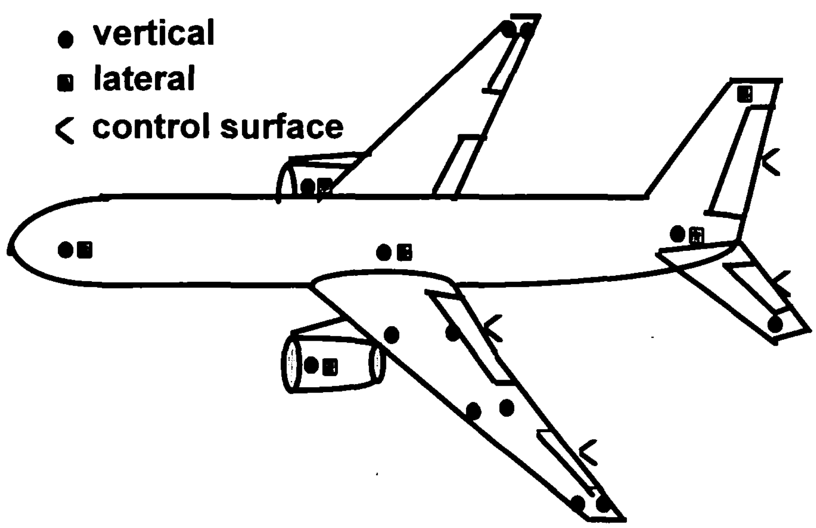
178

Airplane instrumentation

- Uninstrumented flight test is unacceptable
- Sufficient quantity & distribution to identify amplitude of critical flutter modes
- Sufficiently wide frequency band
- Monitor in real time (recording/telemetry)
- Relative displacements double integrated from accelerometers
- Control surface positions measured

179

Airplane instrumentation



180

Methods of exciting the airframe

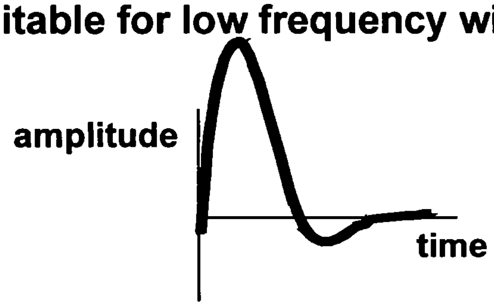
- FAR 23.629(b) Flight flutter tests must be made......and to show that -

  (1) Proper and adequate attempts to induce flutter have been made within the speed range up to V_D (V_{DF} for transport airplanes).

181

Methods of exciting the airframe

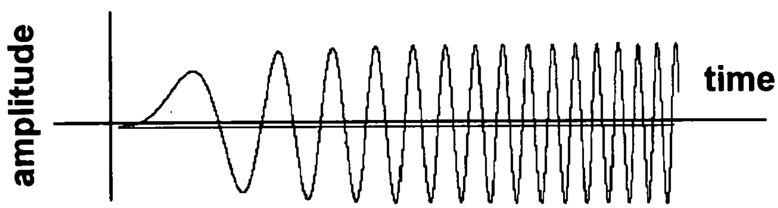
- Abrupt control surface input (kick)
- Kicks always required
- Elevator - symmetric
- Ailerons and rudder - antisymmetric
- Suitable for low frequency wing modes



182

Methods of exciting the airframe

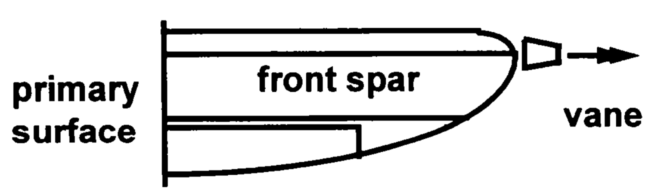
- Control surface sweep
- Usually electronically with sine wave generator
- Broad frequency range
- Limited by frequency response of control system



183

Methods of exciting the airframe

- External airfoil vane
- Also driven by sine wave generator
- Used for high frequencies (to 25Hz)
- Not limited by frequency response of control system
- Vane must be flutter free



184

Methods of exciting the airframe

- Other methods of excitation
  - Inertial rotating mass
  - Explosive impulse (bonkers)
  - Turbulence in the air

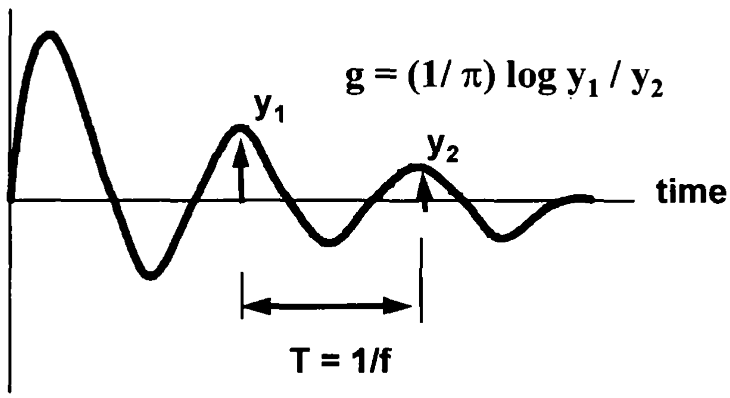
185

Test procedure

- Test at constant altitude beginning at slow speed, incrementally increasing to V_D .
- At each speed, excite airplane and measure frequency and damping of flutter modes.
- Clearance given to higher speed once acceptable damping trends established.
- Configuration held constant throughout test.

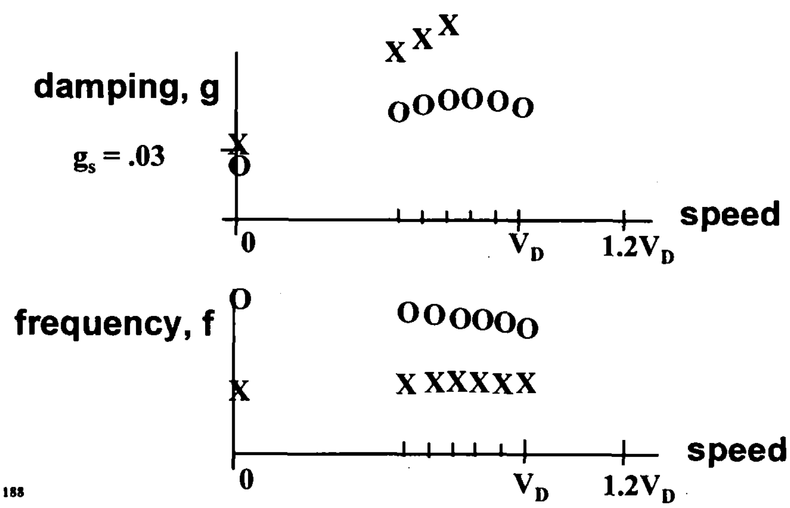
186

Frequency & damping measurement



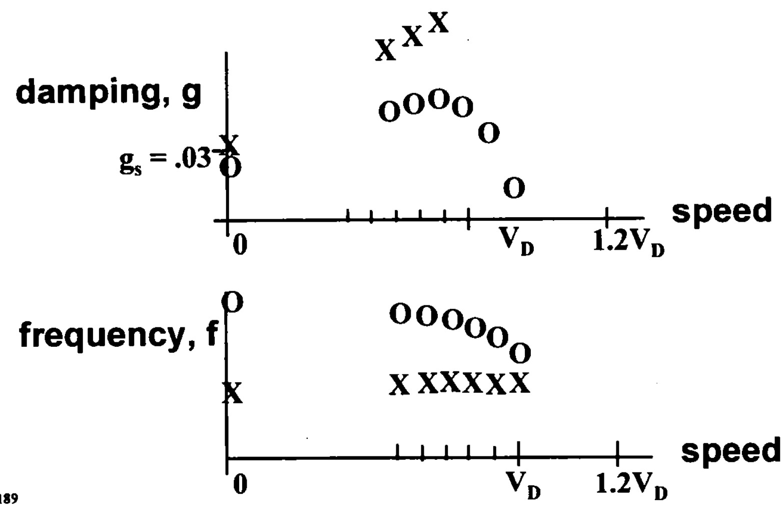
187

Frequency & damping measurement



188

Frequency & damping measurement



189

Flight flutter tests

- Purpose
- Test Article (configurations and conformity)
- Instrumentation and testing techniques
- Flight investigations and test conditions

