CRD

Computational Aeroelasticity

The Cultural and Convention Center
METU
Inonu bulvari
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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

Introduction

Fluid Structure Interaction

- *Any system where the fluid and structure cannot be considered independently to predict the response of the fluid, the structure, or both.*

Some Fields of Application

- Aerospace Vehicles
  - Aircraft, Spacecraft, Rotorcraft, Compressors, Combustors, Turbines
- Utilities
  - Hydroturbines, Steamturbines, Gasturbines, Piping, Transmission Lines
- Civil Structures
  - Bridges, Buildings
- Transportations
  - Trains, Automobiles, Ships

Introduction

Fields of Application (Continued)

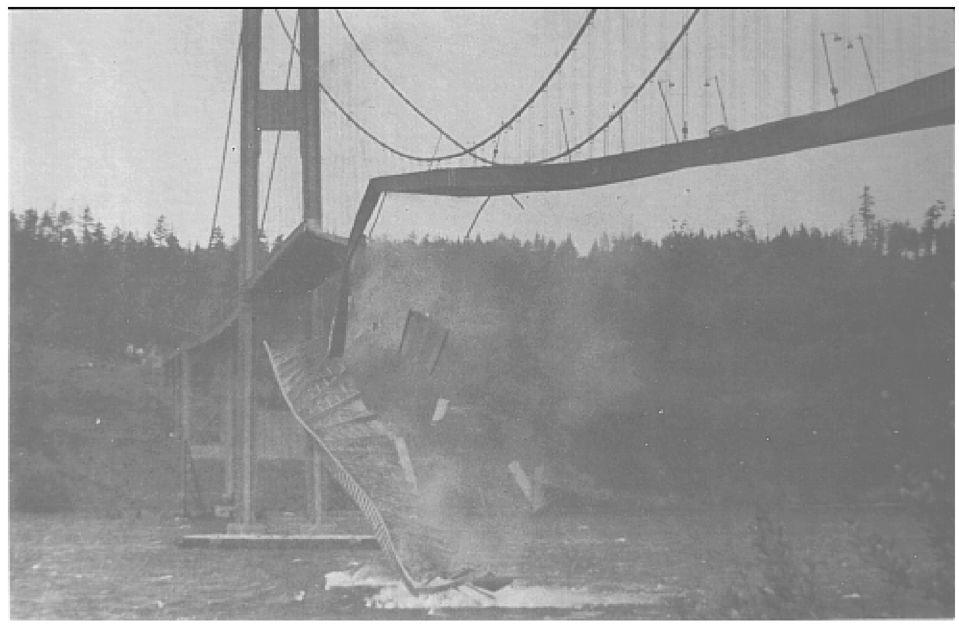
- Medical
  - Blood flow in veins, arteries, and heart
- Marine
  - Submarines, Off-shore Platforms, Docks, Piers
- Computer Technology
  - High velocity flexible storage devices

Introduction

Failure to recognize F-S Interaction

Tacoma Narrows Bridge #1 (Galloping Girtie)

