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Computational Aeroelasticity

The Cultural and Convention Center
METU
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presented by
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General Electric Corporate Research & Development Center
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Presentation Outline

- Introduction
  - Fluid-Structure Interactions
    - Aeroelasticity
  - Aeroelastic analysis/design in an MDA/MDO Environment
- Static Aeroelasticity
- Dynamic Aeroelasticity
- Commercial Programs with Aeroelastic Analysis/Design Capabilities

Dynamic Aeroelastic Phenomena

- Dynamic Response
- Limit Cycle Oscillations (LCO)
- Buffet
- Flutter

Solutions found in time, frequency, and Laplace domain usually with generalized coordinates

Dynamic Response

Transient response due to a rapidly applied load.

- Atmospheric Turbulence
  - Continuous random
  - Discrete random (gust)
- Landing loads
- “Snap” maneuvers
- Store Separation

Dynamic Aeroelasticity

Limit Cycle Oscillations

Typically caused by shock induced oscillations on a surface or flow/ shocks attaching/detaching from a surface trailing edge.

- Panel Flutter
- Control Surface “Buzz”
- Store/Wing configurations

Reduces structural life

Usually requires nonlinear flow conditions and possibly nonlinear structures (cs hinge stiffness)

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Dynamic Aeroelasticity

Buffet

Response due to time-dependent *separated* flows (usually vortical) impinging on structural surfaces.

- Bluffed bodies on horizontal and vertical surfaces
- Wings, strakes etc.. on vertical tails (often a twin tail problem)

Reduces structural life

Requires nonlinear aerodynamics to capture phenomena

Flutter

Dynamic instability where-by the system extracts energy from the free stream flow producing a divergent response.

- Usually resultant of coupling of 2 or more structural modes
  - Wing bending and torsion
  - Wing bending control surface hinge torsion
  - Wing torsion fuselage bending
  - Horizontal or vertical tail and fuselage

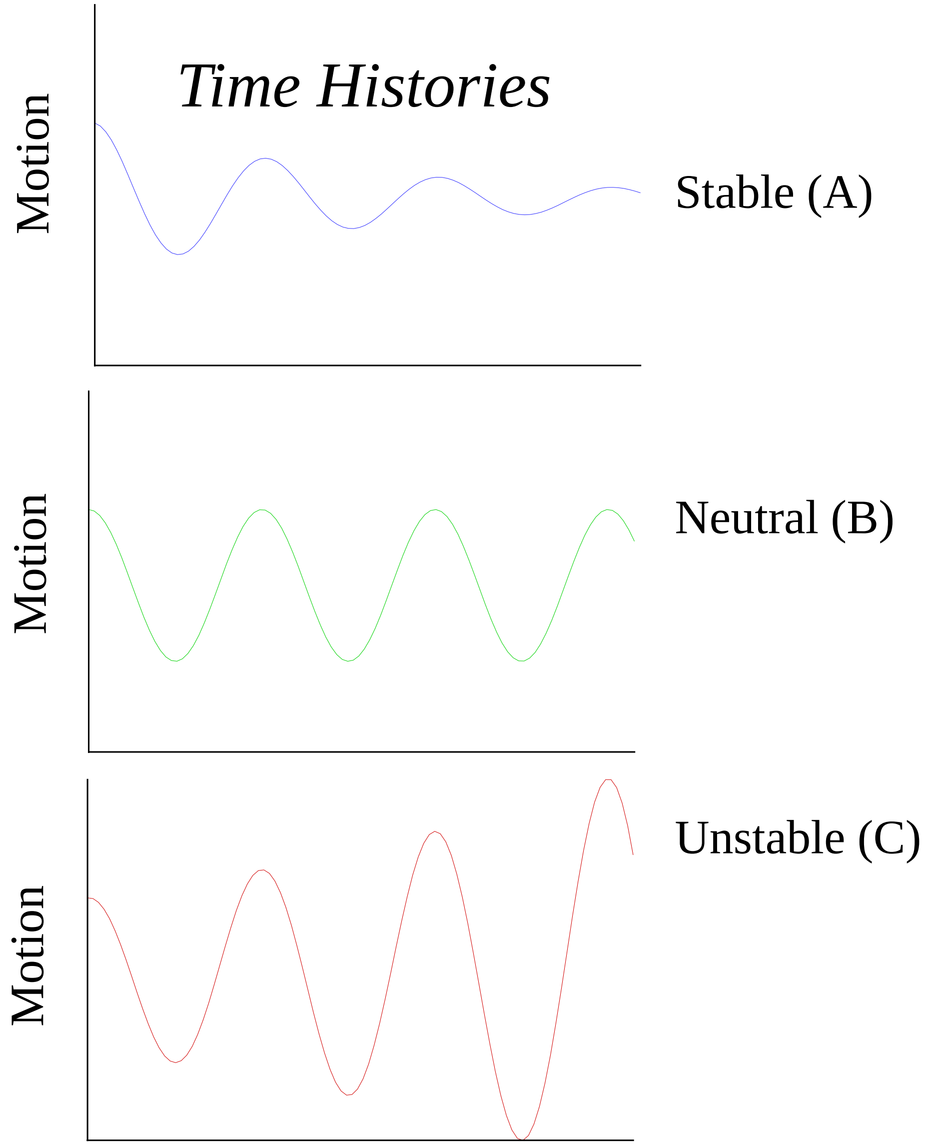
Divergent behavior can occur within a few cycles and be cata-strophic