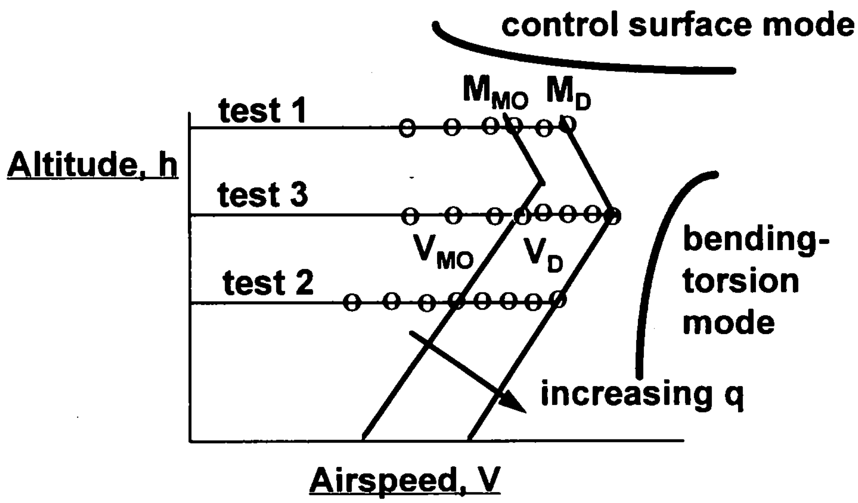
190

Test conditions

- Test at high altitude to M_{DF} (minimum dynamic pressure, q)
- Test at low altitude to V_{DF} (maximum q)
- Test at middle altitude to V_{DF} / M_{DF} (maximum q and critical Mach No.)
- Some modes are critical at high altitude (e.g. control surface flutter)

191

Test conditions



192

Flight test investigations

- Regulatory requirements
- Payload and fuel loading
- Interaction of systems and structures
- Flight conditions, e.g. AOA and load factor
- Flight test of failures and adverse conditions not imposed by FAA

193

Flight flutter tests

- Purpose
- Test Article (configurations and conformity)
- Instrumentation and testing techniques
- Flight investigations and test conditions
- How results are used for compliance

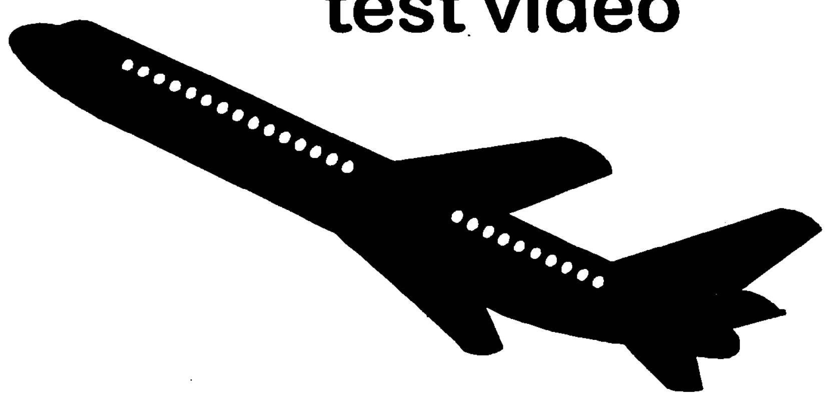
194

Compliance program

- FAA approved test plan
- "Witnessing" of test by instrumentation
- DER should supervise conduct of test
- DER recommend approval of data
- Summary submitted for TIA
- Complete test report submitted before TC

195

Flight flutter test video



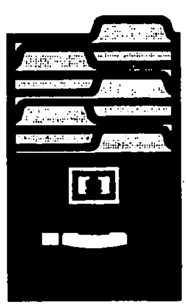
196

Flight flutter tests summary

- Purpose
- Test Article (configurations and conformity)
- Instrumentation and testing techniques
- Flight investigations and test conditions
- How results are used for compliance

197

What affects aeroelastic stability?



Changes
Modifications
Repairs

198

Categories of changes

- Mass or inertial changes
- Structural changes
- Aerodynamic changes
- System changes

199

Inertial changes

- Engine/Nacelle (mass & cg)
- Fuel tank capacities (usage schedules, or activation of dry bays)
- Wing mounted external fuel tanks.
- Significant changes to payload (cargo conversions)

200

Inertial changes

- Painting and repairing of control surfaces
- Installation of mass items on main surfaces (logo or navigation lights, etc)
- Winglets

201

Aerodynamic changes

- Nacelle configuration (quite nacelle modifications)
- Wing tip modifications
- Winglets

202

Structural changes

- Fuselage cut outs (especially aft fuselage cut outs for cargo conversions)
- Wing leading edge cut outs (weather radar, landing lights, etc.)
- Extended fuselages (plugs)
- Cargo floors

203

Automatic controls

- New autopilots or yaw dampers.
- Changes to autopilot or yaw damper gains and phases.
- Changes to control laws:
  - Automatic flight controls
  - Wing load alleviation systems
  - Active flutter suppression systems.

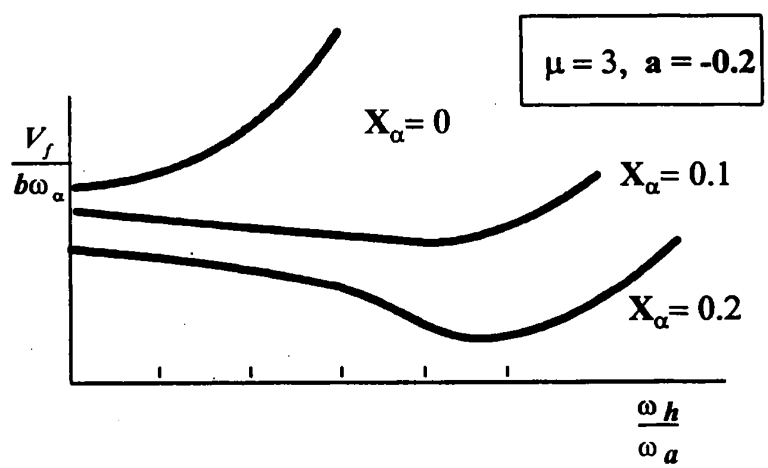
204

Assessing changes

- Structural changes - Vibration analysis plus before-and-after Ground Vibration tests.
- Flight Flutter tests are necessary if there is a significant effect on aeroelastic modes.
- For simple airplanes and simple changes NACA Report 685 might be useful.
- A complete flutter substantiation program is often necessary.

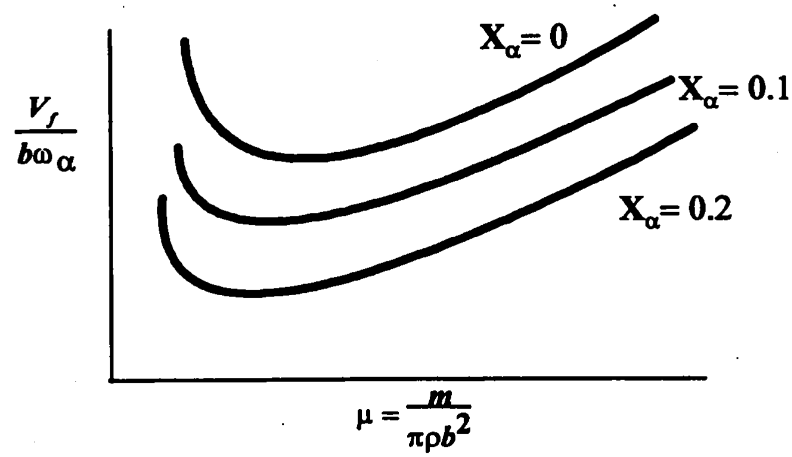
205

Typical curve from NACA 685



206

Typical curve from NACA 685



207

Summary

- Mass or inertial changes
- Structural changes
- Aerodynamic changes
- System changes
- Assessing changes

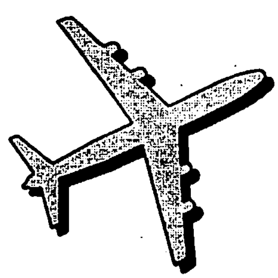
208

What affects flutter?

Just about everything!