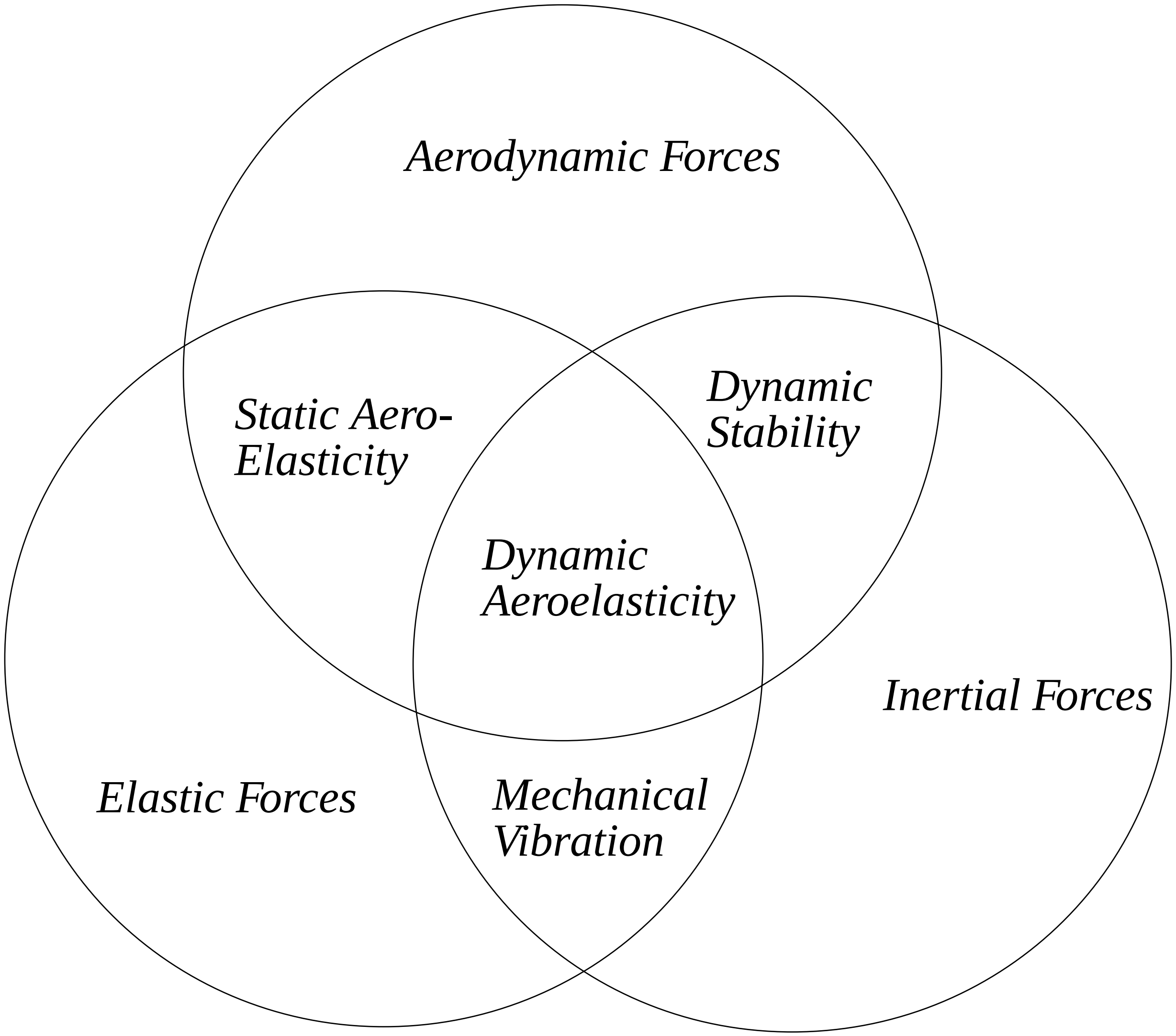
- Chief Designer: Leon Moisseiff
- Length: 5,939 ft.
- 42 MPH winds induced vortical separated flow that lead to torsional flutter
- Piers used in second bridge
- 1992: National Historic Site (natural reef)
- Photos taken by Leonard Coatsworth



Introduction

Aeroelasticity (sub-set of FS Int.)