Theodore Von Karman is said to have remarked that

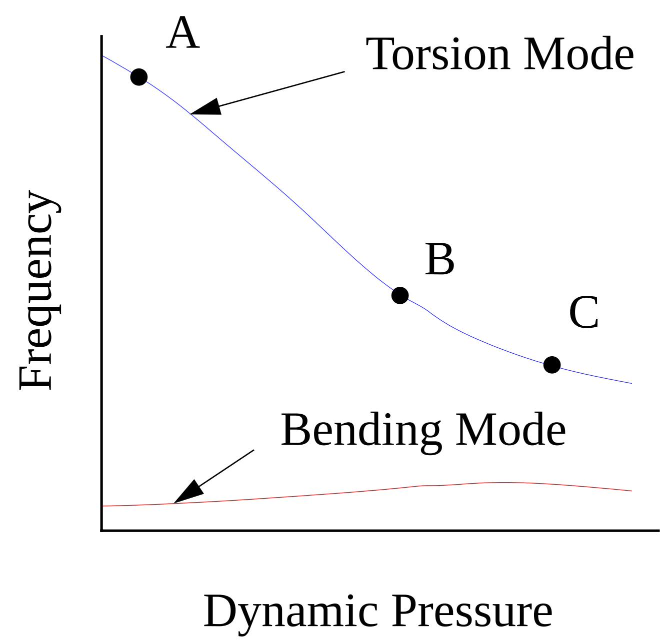
> *"some men fear flutter because they do not understand it, while others fear it because they do"*[8]

Dynamic Aeroelasticity

Flutter



Modal Coupling



Dynamic Aeroelasticity

Flutter

From the aeroelastic EOM

$$M\ddot{u} + Ku = F(u, \dot{u}, \ddot{u}, t) \tag{20}$$

let

$$F(u, \dot{u}, \ddot{u}, t) = F(u, \dot{u}, \ddot{u}) + \bar{F}(t) \tag{21}$$

Where $\bar{F}(t)$ represents motion independent external forces

Eq. (20) can be written as

$$M\ddot{u} + B\dot{u} + Ku = [Q_1]\ddot{u} + [Q_2]\dot{u} + [Q_3]u + \bar{F}(t) \tag{22}$$

For stability solve the homogenous equation from some initial state.

$$M\ddot{u} + B\dot{u} + Ku = [Q_1]\ddot{u} + [Q_2]\dot{u} + [Q_3]u \tag{23}$$

(23) can be solved by time integration or as an eigenvalue problem

Eigenvalue Solutions

Transform (23) to modal coordinates $\{u_h\}$ and assume that the unsteady aerodynamics depend only on displacements

$$M_{hh}\ddot{u}_h + \bar{B}\dot{u}_h + K_{hh}u_h - \frac{1}{2}\rho V^2[Q_{hh}]u_h = 0 \qquad (24)$$

Assume that the structural response is separable and synchronous

$$\{u_h\} = \{q_h\}e^{st} \qquad (25)$$

With $\{q_h\}$ independent of time and $s = \sigma + i\omega$.Substituting into (24) gives

$$\left[M_{hh}s^2 + B_{hh}s + K_{hh} - \frac{1}{2}\rho V^2 Q_{hh}\right]\{q_h\} = 0 \qquad (26)$$

Dynamic Aeroelasticity

- Eq. (26) is the basic flutter eigenvalue equation
- All matrices can be expressed as real but the aeroelastic stiffness matrix $\left[K_{hh} - \frac{1}{2}\rho V^2 Q_{hh}\right]$ is unsymmetric causing roots to be complex conjugate pairs.
- Q_{hh} - Generalized unsteady aerodynamic forces
  - Often assumed harmonic cast in frequency domain with amplitude and phase
  - Doublet Lattice, CPM, Mach Box, Strip Theory
- Several solutions exist for solving (26)
  - K Method
  - $K-E$ Method
  - $P-K$ Method
  - P Method
  - State space

P-K Flutter Solution

s can be expressed as $s = \frac{Vk}{b}(\gamma + i) = \frac{V}{b}p$. (26) becomes

$$\left[\left[\frac{V}{b}\right]^2 p^2 \boldsymbol{M}_{hh} + \frac{V}{b}p\boldsymbol{B}_{hh} + \boldsymbol{K}_{hh} - \frac{\rho V^2}{2}\boldsymbol{Q}(k)_{hh}\right]\boldsymbol{q}_h = 0 \qquad (27)$$

V - selected freestream speed

b - reference semi-chord

$p \equiv k(\gamma + i)$ - complex response frequency and eigenvalue

$\boldsymbol{M}_{hh}$, $\boldsymbol{B}_{hh}$, $\boldsymbol{K}_{hh}$ generalized mass, damping, stiffness matrices

$\boldsymbol{Q}_{hh} = [\boldsymbol{Q}^R + i\boldsymbol{Q}^I]$ - generalized aerodynamic matrix