209

Flutter prevention



Detail design

Service information

210

Flutter prevention

Two areas of primary importance to achieve and maintain freedom from flutter:

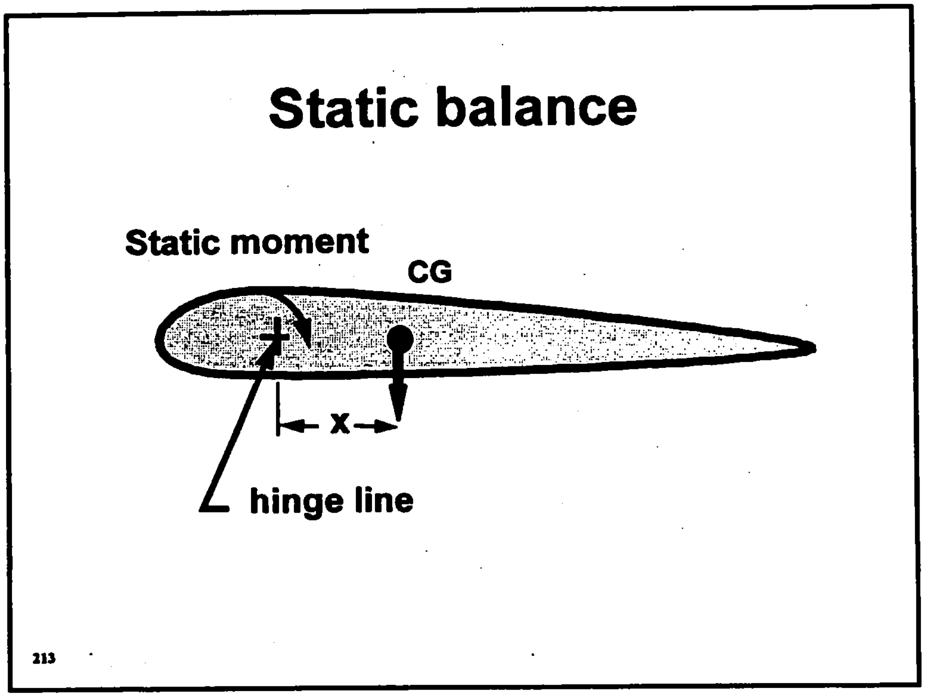
- Maintain mass balance of control surfaces.
- Maintain sufficient rigidity of irreversible control surfaces.

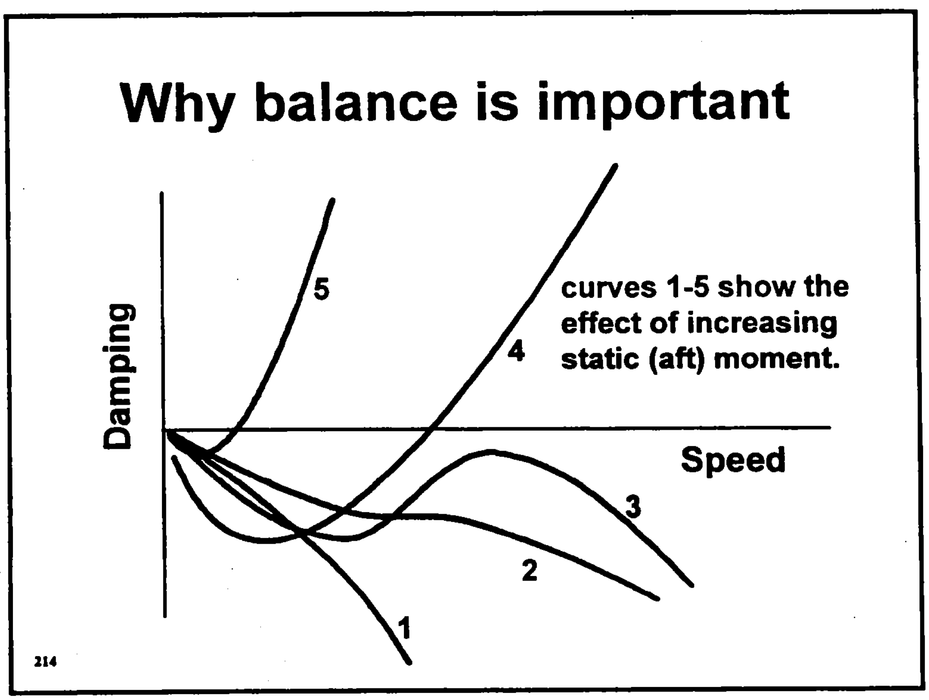
211

Static balance

- Static moment about a single axis.
- A plunging motion of the axis will induce no rotation about the axis if the static balance is zero.
- The static balance can be measured directly in the laboratory by balancing the surface about the hingeline.

212


Static balance
Static moment
CG
X
hinge line
213

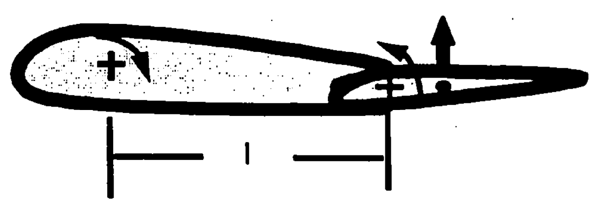

Why balance is important
Damping
Speed
curves 1-5 show the effect of increasing static (aft) moment.
5
4
3
2
1
214

Dynamic balance

- **Acceleration about one axis produces an inertial moment about another axis if the dynamic balance is not zero.**
- **The axes can be parallel or perpendicular (or any angle in between).**

215

Dynamic balance parallel axes



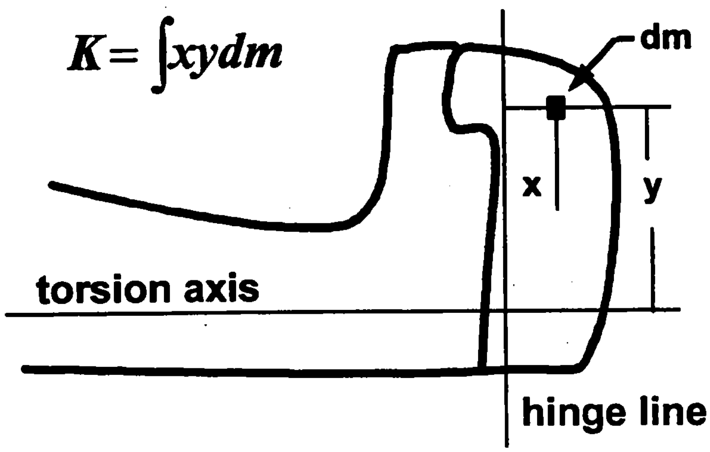
$$P_{\alpha\beta} = S_{\beta}(\lambda) + I_{\beta} = 0$$

$S_{\beta} = -I_{\beta} / \lambda$ **To dynamically balance**

216

Dynamic balance perpendicular axes

$$K = \int xy\,dm$$



217

Control of mass balance

- Prescribe limits for static moment or arm.
- Prescribe specific surface rebalance instructions after repair, including precise locations to add weights.
- Provide drainage holes in surfaces to minimize accumulation of water and ice.
- Provide adequate margin for possible ice and water accumulation.

218

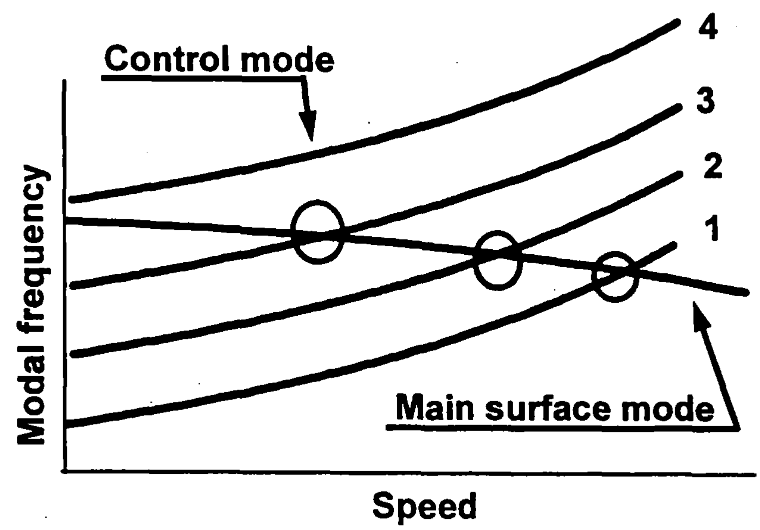
Flutter prevention

Two areas of primary importance to achieve and maintain freedom from flutter:

- **Maintain mass balance of control surfaces.**
- **Maintain rigidity of irreversible control surfaces.**