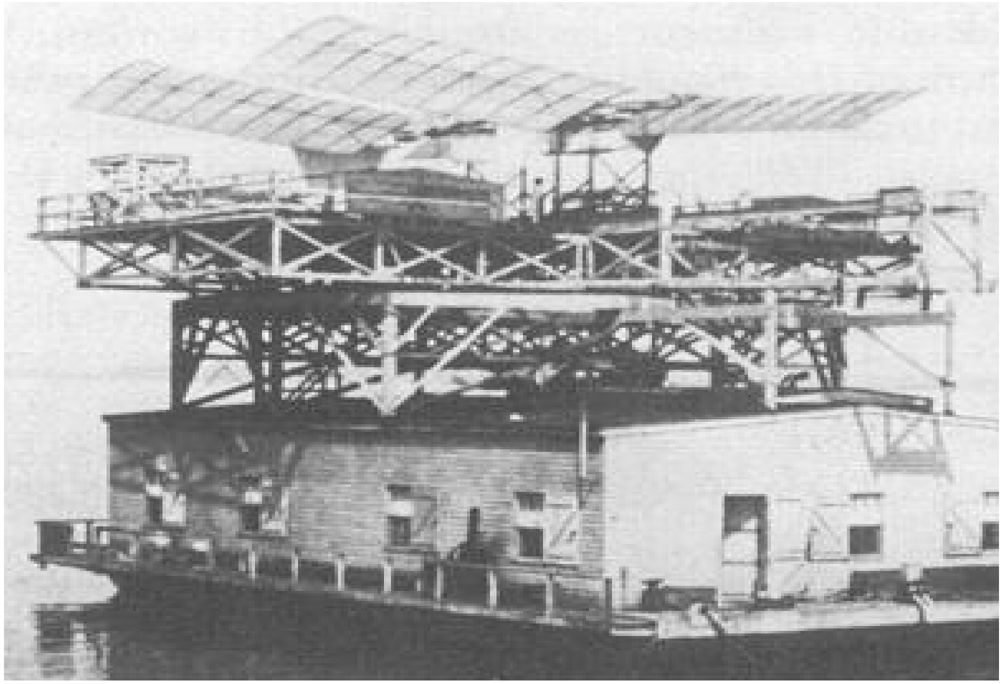
Aeroelasticity (British Engineers Cox and Pugsley credited with term) - *Substantial interaction among the aerodynamic, inertial, and structural forces that act upon and within the flight vehicle.*

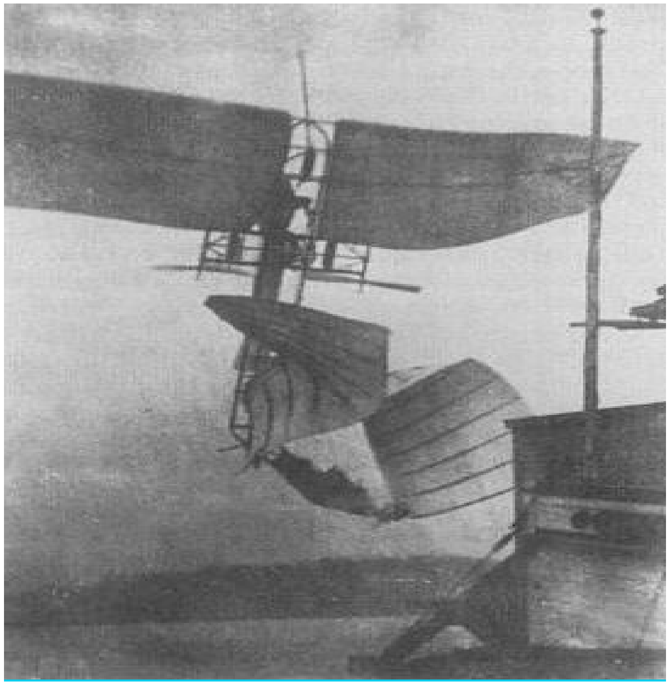


Introduction

Early Aeroelastic Problems

- S. P. Langley's Aerodome (monoplane)
  - 1/2 scale flew
  - October, 1903: Full scale failed, possibly due to wing torsional divergence
  - 1914 Curtis made some modification and flew successfully.





