Aeroelasticity

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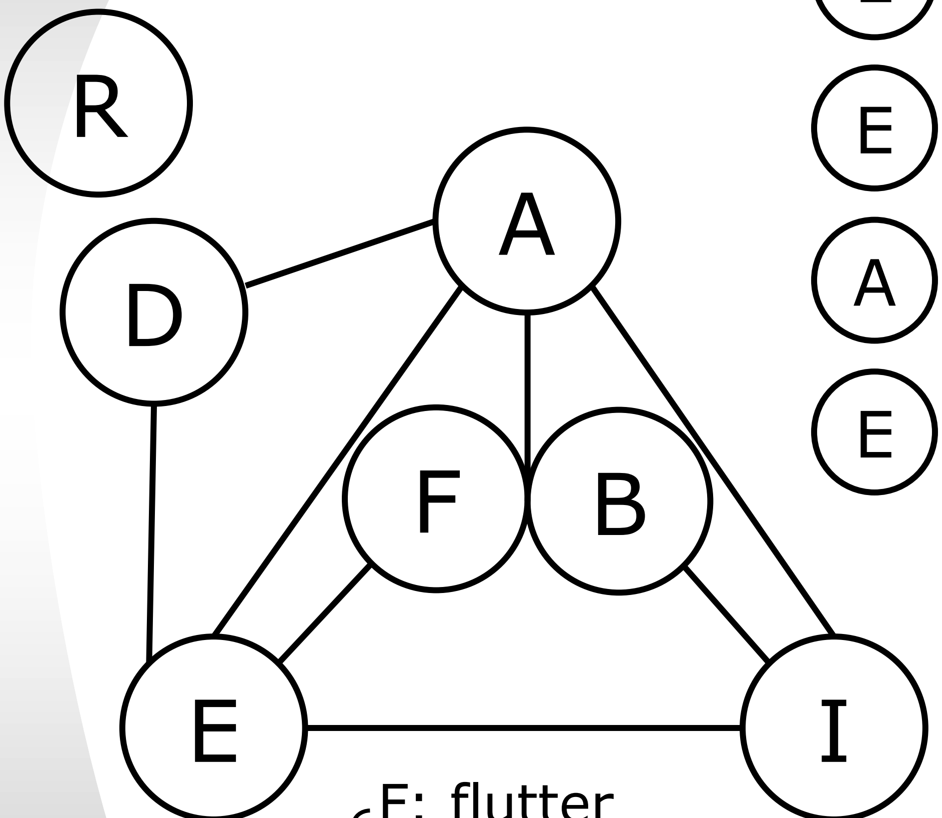
Introduction

Collar's Diagram (Fiangle)



- F: flutter
- B: buffet
- D: divergence
- R: reversal

E + I : Structural Dynamics

E + A : Static Aeroelasticity

A + I : Dynamic Stability (rigid body dynamics)

E + I + A : Aeroelasticity (dynamic aeroelasticity)

"The first fifty years of aeroelasticity" (1978)

- Aeroelastic problem

  : an increase in aerodynamic load will distort a structure in such a manner that incidence changes and increases the aerodynamic force further.

- At critical condition, the disturbing aerodynamic forces balance the restoring elastic forces, whatever the distortion

  → at any higher speed, the aerodynamic forces prevail and distortion increases indefinitely.

  → concerned with stiffness, not strength

- Named "aeroelasticity" ⋯ by Roxbee Cox, Pugsly in early 1930s.

"The first fifty years of aeroelasticity" (1978)

- Aerodynamic loads increase with speed, and aircraft speeds have steadily increased

  → aeroelastic problems cropped up regularly over the years

  → by 1950, treated as a routine aspect of aircraft design

1. The first decade

- Wright Brothers

  : used wing warping to achieve lateral control in man carrying gliders

  → applied to flyer.

- Samuel Langley ··· aeroelastic failure (1903)

  : powered flying machine two crashes → after the accident, the some machine made a successful flight with a greatly stiffened wing

"The first fifty years of aeroelasticity" (1978)

- Bryan (1906)

  : theory of the stability of a rigid aeroplane

  → aircraft stiffness happens to be infinite, only interplay of aerodynamic and inertia forces

2. First world war decade

- Griffith Brower (1913) ··· "The collapse of monoplane wings"
- wing divergence

  : Fokker D-8 ··· unbraced high-wing monoplane

  : As the load progressively applied, the wing twisted and the load being applied was quite unrepresentative of what would be the airload distribution.