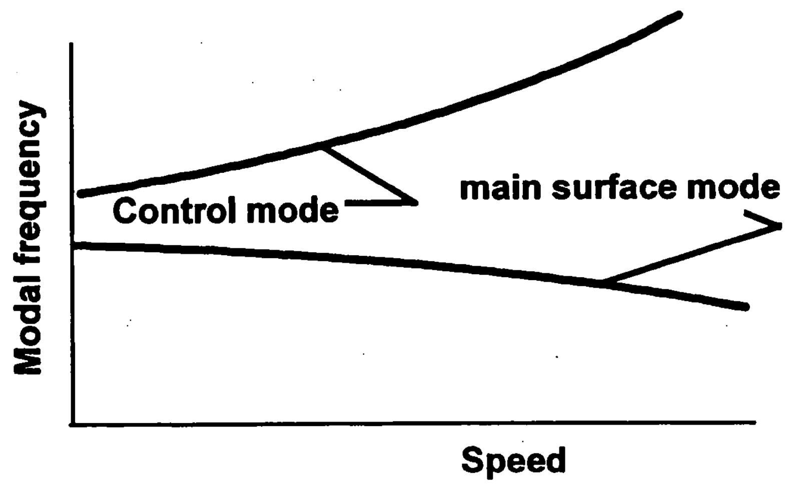
219

Conventional control stiffness



220

Irreversible control stiffness



221

Maintaining rigidity (irreversible controls)

- Control surface rigidity is maintained with the powered hydraulic actuators.
- Mass balance needed to cover failure cases.
- Triple actuators or advanced dual actuators in lieu of providing balance weights.
- Tab is restrained by dual tab rods (both small and transport airplanes).

222

Control of rigidity (powered systems)

- Loss of stiffness - extremely improbable.
- Consider single and multiple failures.
- Provide service checks and/or full time monitors for actuator health.
- Typical advanced actuator designs may use dual seals, inlet check valves, dual springs on compensator, etc.

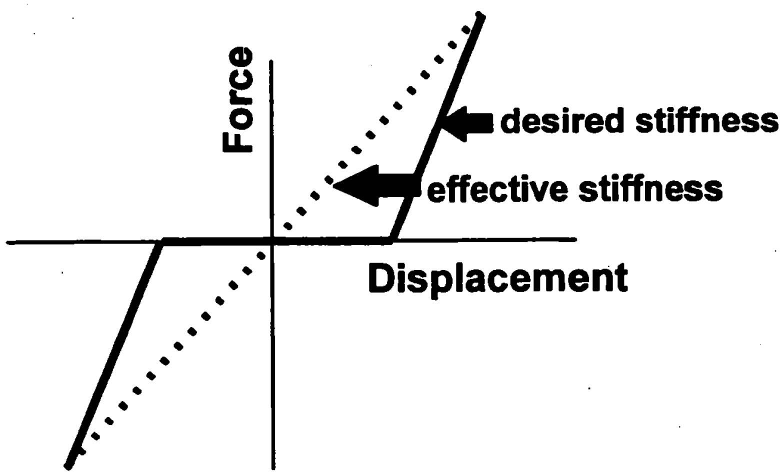
223

Free play

- Rigidity or stiffness of irreversible control surfaces and tabs can be compromised by free play.
- Free play must be controlled throughout the life of the airplane.

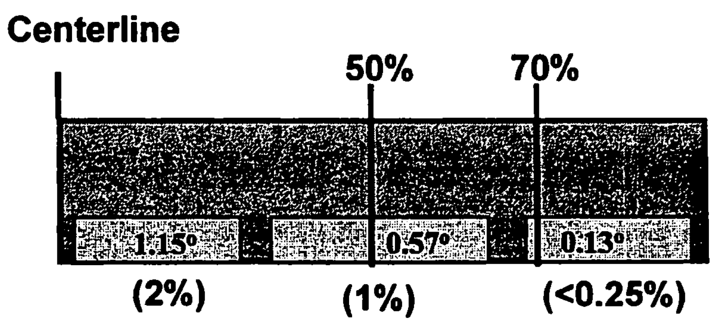
224

Effect of free play



225

Free play limits (control surfaces)

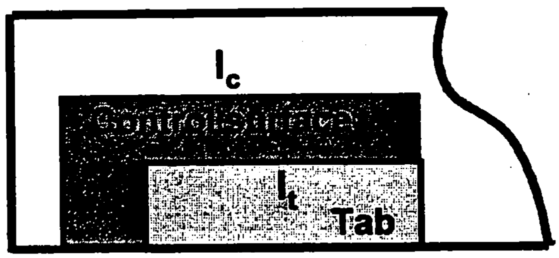


All-movable control surfaces, 0.034 degrees

Ref: Mil-A-8870

226

Free play limits (tabs)



If $l_t/l_c < .35$ then 1.15 degrees (2 percent)

If $l_t/l_c >= .35$ then 0.57 degrees (1 percent)

227

Control of free play

- **Provide service manual limits on free play.**
- **Provide periodic checks of free play.**
- **Provide detailed instructions on how to measure free play.**

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Flutter prevention summary

Two areas of primary importance to achieve and maintain freedom from flutter:

- **Maintain mass balance of control surfaces.**
- **Maintain sufficient rigidity of irreversible control surfaces.**

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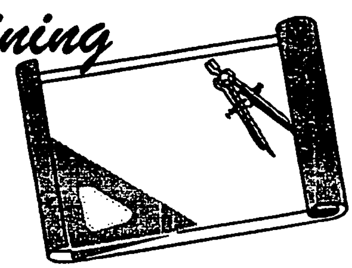
Further study, tools, and training



230

Main referenced texts

- Bisplinghoff, R.L. and Ashley, H.; *Principles of Aeroelasticity*, Dover Publications, Inc. 1962.
- Scanlan, R.H. and Rosenbaum, R.; *Introduction to the Study of Aircraft Vibration and Flutter*, The Macmillian Co., 1962.
- Fung, Y.C.; *An Introduction to the Theory of Aeroelasticity*, Dover Publications, Inc. 1969.

231

Standard analytical tools

- MSC/NASTRAN, The MacNeal-Schwendler Corporation.
- NACA Report 685, Mechanism of Flutter.
- Report 45, Simplified Flutter Criteria.

232

Training courses

- University level class in *Structural Dynamics*
- University level class in *Aeroelasticity*
- University of Cincinnati *Modal Analysis* course
- FAA Seminars

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Training activities

- Take advantages of opportunities to witness or observe ground vibration tests and wind tunnel model tests.
- Review analyses and test reports and ask questions of the specialists and DERs.

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What you have learned

- What aeroelastic instabilities are
- Regulatory requirements
- Acceptable means of compliance
- What affects flutter and flutter prevention
- Avenues of further study and development

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FAR Parts for Flutter/Aeroelastic Stability

Appendix B

FAR 23 Requirements related to flutter and aeroelastic stability

23.629	Flutter
23.251	Vibration and buffeting
23.659	Mass balance
23.677	Trim systems -- paragraph (c)

FAR 25 Requirements related to flutter and aeroelastic stability

25.629	Aeroelastic Stability Requirements
25.251	Vibration and buffeting
25.343	Design fuel and oil loads -- paragraph (b)(3)
25.677	Trim Systems -- paragraphs (c) and (d)

FAR 23 Requirements Related to Flutter and Aeroelastic Stability

§ 23.629 Flutter.

(a) It must be shown by the methods of paragraph (b) and either paragraph (c) or (d) of this section, that the airplane is free from flutter, control reversal, and divergence for any condition of operation within the limit V-n envelope and at all speeds up to the speed specified for the selected method. In addition-

(1) Adequate tolerances must be established for quantities which affect flutter; including speed, damping, mass balance, and control system stiffness; and

(2) The natural frequencies of main structural components must be determined by vibration tests or other approved methods. Flight flutter tests must be made to show that the airplane is free from flutter, control reversal and divergence and to show that-

(1) Proper and adequate attempts to induce flutter have been made within the speed range up to V_D;

(2) The vibratory response of the structure during the test indicates freedom from flutter;

(3) A proper margin of damping exists at V_D; and

(4) There is no large and rapid reduction in damping as V_D is approached.

(c) Any rational analysis used to predict freedom from flutter, control reversal and divergence must cover all speeds up to 1.2 V_D.

(d) Compliance with the rigidity and mass balance criteria (pages 4-12), in Airframe and Equipment Engineering Report No. 45 (as corrected) "Simplified Flutter Prevention Criteria" (published by the Federal Aviation Administration) may be accomplished to show that the airplane is free from flutter, control reversal, or divergence if-

(1) V_D/M_D for the airplane is less than 260 knots (EAS) and less than Mach 0.5,

(2) The wing and aileron flutter prevention criteria, as represented by the wing torsional stiffness and aileron balance criteria, are limited in use to airplanes without large mass concentrations (such as engines, floats, or fuel tanks in outer wing panels) along the wing span, and

(3) The airplane-

(i) Does not have a T-tail or other unconventional tail configurations;

(ii) Does not have unusual mass distributions or other unconventional design features that affect the applicability of the criteria, and

(iii) Has fixed-fin and fixed-stabilizer surfaces.