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Introduction

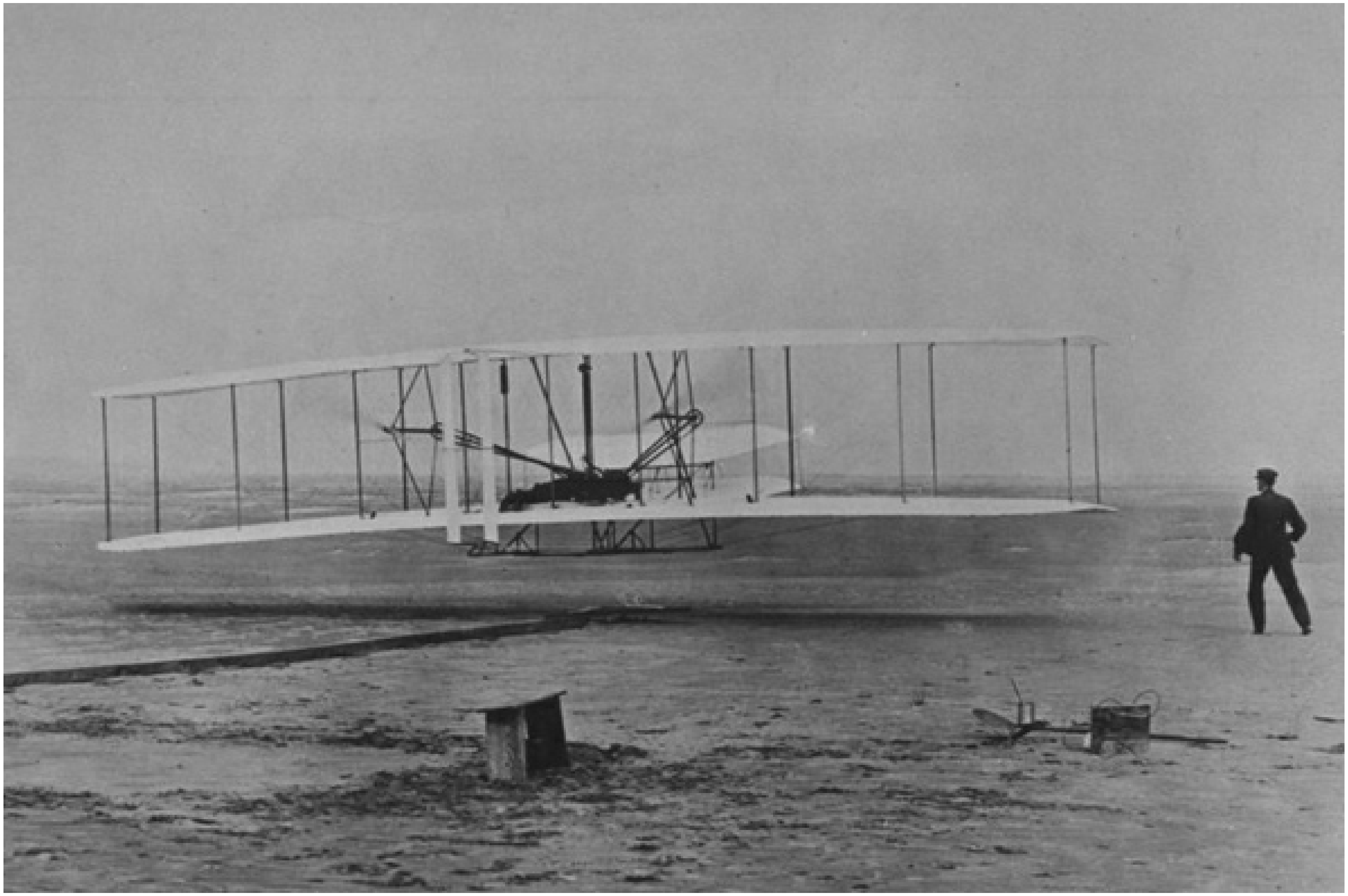
After Langley's failure the U.S. War Department reported -

"We are still far from the ultimate goal, and it would seem as if ***years*** *of constant work ... would still be necessary before we can hope to produce an apparatus of practical utility on these lines."*

9 Days Later ...

Introduction

December 17, 1903



Introduction

Early Aeroelastic Problems

- Hadley Page 0/400 bomber
  - Bi-plane tail flutter problems (fuselage torsion coupled with elevators)
  - DH-9 had similar problems
  - Solution was to add torsional stiffness between right and left elevators.

Introduction

Early Aeroelastic Problems

- Fokker D-8 (credited with last official kill of WW I)
  - D8 had great performance but suffered from wing failures in steep dives
  - Early monoplanes had insufficient torsional stiffness resulting in:
    - wing flutter, wing-aileron flutter
    - loss of aileron effectiveness
  - Solution: Increase torsional stiffness, mass balancing

Introduction

Computational Aeroelasticity

Early Theoretical Developments[1],[3].