"The first fifty years of aeroelasticity" (1978)

4. Decade of theoretical advance

- Aileron reversal

  : R. Cox and Pugsley (1930) ··· wing stiffness criterion

- Buffeting

  : Junkers (1930) ··· oscillation induced by eddies shed from the wing at high incidence

- Air screw flutter

  : Glauert (1929) ··· oscillating airfoil with a single d.o.f. related with "reduced frequency"

  : Duncan, Collar ··· add vertical translation d.o.f

  : Theodorsen (1935) ··· third d.o.f. (oscillating control surface)

"The first fifty years of aeroelasticity" (1978)

5. The fifth decade

- Jet-engine

 : buried in the wing (Meteor) ··· importance of compressibility effects

6. Four major problems

- Vibration

 : resonance tests of A/C to determine vibration characteristics and modes appropriate to flutter

- Quasi-static problems

 : loss and reversal of elevator control → longitudinal static stability

 : Aileron snatch and overbalance (Spitfire) due to upfloat

"The first fifty years of aeroelasticity" (1978)

- Flutter

  : trim and geared tabs with backlash → accident of Meteor

  : virtual inertia, Typhoon detachment of the whole tail

- Theoretical investigation (1943)

  : estimation of wing stiffness for experimental supersonic aircraft with a straight wing, 4% thickness-chord ratio

"Historical Development of Aircraft Flutter", (1981)

1. Introduction

- Aeroelastic problem of windmill

  : empirically solved in Holland four centuries ago by moving the front spars from about the mid-chord to the quarter-chord.

- Civil structures

  : torsionally weak bridges, Tacoma Narrow Bridge (1940)

2. The early years, 1903 ~ 1919

- The Wright Brothers

  : made beneficial use of aeroelastic effect for roll control by use of wing warping in place of aileron

  : loss of thrust of a propeller, due to twisting of blades

  → "little jokers" ~ elevator, or lackward sweep

"Historical Development of Aircraft Flutter", (1981)

- S. P. Langley

  : failure due to insufficient wing-tip stiffness → torsional divergence
- Lanchester and bairstow – the first documented flutter study
- Handley Page

  : violent anti-symmetric oscillation in fuselage and tail

  1) self-excited

  2) increase of torsional stiffness in elevator could eliminate the problem
- Bairstow

  : first theoretical flutter analysis

"Historical Development of Aircraft Flutter", (1981)

- Anthony Fokker – torsional divergence

  : static divergence problem
- H. Reissner (1926)

  : detailed analysis of torsional divergence, importance of relative locations of the aerodynamic center and the elastic axis.

3. Post World War I, to about 1930

- Baumhawer and Koring

  : mass balance of the aileron → decoupling of interacting modes to prevent flutter
- British experiment and research, 1925-1929

  : Frazer, Duncan (1929), "The Flutter Bible", semi-rigid modes

  : Perring (1928), scaled model to determine flutter speeds

"Historical Development of Aircraft Flutter", (1981)

- Unsteady Aerodynamics in the 1920s

  : Birnbaum (1923) ··· classical vortex theory of 2-D steady flow of thin airfoil → harmonically oscillating airfoil

  : Wagner (1925) ··· indicial response function of an airfoil in 2-D flow

  : Glauert (1929) ··· lift and moment of flat-plate airfoil undergoing steady angular oscillations

  : Küssner , improved numerical convergence on Birnbaum's method

- Some early U.S. work

  : Zahm, Bear (1927) ··· analysis on flutter Navy Mo-1 airplane, horizontal tail oscillations

  : M. Rauscher ··· MIT, wind tunnel models

  : J. C. Hunsaker, E.B. Wilson ··· gust and stability study

"Historical Development of Aircraft Flutter", (1981)

- Air racers encounter flutter

  : Boeing P-4 (1922) ··· flutter cure by covering the wing with stiff plywood veneer

  : Curtiss R-6 (1924) ··· sudden vibration

  : Supermarine S-4 racing monoplane

  ··· externally braced wings → crash

4. 1930 to World War II

- British studies

  : Havilland, Puss Moth (1932) ··· wing flutter, rudder & elevator flutter

  : Cox, Pugsley, Duncan, Mac Millan ··· aileron reversal

- Theodorsen ··· two-dimensional flutter theory

  : two-dimensional oscillating flat plate undergoing translation, torsion, and aileron-type motions