(e) For turbopropeller-powered airplanes, the dynamic evaluation must include-

(1) Whirl mode degree of freedom which takes into account the stability of the plane of rotation of the propeller and significant elastic, inertial, and aerodynamic forces, and

(2) Propeller, engine, engine mount, and airplane structure stiffness and damping variations appropriate to the particular configuration.

(f) Freedom from flutter, control reversal, and divergence up to V_D/M_D must be shown as follows:

(1) For airplanes that meet the criteria of paragraphs (d)(1) through (d)(3) of this section, after the failure, malfunction, or disconnection of any single element in any tab control system.

(2) For airplanes other than those described in paragraph (f)(1) of this section, after the failure, malfunction, or disconnection of any single element in the primary flight control system, any tab control system, or any flutter damper.

(g) For airplanes showing compliance with the fail-safe criteria of §§ 23.571 and 23.572, the airplane must be shown by analysis to be free from flutter up to V_D/M_D after fatigue failure, or obvious partial failure, of a principal structural element.

(h) For airplanes showing compliance with the damage tolerance criteria of § 23.573, the airplane must be shown by analysis to be free from flutter up to V_D/M_D with the extent of damage for which residual strength is demonstrated.

(i) For modifications to the type design that could affect the flutter characteristics, compliance with paragraph (a) of this section must be shown, except that analysis based on previously approved data may be used alone to show freedom from flutter, control reversal and divergence, for all speeds up to the speed specified for the selected method.

(Amdt. 23-7, Eff. 9/14/69); (Amdt. 23-23, Eff. 12/1/78); (Amdt. 23-31, Eff. 12/28/84); (Amdt. 23-45, Eff. 9/7/93); (Amdt. 23-48, Eff. 3/11/96)

§ 23.251 Vibration and buffeting.

There must be no vibration or buffeting severe enough to result in structural damage, and each part of the airplane must be free from excessive vibration, under any appropriate speed and power conditions up to V_D/M_D. In addition, there must be no buffeting in any normal flight condition severe enough to interfere with the satisfactory control of the airplane or cause excessive fatigue to the flight crew. Stall warning buffeting within these limits is allowable.

(Amdt. 23-45, Eff. 9/7/93)

§ 23.659 Mass balance.

The supporting structure and the attachment of concentrated mass balance weights used on control surfaces must be designed for-

(a) 24 g normal to the plane of the control surface;

(b) 12 g fore and aft; and

(c) 12 g parallel to the hinge line.

§ 23.677 Trim systems.

(a) Proper precautions must be taken to prevent inadvertent, improper, or abrupt trim tab operation. There must be means near the trim control to indicate to the pilot the direction of trim control movement relative to airplane motion. In addition, there must be means to indicate to the pilot the position of the trim device with respect to both the range of adjustment and, in the case of lateral and directional trim, the neutral position. This means must be visible to the pilot and must be located and designed to prevent confusion. The pitch trim indicator must be clearly marked with a position or range within which it has been demonstrated that take-off is safe for all center of gravity positions and each flap position approved for takeoff.

(b) Trimming devices must be designed so that, when any one connecting or transmitting element in the primary flight control system fails, adequate control for safe flight and landing is available with-

(1) For single-engine airplanes, the longitudinal trimming devices; or
(2) For multiengine airplanes, the longitudinal and directional trimming devices.

(c) Tab controls must be irreversible unless the tab is properly balanced and has no unsafe flutter characteristics. Irreversible tab systems must have adequate rigidity and reliability in the portion of the system from the tab to the attachment of the irreversible unit to the airplane structure.

(d) It must be demonstrated that the airplane is safely controllable and that the pilot can perform all maneuvers and operations necessary to effect a safe landing following any probable powered trim system runaway that reasonably might be expected in service, allowing for appropriate time delay after pilot recognition of the trim system runaway. The demonstration must be conducted at critical airplane weights and center of gravity positions.

(Amdt. 23-7, Eff. 9/14/69); (Amdt. 23-34, Eff. 2/17/87); (Amdt. 23-42, Eff. 2/4/91); (Amdt. 23-49, Eff. 3/11/96)

FAR 25 Requirements Related to Flutter and Aeroelastic Stability

§ 25.629 Aeroelastic stability requirements.

(a) *General.* The aeroelastic stability evaluations required under this section 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 section must be shown by analyses, wind tunnel tests, ground vibration tests, flight tests, or other means found necessary by the Administrator.

(b) *Aeroelastic stability envelopes.* The airplane 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 both constant Mach number and constant altitude. In addition, a proper margin of stability must exist at all speeds up to V_D/M_D and, there must be no large and rapid reduction in stability as V_D/M_D is approached. The enlarged envelope may be limited to Mach 1.0 when M_D is less than 1.0 at all design altitudes, and

(2) For the conditions described in § 25.659(d) below, for all approved altitudes, any airspeed up to the greater airspeed defined by;

(i) The V_D/M_D envelope determined by § 25.335(b); or,

(ii) An altitude-airspeed envelope defined by a 15 percent increase in equivalent airspeed above V_C at constant altitude, from sea level to the altitude of the intersection of 1.15 V_C with the extension of the constant cruise Mach number line, M_C, then a linear variation in equivalent airspeed to M_C + .05 at the altitude of the lowest V_C/M_C intersection; then, at higher altitudes, up to the maximum flight altitude, the boundary defined by a .05 Mach increase in M_C at constant altitude.

(c) *Balance weights.* If concentrated balance weights are used, their effectiveness and strength, including supporting structure, must be substantiated.

(d) *Failures, malfunctions, and adverse conditions.* The failures, malfunctions, and adverse conditions which must be considered in showing compliance with this section are:

(1) Any critical fuel loading conditions, not shown to be extremely improbable, which may result from mismanagement of fuel.

(2) Any single failure in any flutter damper system.

(3) For airplanes not approved for operation in icing conditions, the maximum likely ice accumulation expected as a result of an inadvertent encounter.

(4) Failure of any single element of the structure supporting any engine, independently mounted propeller shaft, large auxiliary power unit, or large externally mounted aerodynamic body (such as an external fuel tank).

(5) For airplanes with engines that have propellers or large rotating devices capable of significant dynamic forces, any single failure of the engine structure that would reduce the rigidity of the rotational axis.

(6) The absence of aerodynamic or gyroscopic forces resulting from the most adverse combination of feathered propellers or other rotating devices capable of significant dynamic forces. In addition, the effect of a single feathered propeller or rotating device must be coupled with the failures of paragraphs (d)(4) and (d)(5) of this section.

(7) Any single propeller or rotating device capable of significant dynamic forces rotating at the highest likely overspeed.

(8) Any damage or failure condition, required or selected for investigation by § 25.571. The single structural failures described in paragraphs (d)(4) and (d)(5) of this section need not be considered in showing compliance with this section if:

(i) the structural element could not fail due to discrete source damage resulting from the conditions described in § 25.571(e), and;

(ii) a damage tolerance investigation in accordance with § 25.571(b) shows that the maximum extent of damage assumed for the purpose of residual strength evaluation does not involve complete failure of the structural element.

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

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

(e) *Flight flutter testing.* Full scale flight flutter tests at speeds up to V_{DF}/M_{DF} must be conducted for new type designs and for modifications to a type design unless the modifications have been shown to have an insignificant effect on the aeroelastic stability. These tests must demonstrate that the airplane has a proper margin of damping at all speeds up to V_{DF}/M_{DF}, and that there is no large and rapid reduction in damping as V_{DF}/M_{DF} is approached. If a failure, malfunction, or adverse condition is simulated during flight test in showing compliance with paragraph (d) of this section, the maximum speed investigated need not exceed V_{FC}/M_{FC} if it is shown, by correlation of the flight test data with other test data or analyses, that the airplane is free from any aeroelastic instability at all speeds within the altitude-airspeed envelope described in paragraph (b)(2) of this section.

(Amdt. 25-23, Eff. 5/8/70); (Amdt. 25-45, Eff. 12/1/78); (Amdt. 25-46, Eff. 12/1/78); (Amdt. 25-72, Eff. 8/20/90); (Amdt. 25-77, Eff. 7/29/92)

§ 25.251 Vibration and buffeting.