ρ - freestream density

k - reduced frequency, $k = \frac{\omega b}{V}$

q_h - eigenvector of modal coordinates

γ - damping factor

$i \equiv \sqrt{-1}$

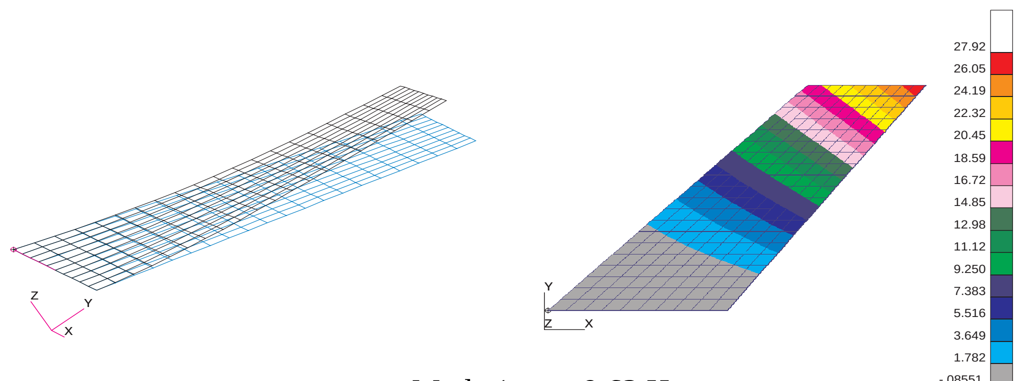
P-K Method Comments

- Matrices are real but non-symmetric yielding complex roots.
- Flutter equation only "*true*" when $\gamma = 0$, an estimate elsewhere
- Mode switching often occurs making results interpretation difficult
- Q_{hh} depends on Mach number and reduced frequency $Q_{hh}(M, k)$
- Solution requires Q_{hh} to be a continuous function of k.
  - Results in curve fitting Q_{hh} which can cause errors
- Above formulation does not allow $k = 0$
- User responsible for determining "match point solutions"

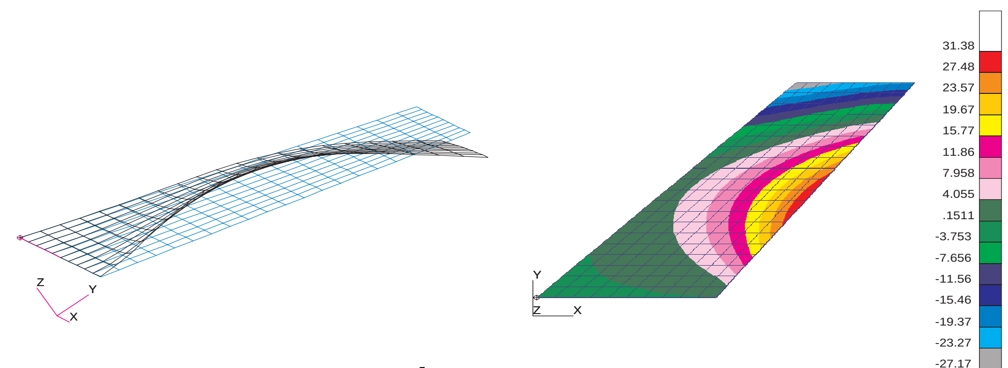
Dynamic Aeroelasticity

AGARD 445.6 Flutter Calculations

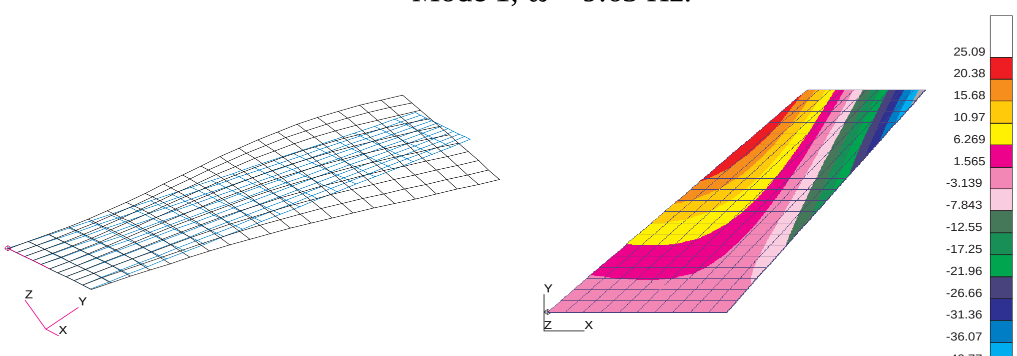
Mode Shapes and frequencies



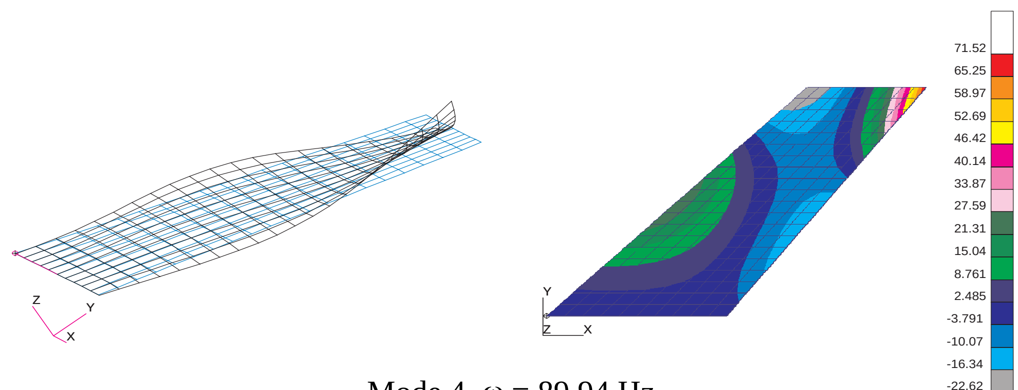
Mode 1, ω = 9.63 Hz.



Mode 3, ω = 50.50 Hz.



Mode 2, ω = 37.12 Hz.