- Wing divergence - Reissner (1926)
- Wing flutter - Frazer and Duncan (1929)
- Aileron reversal - Cox (1932)
- Unsteady aerodynamics and flutter - Glauert, Frazer, Duncan, Kussner, Theodorsen (1935)
- 3 DOF wing aileron flutter - Smlig and Wasserman (1942)

By Early 1930's Analytical methods existed to aid designers to consider both static and dynamic aeroelastic phenomena

Introduction

Computational Aeroelasticity

Designs from the 40's-70's "designed out" Aeroelastic Effects

- Accomplished by increasing structural stiffness or mass balancing (always at weight cost)

70's & 80's brought technology developments in three key areas

- Structures, Controls, and Computational Methods
  - Advanced composite materials enabled aeroelastic tailoring
  - Fly By Wire and Digital Control Systems enabled statically unstable aircraft
  - FEM, CFD, Optimization, Computational Power enabled advanced designs.

Introduction

Aeroelastic Successes

- DARPA sponsored X-29 (First flight 1984)
  - Aeroelastic tailored (graphite epoxy) forward swept wing
  - Fly By Wire triple redundant digital and analog control system
  - Germany proposed FSW designs (He 162) in WWII

Introduction

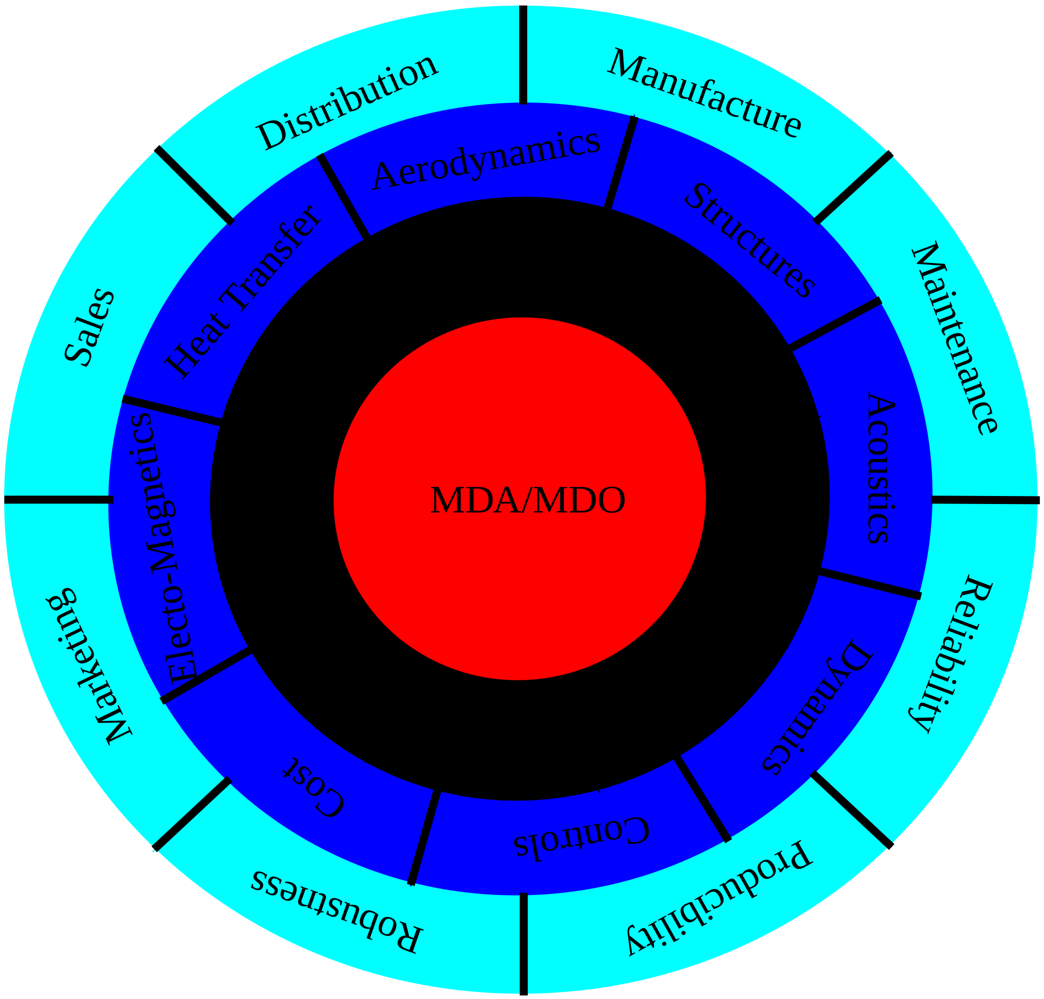
Aeroelastic Successes

- Active Aeroelastic Wing USAF/NASA (AAW)
  - Use control surfaces (leading and trailing edge) as tabs to twist the wing for maneuvers
  - Use TE surfaces beyond reversal
  - Produces lighter more maneuverable aircraft

Dryden Flight Research Center EC93-4194-4 Photographed 1993
F-18 SRA

Introduction

Product Structural Design in an MDA/MDO Environment



Computational Aeroelasticity

Goal of Computational Aeroelasticity

To accurately ***predict*** static and dynamic response/stability so that it can be accounted for (avoided or taken advantage of) early in the design process.

Computational Aeroelasticity

Aeroelastic Equations of Motion

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

K – Structural Stiffness