"Historical Development of Aircraft Flutter", (1981)

→ lags between the airfoil motions and the forces and moments that arise

→ good agreement with basic theory

- Propulsion of flapping wings and aerodynamic energy

  : Burgers ··· application of Birnbavrn's theory to the calculation of the horizontal forces on a flapping wing

  : Wu, Lighthill, "biofluid-dynamics"

- Oscillatory/indicial aerodynamics

  : frequency response function and Heaviside response to unit step excitation

  Wagner's function $K_1(s)$ ← Fourier → Theodorsen's function

  Küssner's function $K_2(s)$ ← Fourier → Sear's gust function

"Historical Development of Aircraft Flutter", (1981)

- Aerodynamic hysteresis

  : Farren ··· complex nonlinear hysteresis effects for an oscillating airfoil
- Empirical criteria

  : Küssner, a criterion based on the reduced torsional frequency

  : Cox, based on wing torsional stiffness
- Flight flutter testing

  : Schilippe ··· resonance testing – plot of resonance amplitude against airspeed

  : Junker ··· 400-hp motor in the fuselage to drive vibration in the wings
- Propeller whirl flutter

  : Tayler ··· Browne, gyroscopic precession of a flexibly mounted engine-propeller system

"Historical Development of Aircraft Flutter", (1981)

- Matrix methods

  : Frazer ··· Duncan, Collar (1938)

  : Loring ··· matrix methods both in structure and aerodynamics

- Compressibility effects

  : Prandtl ··· introduced the useful concept of acceleration potential

  : Possio ··· applied acceleration potential to the 2-D non-stationary problem → integral eqn. (Possio's eqn.)

- Finite span considerations

  : Prandtl ··· lifting-line method, developed by Cicala

- General lifting line theory

  : Küssner ··· Küssner's kernel function K

  → general explicit expression developed by NASA Langley engineers

"Historical Development of Aircraft Flutter", (1981)

5. World War II to the Mid-1950s

- V, g flutter diagram

  : Smilg, Wassernam (1942) ··· comprehensive table of unsteady aerodynamic coefficients based on Theodorsen theory

  : v. g flutter diagram ··· flutter condition is represented by the crossing of g=0

- Unsteady Aerodynamic measurements and aeroelastic modes

  : "wattmeter" harmonic analyzer, Kennedy-Parncu vector method

  ··· vibration measurement and analysis

  : replica- type wind tunnel model

  ··· PBM-1, Valtee XP-54 (elevator flutter)

  ··· Junker JU-288 (suspended by wires)

"Historical Development of Aircraft Flutter", (1981)

: much simpler model ··· single metal spar + aerodynamic form (balsa wood pods)

: 4 ft wind tunnel (1946) ··· Langley lab., test medium → TDT

- Transonic flutter problems

: "aileron buzz" ··· P-80, a single d.o.f. flutter caused by the coupling of aileron rotation and chordwise motion of shock waves on the wing

→ Increased control stiffness, dampers, profile shape change

: Arthur A. Regier ··· empirical criterion for avoidance of flutter

$$(\omega_\beta c_\beta / z_\infty) > 0.2 \sim 0.3$$

: B-47 ··· sweep and aeroelastic tailoring

: transonic wind tunnel test ··· model dropped from high flying aircraft

··· ground-launched rocket-propelled model

"Historical Development of Aircraft Flutter", (1981)

: transonic wind tunnel test ··· model dropped from high flying aircraft

··· model placed on the upper surface of an airplane wing

··· rocket sleds capable of transonic speed

- Flutter of supersonic speeds

: rearward shift of aerodynamic center → classical coupled flutter less likely to occur, flutter would not be ruled out due to sweep, etc. nonlinear effects of thickness

: panel flutter ··· occur involving the skin covering, standing or travelling ripples persisted → V-2. Saturn V

"Historical Development of Aircraft Flutter", (1981)

- Flutter incidences

: NACA sub committee (1956) ··· 54 flutter difficulties

- 21 transonic control surface buzz
- 7 wing flutter associated with externally mounted
- stores including pylon-mounted engine
- 4 flutter encounters with all-movable control surfaces