Mode 4, ω = 89.94 Hz.

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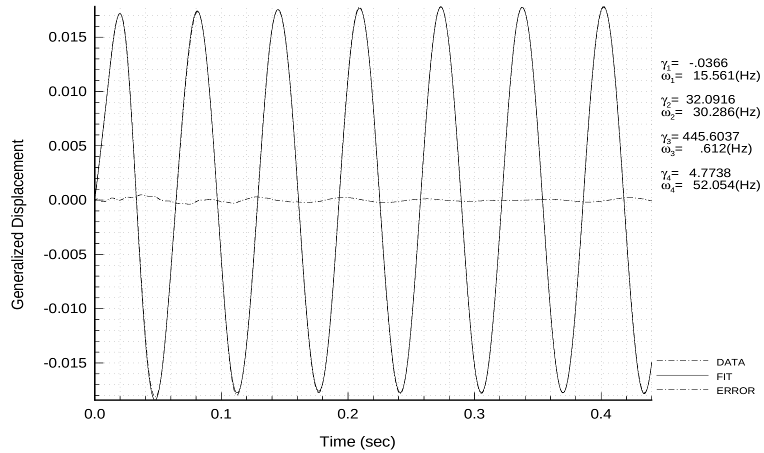
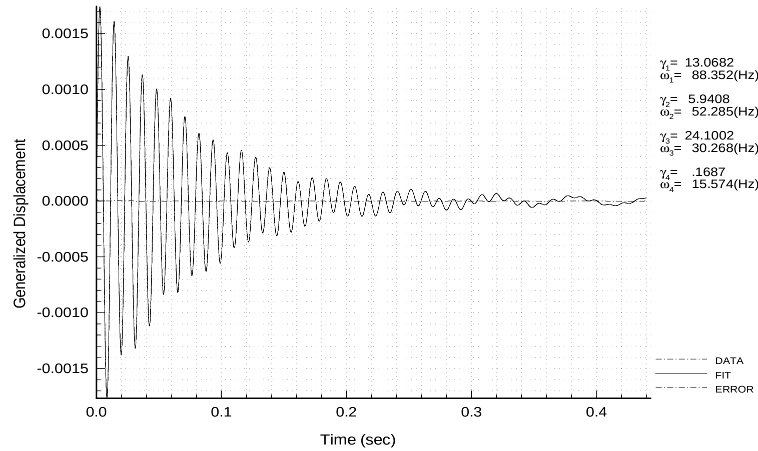
AGARD 445.6 Time Integration Response

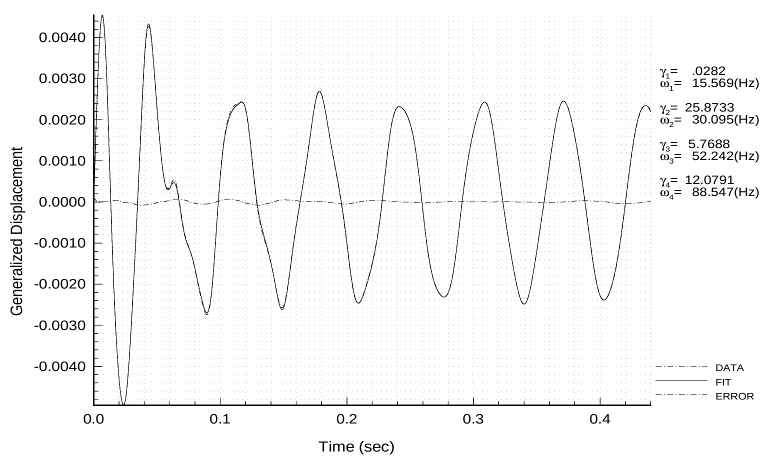
$$M = 0.901,\ q = 0.66\text{psi},\ U = 11908\ \text{in/sec}$$