(a) The airplane must be demonstrated in flight to be free from any vibration and buffeting that would prevent continued safe flight in any likely operating condition.

(b) Each part of the airplane must be demonstrated in flight to be free from excessive vibration under any appropriate speed and power conditions up to V_{DF}/M_{DF}. The maximum speeds shown must be used in establishing the operating limitations of the airplane in accordance with § 25.1505.

(c) Except as provided in paragraph (d) of this section, there may be no buffeting condition, in normal flight, including configuration changes during cruise, severe enough to interfere with the control of the airplane, to cause excessive fatigue to the crew, or to cause structural damage. Stall warning buffeting within these limits is allowable.

(d) There may be no perceptible buffeting condition in the cruise configuration in straight flight at any speed up to V_{MO}/M_{MO}, except that stall warning buffeting is allowable.

(e) For an airplane with M_D greater than .6 or with a maximum operating altitude greater than 25,000 feet, the positive maneuvering load factors at which the onset of perceptible buffeting occurs must be determined with the airplane in the cruise configuration for the ranges of airspeed or Mach number, weight, and altitude for which the airplane is to be certificated. The envelopes of load factor, speed, altitude, and weight must provide a sufficient range of speeds and load factors for normal operations. Probable inadvertent excursions beyond the boundaries of the buffet onset envelopes may not result in unsafe conditions.

(Amdt. 25-23, Eff. 5/8/10); (Amdt. 25-72, Eff. 8/20/90); (Amdt. 25-77, Eff. 7/29/92)

§ 25.343 Design fuel and oil loads.

(a) The disposable load combinations must include each fuel and oil load in the range from zero fuel and oil to the selected maximum fuel and oil load. A structural reserve fuel condition, not exceeding 45 minutes of fuel under the operating conditions in § 25.1001(e) and (f), as applicable, may be selected.

(b) If a structural reserve fuel condition is selected, it must be used as the minimum fuel weight condition for showing compliance with the flight load requirements as prescribed in this subpart. In addition-

(1) The structure must be designed for a condition of zero fuel and oil in the wing at limit loads corresponding to-

(i) A maneuvering load factor of +2.25; and

(ii) The gust conditions of § 25.341(a); but assuming 85% of the design velocities prescribed in § 25.341(a)(4).

(2) Fatigue evaluation of the structure must account for any increase in operating stresses resulting from the design condition of paragraph(b)(1) of this section; and

(3) The flutter, deformation, and vibration requirements must also be met with zero fuel.

(Amdt. 25-18, Eff. 9/29/68); (Amdt. 25-72, Eff. 8/20/90); (Amdt. 25-86, Eff. 3/11/96)

§ 25.677 Trim systems.

(a) Trim controls must be designed to prevent inadvertent or abrupt operation and to operate in the plane, and with the sense of motion, of the airplane.

(b) There must be means adjacent to the trim control to indicate the direction of the control movement relative to the airplane motion. In addition, there must be clearly visible means to indicate the position of the trim device with respect to the range of adjustment.

(c) Trim control systems must be designed to prevent creeping in flight. Trim tab controls must be irreversible unless the tab is appropriately balanced and shown to be free from flutter.

(d) If an irreversible tab control system is used, the part from the tab to the attachment of the irreversible unit to the airplane structure must consist of a rigid connection.

(Amdt. 25-23, Eff. 5/8/70)

Aeroelastic Instability Definitions

Compiled and Edited by Gerry Lakin and Jim Haynes

Appendix C

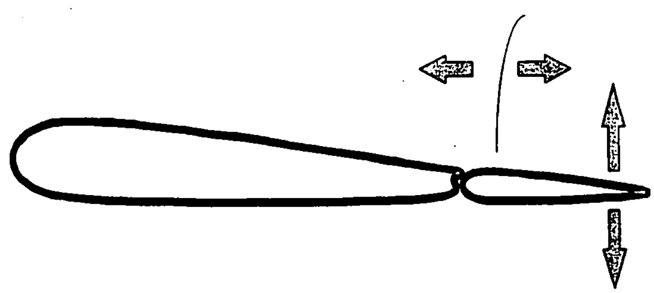
Many of these definitions were published in the Federal Register, Vol. 54, No. 176, September 12, 1989

Flutter: An unstable self-excited structural oscillation at a definite frequency where energy is extracted from the airstream by the motion of the structure. The deformation and motion of the structure result in forces on the structure that tend to <u>maintain or augment</u> the motion.

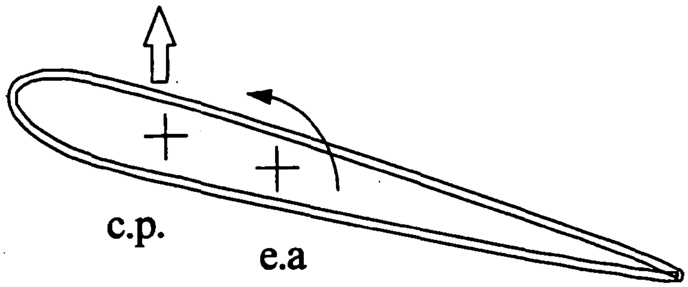
Whirl flutter: Flutter in which the aerodynamic and gyroscopic forces associated with rotations and displacements in the plane of a propeller or large turbofan play an important role. The displacement modes associated with whirl flutter are often called "whirl modes".

Limit cycle flutter: Flutter in which the amplitude is limited to a constant level, usually brought about by non-linearities in the system.

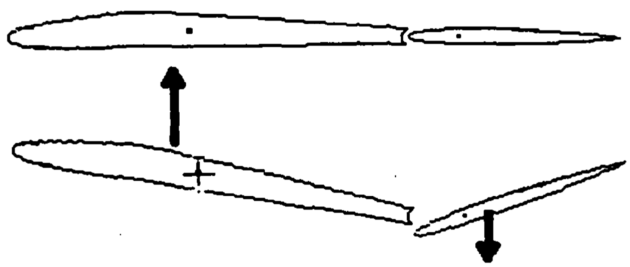
Aileron buzz: A situation in which the motion of a standing shock on the aileron creates hinge moments that move the aileron, which in return causes the shock to displace. This high frequency coupling is always limited in amplitude.



Divergence: A static instability at a speed where the aerodynamic forces resulting from the deformation of the structure exceed the elastic restoring forces resulting from the same deformation.



Control Reversal: A condition in which the intended effects of displacing a given component of the control system are completely overcome by the aeroelastic effects of structural deformation, resulting in reversed command at higher speeds.



Deformation Instability: The loss of airplane static or dynamic stability and control resulting from the aeroelastic effects of structural deformation.

Buffeting: Irregular oscillations of the structure resulting from turbulent flow. Classical buffeting occurs when one part of the aircraft is situated in or near the wake from some other part of the aircraft. <u>Buffeting is NOT an instability</u>.

Flutter Analysis

by Gerry Lakin and Jim Haynes

Appendix D

A. Developing the flutter stability equation

1. **The mathematical model.** The structural dynamic system can be represented by the following equation.

$$[M]\{x\} + [K]\{x\} = \{F\}$$

Assume that the vibration has a constant amplitude and is sinusoidal (harmonic motion).

$$\{x\} = -\omega^2 x$$
$$-\omega^2[M]\{x\} + [K]\{x\} = \{F\}$$

The matrix {x} above represents the displacement degrees of freedom in the model. This mathematical model may have thousands of degrees of freedom. In actual practice, the system is represented as a *structural dynamic model* to represent the structure and mass and an *aerodynamic model* to represent the aerodynamic forces.

2. **Structural dynamic model.** A structural dynamic model (Figure 1) is developed in a finite element program to represent the structure, mass of the airframe. Usually a "stick model" representing the elastic axes, along with lumped masses to represent inertial properties, is sufficient to represent even very complex airplanes. This model is refined and validated using the results of ground vibration test testing.