- The computer revolution and Finite Element Method

: Analog ··· V. Bush, differential analyzer

: Digital ··· early 50's symposium on flutter sponsored by IBM

: Difference eqn. ··· finite element analysis

“Historical Development of Aircraft Flutter”, (1981)

- The transonic dynamics tunnel

: A. A. Regier (1951)

1) large as feasible to enable accurate simulation of mode details, such as control surfaces
2) Wide range of density to simulate various altitude conditions
3) test medium ··· Freon gas to enable a use of heavier, less expensive model, higher Reynold No., less tunnel power
4) Mach No. ~ 1.2

→ Operational in 1960

"The Renaissance of Aeroelasticity and its Future", (1999)

1. Progress in 1970-1986

- rotary-wing aeroelasticity

: understanding of the flap-lag instability

: recognition that it is inherently nonlinear

: fundamental mechanism of coupled flap-lag-torsional instability in hover/forward flight

: correct numerical treatment of eqn. with periodic coefficients

: fundamental understanding of the coupled rotor-fuselage aeromechanical problems

: tilt-rotor aeroelastic problems

: active control vibrations in helicopter

“The Renaissance of Aeroelasticity and its Future”, (1999)

2. Aeroservoelasticity

- Historical perspective

: flight/wind tunnel test with active flutter suppression or load alleviation devices – CCV B-5ZE, DAST (drones for aeroservoelastic testing, NASA), YF-16, YF-17, X-29A

- Analytical method and some observations

: flutter suppression

··· aerodynamic energy concept, frequency-domain aerodynamics

: rational function approximation (RFA) ··· time domain

: optimal control theory ··· full-state feedback (LQR)

: reduced-order controller

"The Renaissance of Aeroelasticity and its Future", (1999)

- Adaptive control example

: 2-D typical cross section with a trailing-edge control surface

: unsteady aerodynamics ··· exact solution of the Euler eqns using a mixed Eulerian-Lagrangian formulation

: adaptive controller ··· ARMA model, deterministic

: flutter suppression in the presence of strong moving shock

··· NACA 64A006 airfoil, M=0.85, 20% above flutter speed

- Active flexible wing (AFW) program

: Rockwell, Air Force Wright Lab., NASA Langley

: actively controlled, statically and dynamically, full-span, wind tunnel model of an advanced tailless fighter

"The Renaissance of Aeroelasticity and its Future", (1999)

: flutter suppression system ··· discrete, low-order, robust control laws

→ Only one scheme achieved 24% increase of unaugmented flutter dynamic pressure

3. Selected topics in computational and nonlinear aeroelasticity

- Use of CFD ··· (a) transonic, low a.o.a.
  ··· (b) lower speed, high a.o.a.
  ··· (c) hypersonic
- Transonic flutter

: transonic dip ··· one of the most critical flutter conditions
··· flutter speed reaches minimum at the high subsonic Mach No.

"The Renaissance of Aeroelasticity and its Future", (1999)

: fluid dynamic model

1) classical, linear, small disturbance eqn.

2) nonlinear potential eqn. - transonic small disturbance (TSD)

- full potential (FP)

3) Eulerian eqn. (EE)

4) thin-layer Navier-Stokes (TLNS), complete Navier-Stokes (CNS)

- Computation of Transonic Bucket - examples

: CAP-TSDN code ⋯ lag-entrainment integral boundary layer method

+ CAP-TSD → 3-D case

: AGARD 445.6 wing ⋯ flutter speed index $V_f = \dfrac{V}{bs\omega_\alpha\sqrt{\mu}}$ (Fig. 6)

⋯ good agreement, incapable of capturing ascent

from transonic bucket

"The Renaissance of Aeroelasticity and its Future", (1999)

: STARS program ⋯ worse agreement, able to capture ascent (Fig. 7)

: Business jet wing ⋯ (Fig. 8)

- The mixed Eulerian-Lagrangian approach

: classical approach ⋯ fluid, structure modeled separately, coupled by specifying kinematic boundary conditions

: mixed F-L scheme ⋯ fluid structure system treated as a single continuum dynamics problem, kinematic/kinetic boundary conditions satisfied locally at the fluid/structure boundary. (Fig. 9, 10)

- Reduced order models

: Eigen solution from linearized eqn. → modal structure of fluid

→ Much smaller set of decoupled eqns

“The Renaissance of Aeroelasticity and its Future”, (1999)