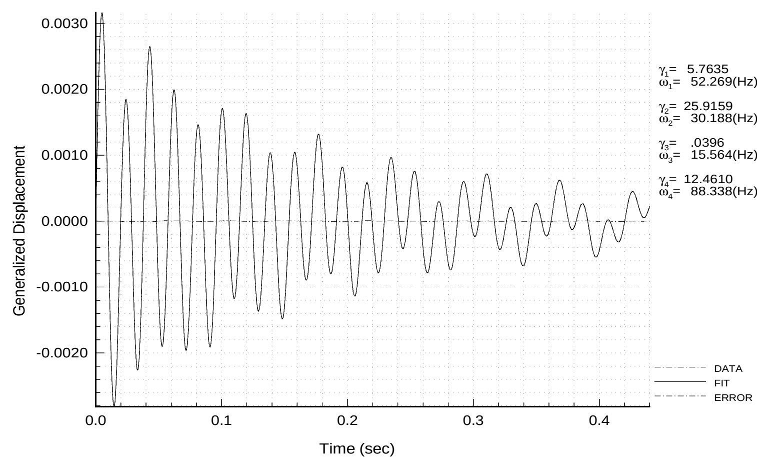
Mode 1



Mode 3



Mode 2



Mode 4

Dynamic Aeroelasticity

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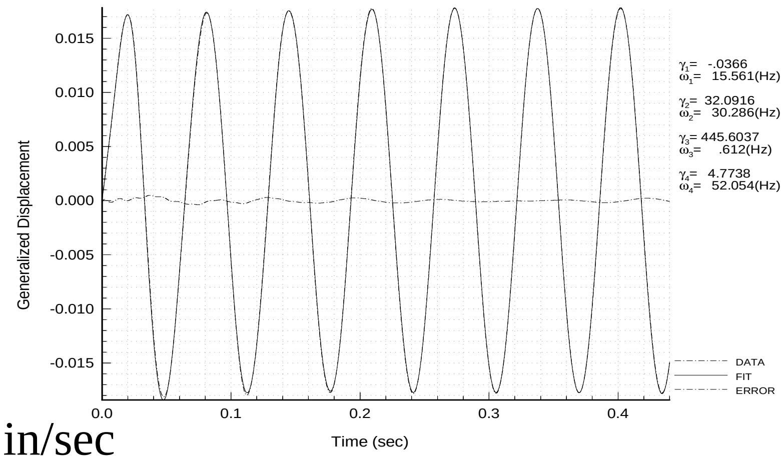
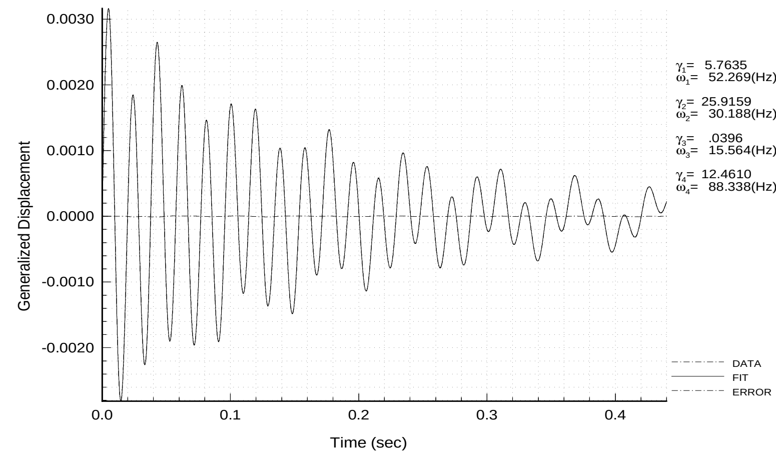
AGARD 445.6 Time Response Integration