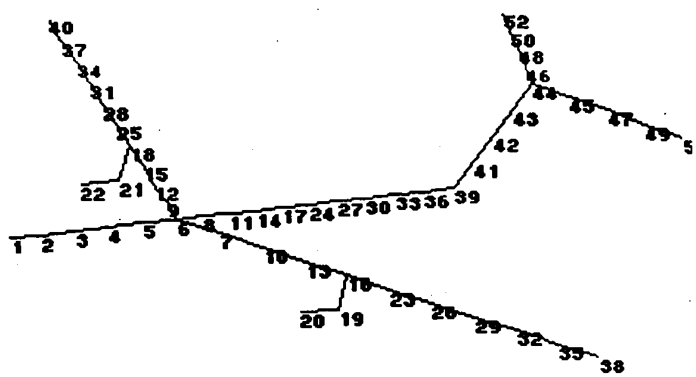


Figure 1 - Structural dynamic model

3. **Selecting structural modes.** The large structural dynamic model is first solved for the structural vibration modes without any aerodynamic forces.

$$-\omega^2 [M] \{x\} + [K] \{x\} = \{0\}$$

There are as many structural vibration modes as there are degrees of freedom in the model, however the very high frequency modes are not significant for flutter and are not reliable. Select a set of the lower frequencies and mode shapes to represent the behavior of the airplane (common practice is to use the first 20-30 modes, or up to 35-40 Hz). These modes are put into a modal matrix [Φ], each column of which represents the relative displacement state of the model in one of the modes.

4. **Superposition of modes and generalized coordinates.** When the airplane moves through the air, it is a different dynamic system than on the ground. The air moving past the airplane actually adds effective mass, damping forces and spring forces to the structure. Therefore, the aeroelastic modes are not the same in flight and, in fact, are different for each airspeed and altitude.

Assume that the flutter modes (when moving through the air) consist of a linear superposition of the selected structural modes that were derived from the structural dynamic model.

$$\{x\} = q_1 \{\phi_1\} + q_2 \{\phi_2\} + \ldots q_n \{\phi_n\}$$

$$\{x\} = [\Phi] \{q\}$$

The new unknown scalar variables, "q_i", are the proportions of each structural mode contained in the flutter mode. They are called the generalized coordinates.

Substitute the generalized coordinates for {x}.

$$-\omega^2 [M][\Phi]\{q\} + [K][\Phi]\{q\} = \{F\}$$

Multiply through from the left by the transpose of the modal matrix [Φ].

$$-\omega^2 [\Phi]^T [M][\Phi]\{q\} + [\Phi]^T [K][\Phi]\{q\} = [\Phi]^T [F]$$

Define the following terms:

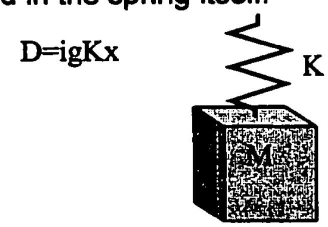
$$\Phi]^T[M][\Phi] = \overline{M} \;=\; \text{generalized mass}$$
$$\Phi]^T[K][\Phi] = \overline{K} \;=\; \text{generalized stiffness}$$

Substituting this nomenclature results in:

$$-\omega^2 \overline{M}\{q\} + \overline{K}\{q\} = [\Phi]^T[F]$$

5. **Including structural damping.** Structural damping is proportional to the spring force but 90 degrees out of phase. For example, consider a simple single degree spring mass system with the structural damping included in the spring itself:

$$Mx + igKx + Kx = 0$$
$$Mx + (1 + ig)Kx = 0$$
$$Mx + K_1x = 0, \quad \text{where } K_1 \text{ is complex}$$



Structural damping could be ignored for now and a global structural damping considered when plotting the final results. (AC23.629-1A or Method 1 of AC25.629-1). Or..

The structural damping that is measured for each mode in the ground vibration test can be included directly in the generalized stiffness matrix. The generalized equation would still be the same form except that the coefficients of the generalized stiffness matrix would be complex numbers. In actual practice this involves multiplying the diagonal elements of the generalized stiffness matrix by $1+ig_i$ for each mode.

Assume for now that the structural damping measured for each mode has been incorporated into the stiffness matrix. The equation still looks the same even though the stiffness matrix includes damping and is complex.

$$-\omega^2 \overline{M}\{q\} + \overline{K}\{q\} = [\Phi]^T [F]$$

6. **Unsteady aerodynamics and "reduced frequency."** When an aerodynamic surface oscillates in the airstream, the aerodynamic forces lag behind the displacement. For very low frequency oscillations, the forces approach those normally encountered in steady aerodynamics. However, for higher frequency oscillations, the phase lag can be quite significant. The phase depends on a dimensionless number called the reduced frequency, k:

$$k = \frac{b\omega}{V}$$

   where ω is the frequency (rad/sec), b is a reference dimension, and V is the velocity of the airstream.

7. **Developing the aerodynamic forces.** Two aerodynamic theories commonly used for flutter analyses are ***strip theory*** and ***doublet lattice***.

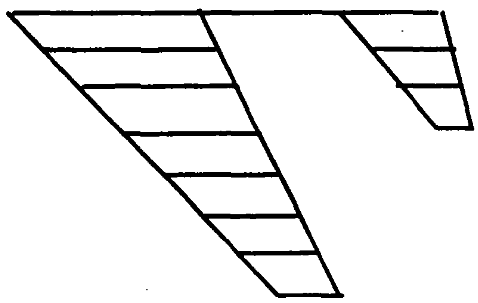


Figure 2 - Strip theory

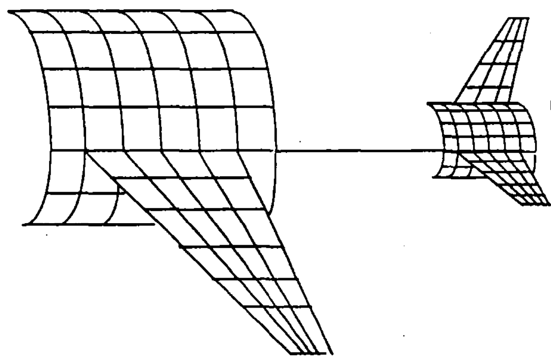


Figure 3 - Doublet lattice

Strip theory is the older method and is limited to higher aspect ratio airplanes. It is the simpler model to employ and is easier to adjust and fine tune to match test results. The ***doublet lattice*** method is the newer, more sophisticated method. It is capable of treating interference effects between panels, including the interference effects of wing/body and empennage surfaces. Both methods are employed extensively in modern flutter analysis, although the doublet lattice is becoming the more popular among the manufacturers.

8. **Generalized Aerodynamic forces.** For ***steady*** aerodynamics, the lift forces are:

$F = 1/2\rho V^2 C_{L\alpha}\alpha S$ or in matrix form:

$F = 1/2\ \rho V^2[AIC]\{x\}$ where:

AIC = Aerodynamic Influence Coefficient matrix
{x} = the displacement state of the aerodynamic surfaces

For ***unsteady*** aerodynamics, the development is analogous except that the aerodynamic coefficients depend on the reduced frequency, ***k***.

Usually the aerodynamic force equation will look something like the following, depending on what geometric terms are left in the AIC and what parameters are factored out of it. The variable Q will usually consist of the dynamic pressure and the reference dimension used to define the reduced frequency. The AIC is developed in computer programs from the user-described geometry using doublet lattice or strip theory aerodynamic models. The AIC is a matrix of complex aerodynamic coefficients.

$F = -\omega^2 Q[AIC]\{x\}$ or $-\omega^2 Q[AIC][\phi]\{q\}$
so:

$$[\Phi]^T F = -\omega^2 Q[\Phi]^T[AIC][\Phi]\{q\}$$

define:

$$[\Phi]^T[AIC][\Phi] = \overline{A} \quad = \quad \text{generalized aerodynamic matrix}$$

9. **The generalized flutter stability equation.**

$$-\omega^2\ \overline{M}\{q\} + \overline{K}\{q\} = \omega^2\ QA\ \{q\}$$

$$[-\omega^2\ \overline{M} + \omega^2\ Q\overline{A} + \overline{K}]\ \{q\} = 0$$

$$[\overline{K}^{1}\ \overline{M} - Q\overline{K}^{1}\ \overline{A} - (1/\omega^2)\ I]\ \{q\} = 0$$

B. Solving and interpreting results

1. **Difficulties in solving the stability equation.** The equation has two significant problems that must be overcome in order to obtain a successful solution.

   a. The equation is inconsistent since it is only solvable for neutral stability, yet it has damping. The damping comes from aerodynamic forces and possibly from structural damping if included in the stiffness matrix.

   b. The AIC depends on reduced frequency, k, and k depends on the flutter frequency which is unknown.