- Nonlinear aeroelasticity

(1) rotary-wing

(2) transonic

(3) high a.o.a. (stall flutter, maneuvering flight)

(4) panel flutter

(5) free-play type of structural nonlinearity

: Transonic LCO ··· highly maneuverable fighter aircraft, $0.8<M<1.1$

··· nonlinear aerodynamic forces

: Free-play type of structural nonlinearity

··· nonlinear restoring force/moment (Fig. 11)

→ (Fig. 12), nonlinear flutter

··· preloaded free-play nonlinearity (Fig. 13)

"The Renaissance of Aeroelasticity and its Future", (1999)

4. Rotary wing aeroelasticity

- Fundamental Differences between rotary-wing and fixed-wing

: fixed wing ··· coupled bending-torsion → linear

: rotary wing ··· coupled flap-lag-torsion → inherently nonlinear due to moderate (large) deflections

: hover ··· const. coefficient ← eigen analysis

: forward flight ··· periodic coefficient ← Floquet theory

: Trim ··· propulsive trim, wind-tunnel trim

: coupled rotor/fuselage instability ··· aeromechanical problems, ground/air resonance

: vibration prediction and control, unsteady free wake

"The Renaissance of Aeroelasticity and its Future", (1999)

- Primary activities during the last six years

: composite blade → hingeless, bearingless, tiltrotor

: effect of lag dampers … nonlinear properties of elastomeric dampers

: comprehensive helicopter analysis code … CAMRAD II, 2GCHAS,
RDYNE, COPTER

: improved wake models, periodic system and trim procedures

: aeroelastic response or vibration reduction wing active control

- Representative examples

1) vibration reduction using a actively controlled flap (ACF)

… 91 % reduction of hub shear, 10-20 times less power, no effect on vehicle airworthiness

“The Renaissance of Aeroelasticity and its Future”, (1999)

2) aeroelatic stability with elastomeric lag dampers

··· nonlinear inelastic displacement field (ADF) damper

3) ACSR to vibration reduction

··· controlled forcing inputs at selected locations

coupled rotor/fuselage model (Fig. 21), very low power requirements

5. Impact of New Technologies on Aeroelasticity

: composite materials → aeroelastic tailoring

: active materials ··· static aeroelasticity, wing-lift effectiveness, divergence, supersonic panel flutter, flutter and dynamic load alleviation, vibration reduction in helicopter rotors, wing/store flutter suppression

"The Renaissance of Aeroelasticity and its Future", (1999)

1) Strain-actuated active aeroelastic wing

: MIT, Langley ··· in-plane isotropic piezoelectric actuator to produce bend-twist coupling → 12% of the wing weight

considerably lower flutter dynamic pressures

2) Wing/store flutter suppression using a piezo-strut

: piezoceramic wafer actuator to replace the passive decoupler pylon

→ Flutter of wing/store configuration → 6.25% increase

3) Magneto-strictively actuated control flaps in helicopter

: flap actuated by a magnetostrictive rod made of Terfnol-D

→ vibration reduction system: 6% of blade weight

→ 90% reduction of vibration reduction of cruise condition

"The Renaissance of Aeroelasticity and its Future", (1999)

4) Smart rotor program at U. Maryland

: trailing-edge flap with piezo-induced bending-torsion coupled actuator is the most promising one.

5) Mesoscale actuator devices for rotorcraft

: substantially enhance the force and stroke capability

6. Experimental Verification

- NASA Ames ··· 40 x 80 ft rotorcraft tunnel, very few correlation
- Aeroelastic scaling ··· small models with adaptive materials → overly optimistic results → aeroelastic scaling carefully considered.

"The Renaissance of Aeroelasticity and its Future", (1999)

7. New configurations

- X-33 advanced technology demonstrator

··· hypersonic vehicle, N-S eqn.

- Large, high flying UAVs ··· very flexible, high altitude, low Reynolds No.

→ ASE challenges

8. Aeroelasticity and Design

- Wing/control shape optimization with active control and ASE constraints
- Structural optimization of helicopter with multidisciplinary constraints

9. The Future

- ASE ··· advanced control theory, UCAV
- Rotary-wing ··· computational unsteady aerodynamics, BVI studies, ACF
- Adaptive structures ··· both in rotary and fixed-wing applications
- Turbomachinery