$$M = 0.901,\ q = 0.67\text{psi},\ U = 11998 \text{ in/sec}$$



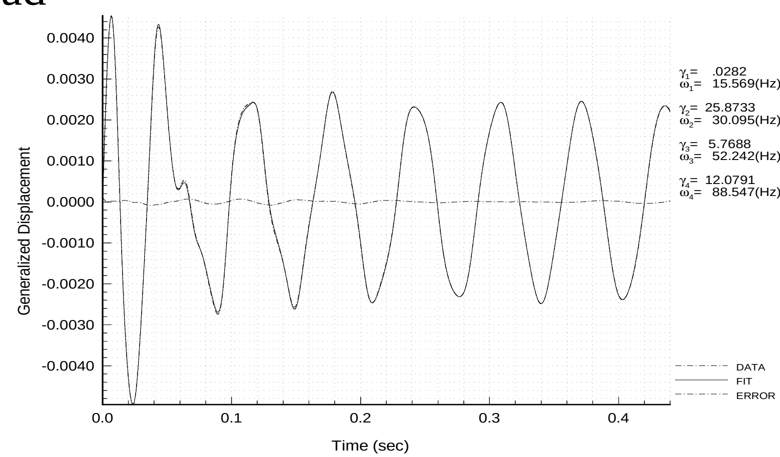
Mode 1



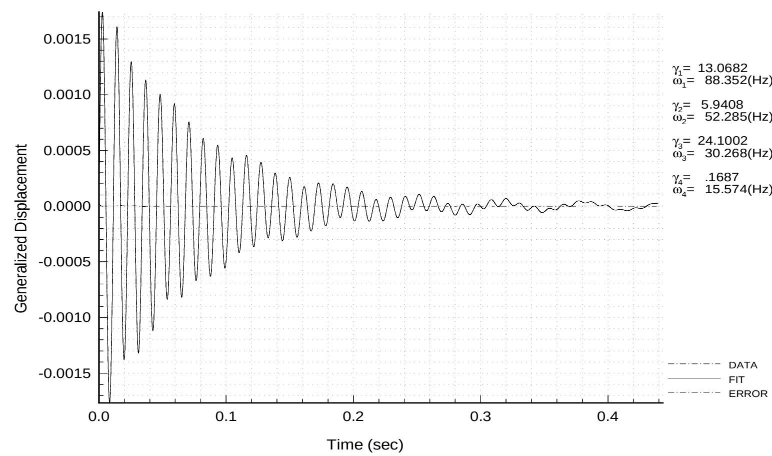
Mode 3

$V_f = 11{,}971$ in/sec

$\omega_f = 90$ rad

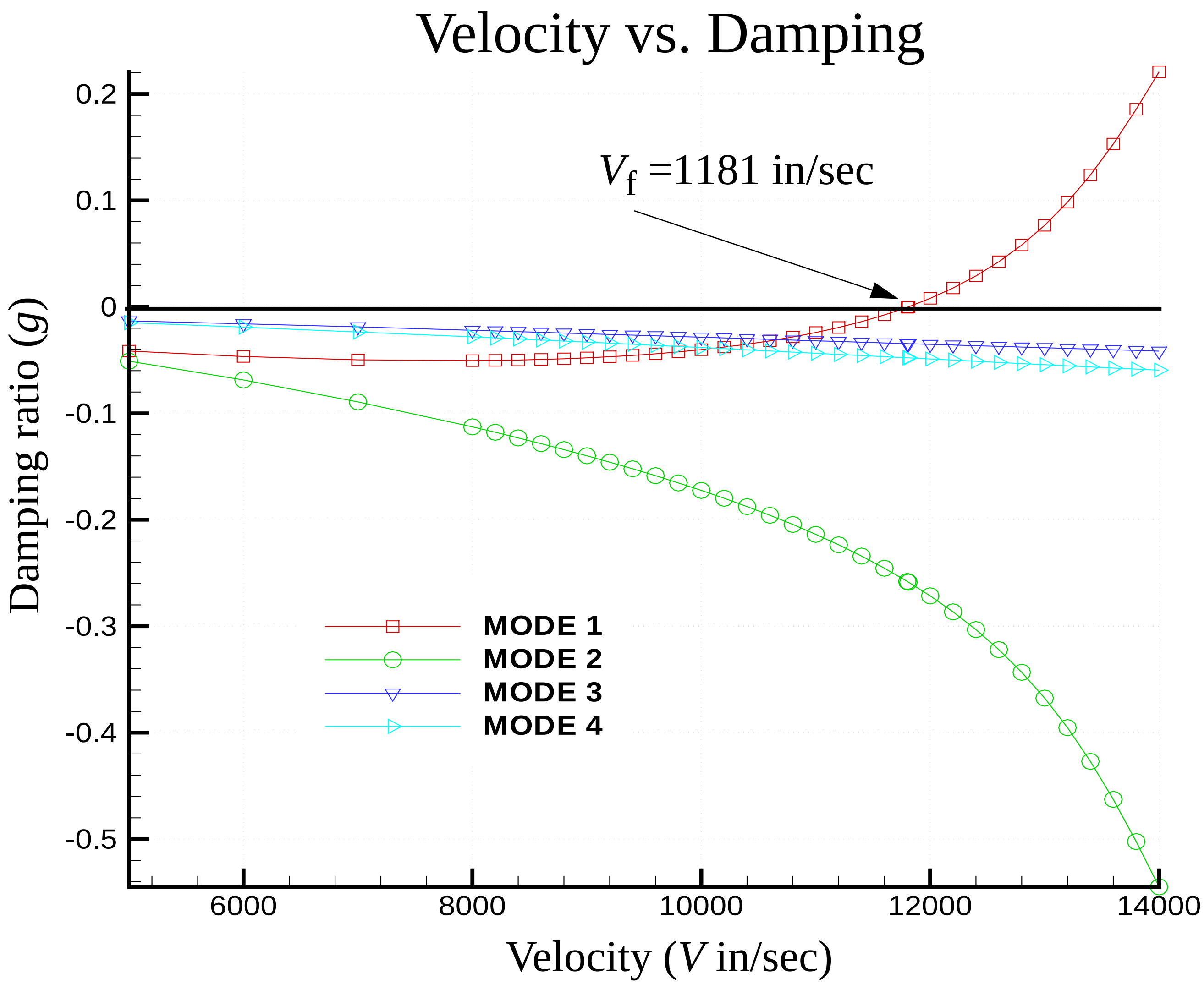


Mode 2

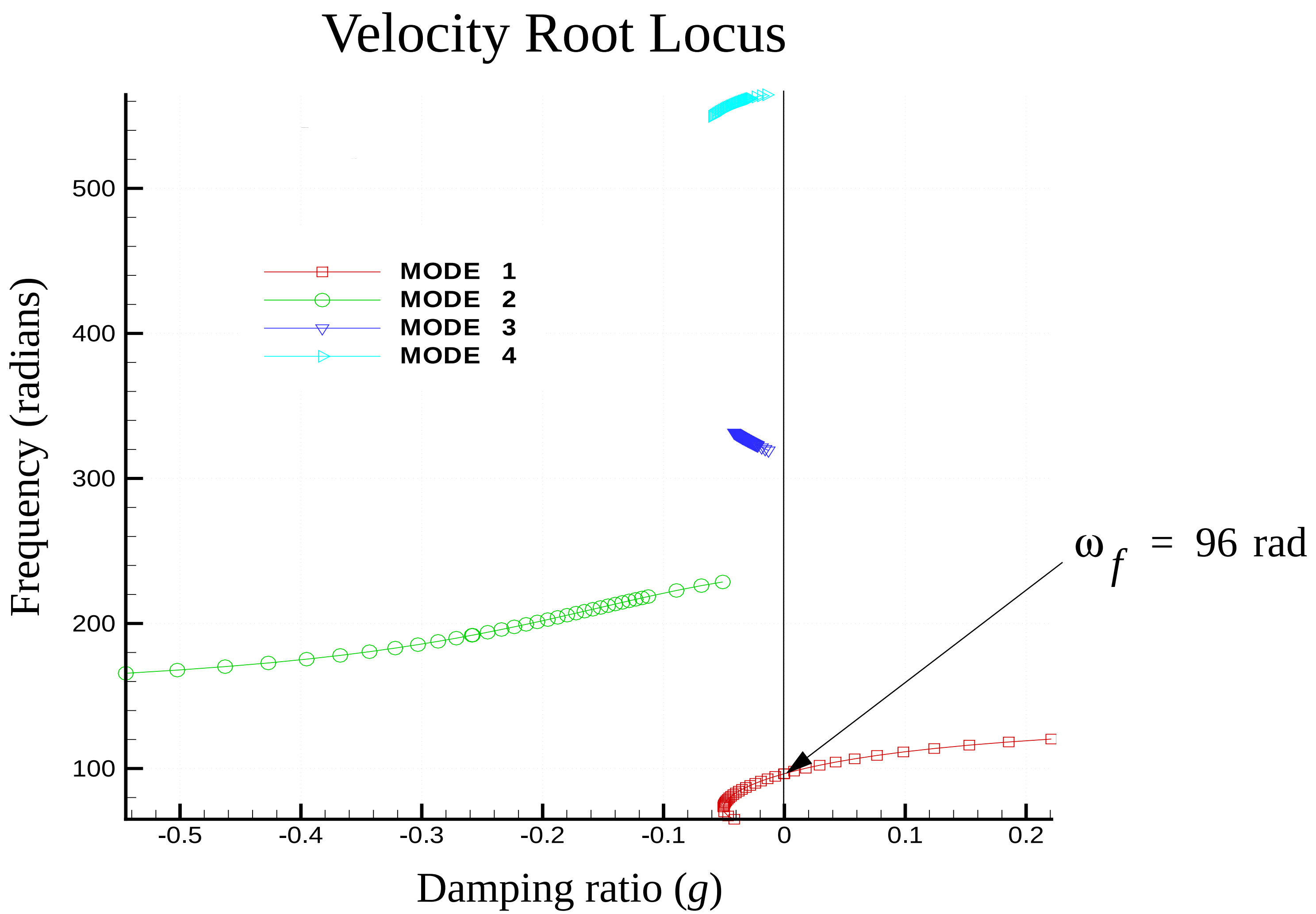


Mode 4

AGARD 445.6 P-K Flutter Solution

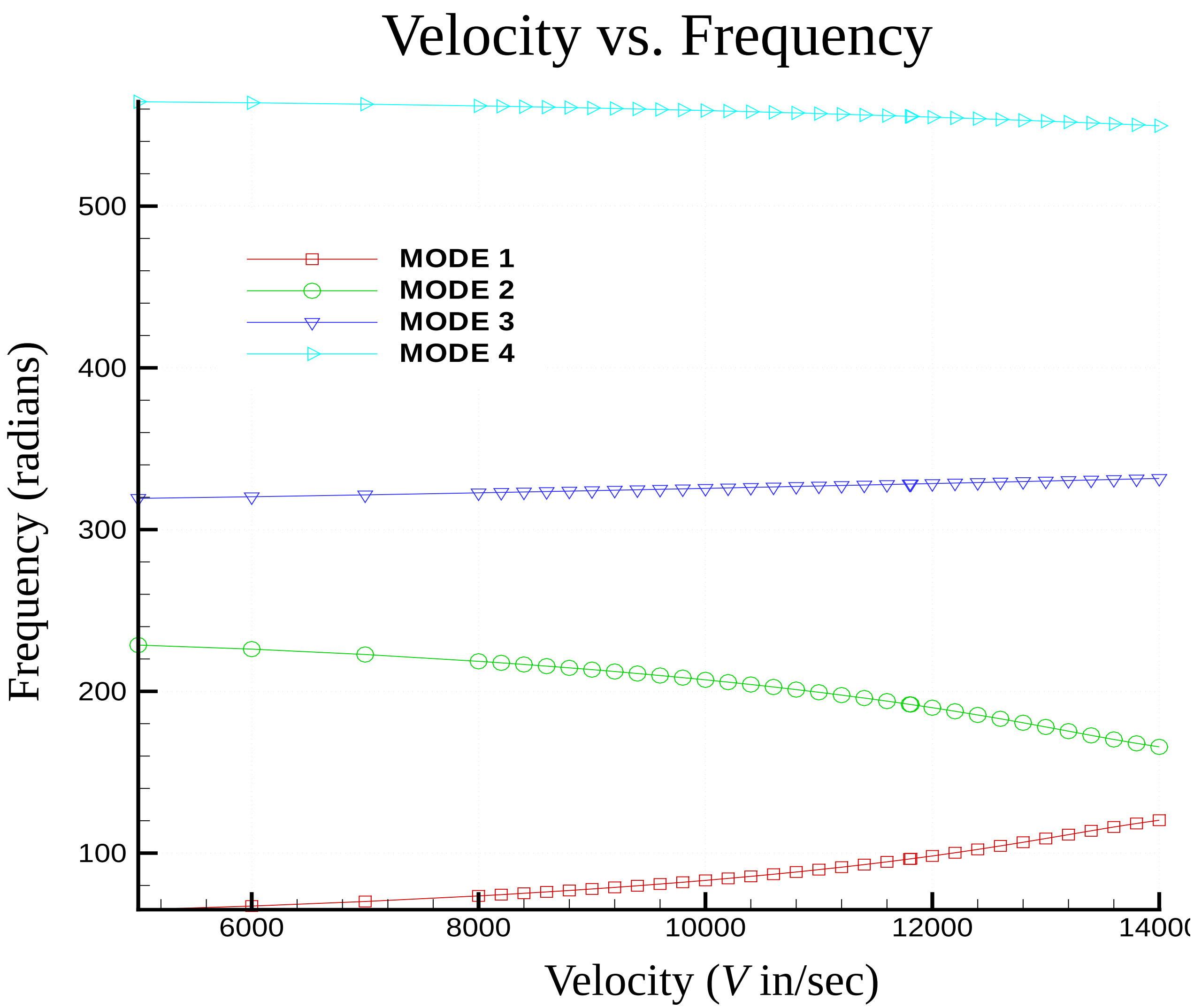


AGARD 445.6 P-K Flutter Solution



Dynamic Aeroelasticity

AGARD 445.6 P-K Flutter Solution



Aeroelastic Software

Global Aeroelastic Software Developments

- MSC/NASTRAN (U.S.)
- UAI/ASTROS (recently bought by MSC) (U.S.)
- UAI/NASTRAN (U.S.)
- ELFINI (France, Dessault)
- LAGRANGE (Germany, formerly MBB)
- STARS (Great Britain, RAE)
- OPTSYS (Sweden, SAAB)
- COMPASS (China)
- ARGON (Russia, Central Aerohydrodynamic Institute)