2. **Modifying the equation: Adding artificial damping**. The equation can only be solved for the case of neutral stability (i.e. constant amplitude sinusoidal vibration). So *artificial* structural damping is added as a variable that can counteract any damping (aerodynamic or structural) already in the system. Artificial damping forces will be:

$$ig\overline{K}\{q\}$$

The main idea is that we can solve for the "artificial" damping that results in neutral stability, then the total system damping must be the negative of this result.

$$-\omega^2\overline{M}\{q\}+(1+ig)\overline{K}\{q\}=-\omega^2 Q\overline{A}\{q\}$$

Remember that the actual structural damping for each mode $(1+ig_i)$ may already be included in the generalized stiffness matrix.

3. Final flutter equation.

$$\left[\overline{K}^{-1}\overline{M} - Q\overline{K}^{-1}\overline{A} - \frac{(1+ig)}{\omega^2} I\right]\{q\} = \{0\}$$

These matrices can all be determined and the mathematical manipulation would lead to a matrix we can call, *D*. The determinant of *D* is often called the flutter stability determinant.

$[D-(1+ig)/\omega^2)I]\{q\}=\{0\}$

This is the standard eigenvalue form:

$$[D-\lambda I]\{q\}=\{0\}$$

where:

$$\lambda=(1+ig)/\omega^2$$

where: *g* is the unknown artificial damping, and
ω is the flutter frequency

4. Solving the flutter equation. The matrix *D* is a complex matrix that depends on reduced frequency, *k*, and the density (altitude). Depending on the type of aerodynamic model, it may also depend on Mach number -- but ignore compressibility for now.

- For the desired altitude, choose a value of *k*.
- Solve for λ's using an eigenvalue extraction algorithm.
- From λ (complex number) get *g* (artificial damping) and ω for each mode.
- Then from the assumed $k=b\omega/V$, find *V*
- Plot ω and *g* against *V* for each mode.
- Choose another *k* and repeat these steps.

If compressibility were important, then an iteration would be necessary since the AIC would depend on both Mach number and reduced frequency, k. For each chosen k, a trial Mach number is chosen, then a loop is repeated (choosing a different Mach number each time) until the calculated V results in a Mach number matching the chosen one. This is called a "matched point" solution.

5. **Plotting and interpreting the results.** It is traditional to plot the calculated *artificial damping*. Artificial damping is the amount of extra damping needed to make the system neutrally stable. For a system that is well damped, the artificial damping would have to be negative to counteract the system damping and force it to neutral stability. So negative artificial damping indicates a *stable system*, and positive artificial damping indicates an *unstable system*.

   If actual structural damping were included in the stiffness matrix before solution, then the results will appear as in Figure 4. In this figure, each damping curve starts off at the ordinate with a value on the ordinate. This value will correspond to the negative of the amount of actual structural damping included for that mode from the ground vibration test results. In Figure 4, any damping line crossing the abscissa indicates instability.

   If actual structural damping had not been included the stability equation, the results would look like those in Figure 5, with all the damping curves starting at the origin. In this case a global structural damping coefficient can be assumed to be present and represented on the plot by a straight line above the abcissa (dashed line in Figure 5). Instability would occur when a damping curve crosses the dashed line where the net damping available is zero.

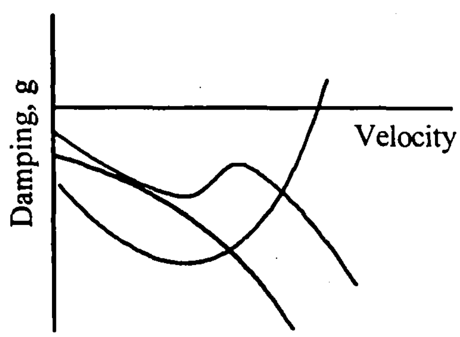


Figure 4

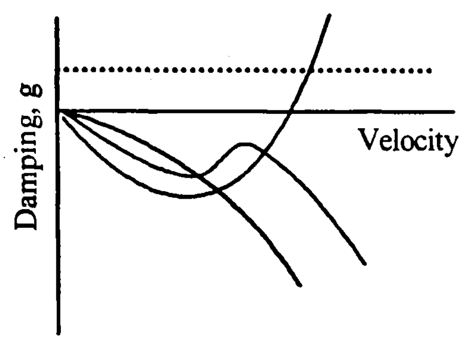


Figure 5

Appropriate damping margins as required by the FAR are recommended in the Advisory Circulars, 23.629-1A and 25.629-1.

Self-Study Video
Course Evaluation Form

Appendix E

SELF-STUDY VIDEO COURSE EVALUATION

Please give us your candid opinions concerning the training you've just completed. Your evaluation of the self-study video course is important to us, and will help us provide the best possible products and services to you.

Course title: ______________________________

Date: ____________________

Number of years of FAA experience: __________

(Optional)

Name: Office phone: (   )

For the following, please completely darken the circle appropriate to your response.

	Very Good	Good	Average	Poor	Very Poor	N/A
1. Length of course	O	O	O	O	O	O
2. Depth of information	O	O	O	O	O	O
3. Pace of training	O	O	O	O	O	O
4. Clarity of objectives	O	O	O	O	O	O
5. Sequence of content	O	O	O	O	O	O
6. Amount of activities/practice	O	O	O	O	O	O
7. Quality of course materials	O	O	O	O	O	O
8. Effectiveness of instructor(s)	O	O	O	O	O	O
9. Overall quality of the course	O	O	O	O	O	O
10. Overall effectiveness of the self-study video format	O	O	O	O	O	O

11. Rate your level of knowledge of the topic before and after taking this self-study course.

	Very Low	Low	Moderate	High	Very High
BEFORE THE COURSE:	O	O	O	O	O
AFTER THE COURSE:	O	O	O	O	O

12. What did you like best about the course?

13. What would you improve in the course?

14. What previous experience, if any, have you had with self-study courses?

O None O Moderate O Considerable

15. Were you comfortable with the self-study video format? O Yes O No O Undecided
If not, why not?

16. Would you like to take other self-study video courses? O Yes O No O Undecided
If not, why not?

17. Additional comments:

PLEASE SEND THIS COMPLETED FORM TO YOUR DIRECTORATE/DIVISION TRAINING MANAGER (ATM). THANK YOU.

IVT Course Evaluation Form

Appendix E

END-OF-COURSE EVALUATION

Please give us your candid opinions concerning the training you have just completed. Your evaluation of the interactive video teletraining experience is important to us, and will help us provide the best possible products and services to you.

Course title: ____________________

Training site: ____________________

Date: ____________________

Number of years of FAA experience: __________

For the following, please completely darken the circle appropriate to your response.

	Very Good	Good	Average	Poor	Very Poor	N/A
1. Length of course	O	O	O	O	O	O
2. Depth of information	O	O	O	O	O	O
3. Pace of training	O	O	O	O	O	O
4. Clarity of objectives	O	O	O	O	O	O
5. Sequence of content	O	O	O	O	O	O
6. Amount of activities/practice	O	O	O	O	O	O
7. Quality of course materials	O	O	O	O	O	O
8. Effectiveness of instructor(s)	O	O	O	O	O	O
9. Equipment used in course	O	O	O	O	O	O
10. Quality of facilities/learning environment	O	O	O	O	O	O
11. Communications between student and instructor	O	O	O	O	O	O
12. Timeliness of feedback to student	O	O	O	O	O	O
13. Quality of graphics/visual aids	O	O	O	O	O	O
14. Adequacy of monitor screen size	O	O	O	O	O	O

	Very Good	Good	Average	Poor	Very Poor	N/A
15. Monitor picture quality	O	O	O	O	O	O
16. Monitor sound quality	O	O	O	O	O	O
17. Readability of text on monitor	O	O	O	O	O	O
18. Availability of site facilitator	O	O	O	O	O	O
19. Overall quality of the course	O	O	O	O	O	O
20. Overall effectiveness of interactive video teletraining process	O	O	O	O	O	O

	Yes	No	N/A
21. Were you given adequate instruction on the student One-Touch response system?	O	O	O
22. Did the One-Touch response system function satisfactorily?	O	O	O

23. What previous experience, if any, have you had with interactive video teletraining?

O None   O Moderate   O Considerable

24. Were you comfortable with interactive video teletraining?   O Yes   O No   O Undecided
If not, why not?

25. Would you like to take other interactive video courses?   O Yes   O No   O Undecided
If not, why not?

26. Rate your level of knowledge of the topic before and after taking this IVT course.

	Very Low	Low	Moderate	High	Very High
BEFORE THE COURSE:	O	O	O	O	O
AFTER THE COURSE:	O	O	O	O	O

27. What did you like best about the course?

28. What would you improve in the course?

29. Additional comments:

THANK YOU

(Optional)	
Name	Office phone ( )