B – Structural Damping

M – Structural Mass

$F(u, \dot{u}, \ddot{u}, t)$ – External Aerodynamic Loads

Discretization of EOM

- Structures K, B, M - Typically, although not necessarily, represented by Finite Elements in either physical or generalized coordinates. Derived in a *Lagrangian* frame of reference.

- External Loads $F(u, \dot{u}, t)$ - Aerodynamic loads. Representations range from Prandtl's lifting line theory to full Navier-Stokes with turbulence modeling. Represented in physical and generalized coordinates in a (usually) *Eulerian* frame of reference.

Fluid-Structural Coupling Requirements

- Must ensure spatial compatibility - proper energy exchange across the fluid-structural boundary
- Time marching solutions require proper time synchronization between fluid and structural systems
- For moving CFD meshes GCL[6] must be satisfied

If coupling requirements for time-accurate aeroelastic simulation are not met then dynamical equivalence cannot be achieved. That is, regardless of the fineness of the CFD/CSM meshes and the reduction of time step to 0, the scheme may converge to the "wrong" equilibrium/instability point.[5]

General Modeling Comments

- Use appropriate theory to capture desired phenomena

  - Fluids - Navier-Stokes vs. Prandtls' lifting line theory
  - Structures - Nonlinear FEM vs. Euler beam theory

- Model the fluid and structure with a consistent fidelity

  - For a wing don't model the fluid with NS and the structure with beam theory

Aeroelastic Phenomena

Static Aeroelastic Phenomena

- Lift Effectiveness
- Divergence
- Control Surface Effective-ness/Reversal
- Aileron Effectiveness/ Reversal

Dynamic Aeroelastic Phenomena

- Flutter
- Gust Response
- Buffet
- Limit Cycle Oscillations (LCO)
- Panel Flutter
- Transient Maneuvers
- Control Surface Buzz

Static Aeroelasticity

Static Aeroelastic Phenomena

- Lift Effectiveness
- Divergence
- Control Surface Effectiveness/Reversal
- Aileron Effectiveness/Reversal