Aeroelastic Software

MSC/NASTRAN

- Steady Aerodynamics
  - Subsonic
    - Doublet Lattice (k=0)
    - 3-D panel Method (available in the near future)
    - Bypass option for any AIC
  - Supersonic
    - ZONA51
    - Bypass option for any AIC
    - Aerodynamic database
    - Import/export loads data

- Unsteady Aerodynamic
  - Subsonic
    - Doublet Lattice with body interference
    - Strip Theory
  - Supersonic
    - Mach Box

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Aeroelastic Software

- Piston Theory
- ZONA51

- Structural Modeling
  - Very rich selection of FE

- Static Aeroelastic Analysis
  - 5 DOF trim (no drag/thrust trim)
  - Flexible increment analysis
  - Computes rigid, restrained and unrestrained flexible stability derivatives
  - Able to add experimental load correction factors to AIC
  - Divergence of restrained vehicle
  - Slender body models
  - Multiple set selectable aerodynamic models
  - Aeroelastic database
  - Import/export loads data

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Aeroelastic Software

- Dynamic Aeroelasticity
  - Frequency response analysis
  - Random analysis
  - Transient analysis
  - Gust (random and discrete 1-d)
  - Flutter P-K, K, K-E (K-E allows k=0)
  - $Q(M, k)$ curve fits cubic through all points
- F-S Interface
  - Infinite plate spline
  - Thin plate spline
  - Finite plate spline
  - Beam spline
  - Rigid load Transfer
- Pre-Post Processing
  - Extensive Flight Loads pre/post processing functionality in PATRAN environment

UAI/ASTROS Aeroelastic Capabilities

- Steady Aerodynamics
  - Subsonic
    - USSAERO (Woodward Aerodynamics, flat panel)
    - QUADPAN (Lockheed Martin, 3-D panel)
    - Bypass option for any AIC
    - Multiple set selectable aerodynamic models
  - Supersonic
    - USSAERO (flat panel)
    - QUADPAN (3-D panel)
    - Bypass option for any AIC
- Unsteady Aerodynamic
  - Subsonic
    - Doublet Lattice
  - Supersonic
    - Constant Pressure Method (Apa, Northrop)

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Aeroelastic Software

- Structural Modeling
  - Membrane type FEM (Rods, Beams, Shear panels, Quadrilateral Plates, Composites)
- Static Aeroelastic Analysis
  - Full 6 DOF Trim
  - Computes rigid and four types of flexible stability derivatives
  - User defined loads
  - Trim Optimization
- Dynamic Aeroelasticity
  - Gust Response
  - Flutter P-K (computes flutter velocity)
  - Several choices for $Q(M, k)$ curve fits
- F-S Interface
  - Infinite Plate spline

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Aeroelastic Software

- 3-D surface spline
- Beam spline
- Rigid load Transfer

• Very easy to add user defined functionality and tailor the system

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References

1. Bisplinghoff, Ashley and Halfman “Aeroelasticity”, Dover Publications, Addison-Wesley Publishing Company, Inc., 1995.

2. Weisshaar, “Fundamentals of Static and Dynamic Aeroelasticity”, Purdue University School of Aeronautics and Astronautics, West Lafayette, IN 1992.

3. Smilg, B. and Wasserman, L. S., “Application of Three Dimensional Flutter Theory to Aircraft Structures”, USAAF TR 4798, 1942.

4. Neill, D.J., Herendeen, D.L., Venkayya, V.B., “ASTROS Enhancements, Vol III-ASTROS Theoretical Manual”, WL-TR-95-3006.

5. Bendiksen, Oddvar O., “Fluid-Structure Coupling Requirements for Time-Accurate Aeroelastic Simulations”, AD-Vol.53-3, Fluid-Structure Interaction, Aeroelasticity, Flow-Induced Vibration and Noise, Volume III ASME, 1997.

6. Farhat, C., “Special course on Parallel Computing in CFD”, AGARD-R807, October 1995.

7. MacNeal, R. H., “The NASTRAN Theoretical Manual,” NASA-SP-221(01), April, 1971.

8. I.E. Garrick and W.H. Reed, III “Historical Development of Aircraft Flutter,” Journal of Aircraft, Vol. 18, No. 11, November 1981.

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References

9. Grumman Aerospace Corporation, “An Automated Procedure for Flutter and Strength Analysis and Optimization of Aerospace Vehicles Volume I. Theory and Application,”, AFFDL-TR-75-137.

10. Hassig, H.J., “An Approximate True Damping Solution of the Flutter Equation by Determinant Iteration,” Journal of Aircraft, Vol. 8, No. 11, November 1971, pp. 885-889.

11. Neill, D.J., “MSC/Flight Loads and Dynamics Training,”, The MacNeal-Schwendler Corporation, 815 Colorado Boulevard, Los Angeles, CA, August 1999.