Static Aeroelasticity

Static Aeroelastic Effects

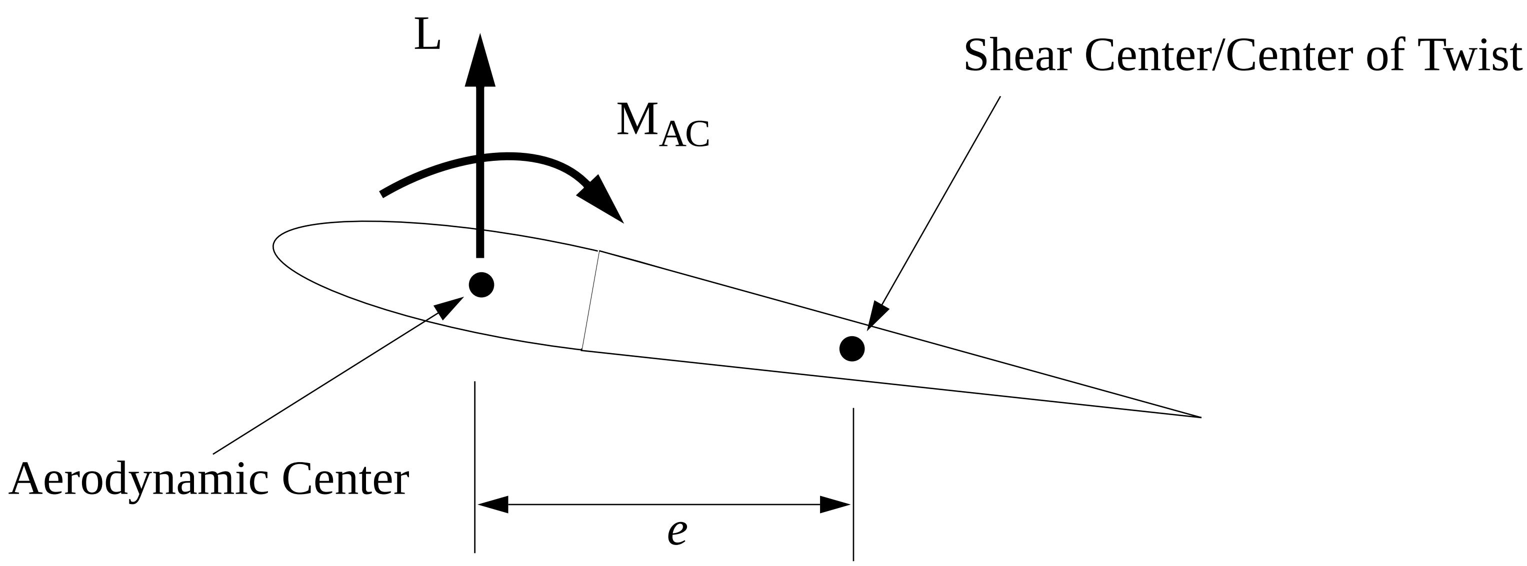
- For *trimmed* flight aeroelastic effects change only load distribution.

  - Lift
  - Drag
  - Pitching Moment
  - Rolling Moment

- For *constrained* flight (wind tunnel models) aeroelastic effects change both magnitude and distribution of loads.

Static Aeroelasticity

Useful 2-D Section Definitions



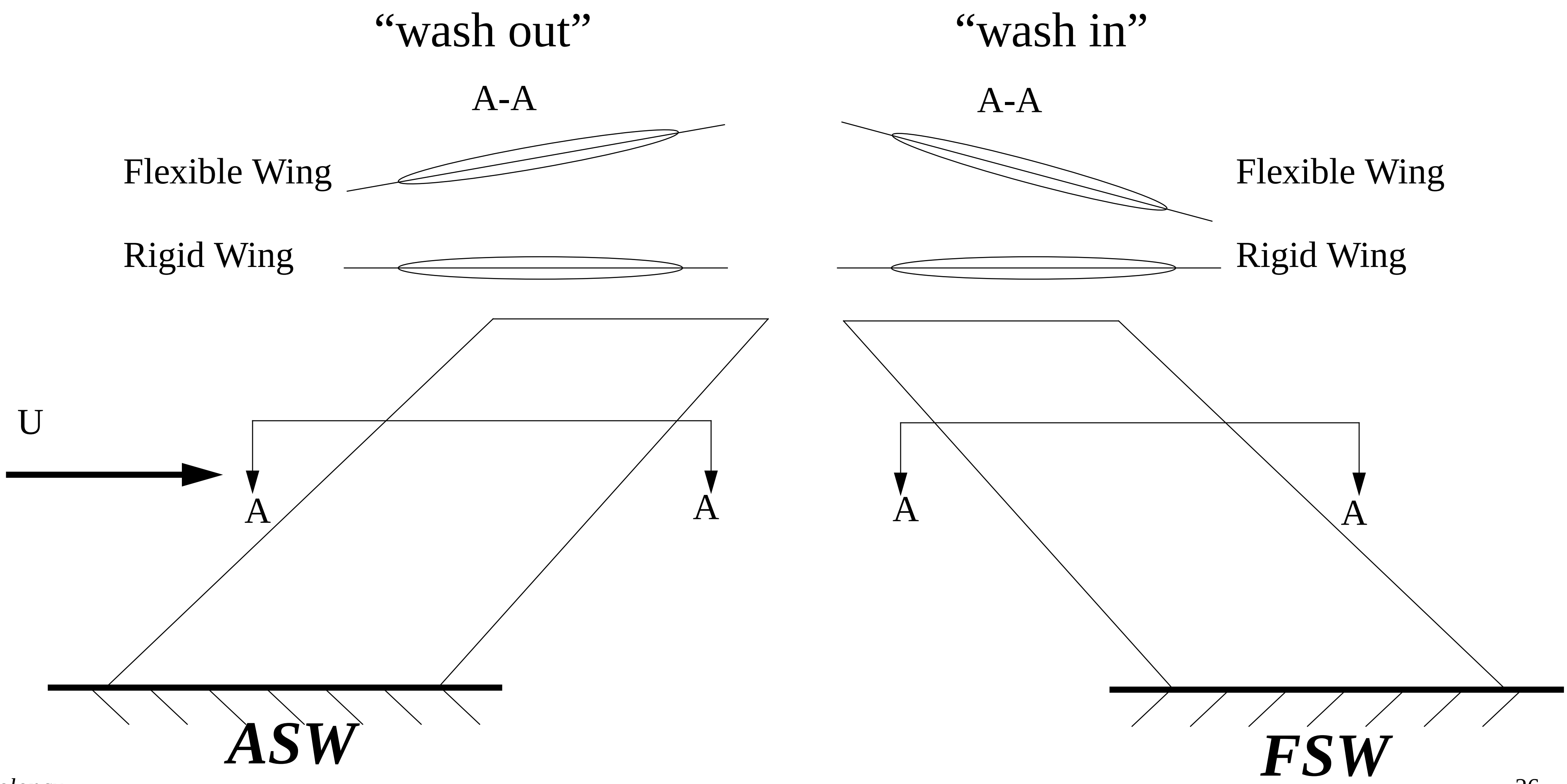
Shear Center/Center of Twist - Applied Shear force results in no moment or twist
- Applied moment produces no shear force or bending

Aerodynamic Center - Pitching moment independent of angle of attack
- 0.25c for subsonic, 0.5c for supersonic

Center of Pressure - Total Aerodynamic Moment equal zero (AC=SC for symm. airfoil)

e - Eccentricity

Effect of Swept Wing Bending on Streamwise Aerodynamic Incidence



Linear Static Aeroelasticity

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EOM

$$[K]\{u\} + [M]\{\ddot{u}\} = \{F(u)\} \qquad (1)$$

$\{\ddot{u}\}$ - rigid body accelerations only, used for inertial relief and trim

$F(u)$ - Steady aerodynamic forces can be represented as

$$F(u) = \bar{q}[G]^T[AIC][G_S]\{u\} + \bar{q}[G]^T[AIRFRC]\{\delta\}$$

or

$$'(u) = \bar{q}[AICS]\{u\} + \bar{q}[P^a]\{\delta$$

Now (1) can be written as

$$[K - \bar{q}AICS]\{u\} + [M]\{\ddot{u}\} = \bar{q}[P^a]\{\delta\} \qquad (2)$$

For Linear Aerodynamics [AIC] & [AIRFRC] depend only on Mach Number (M)

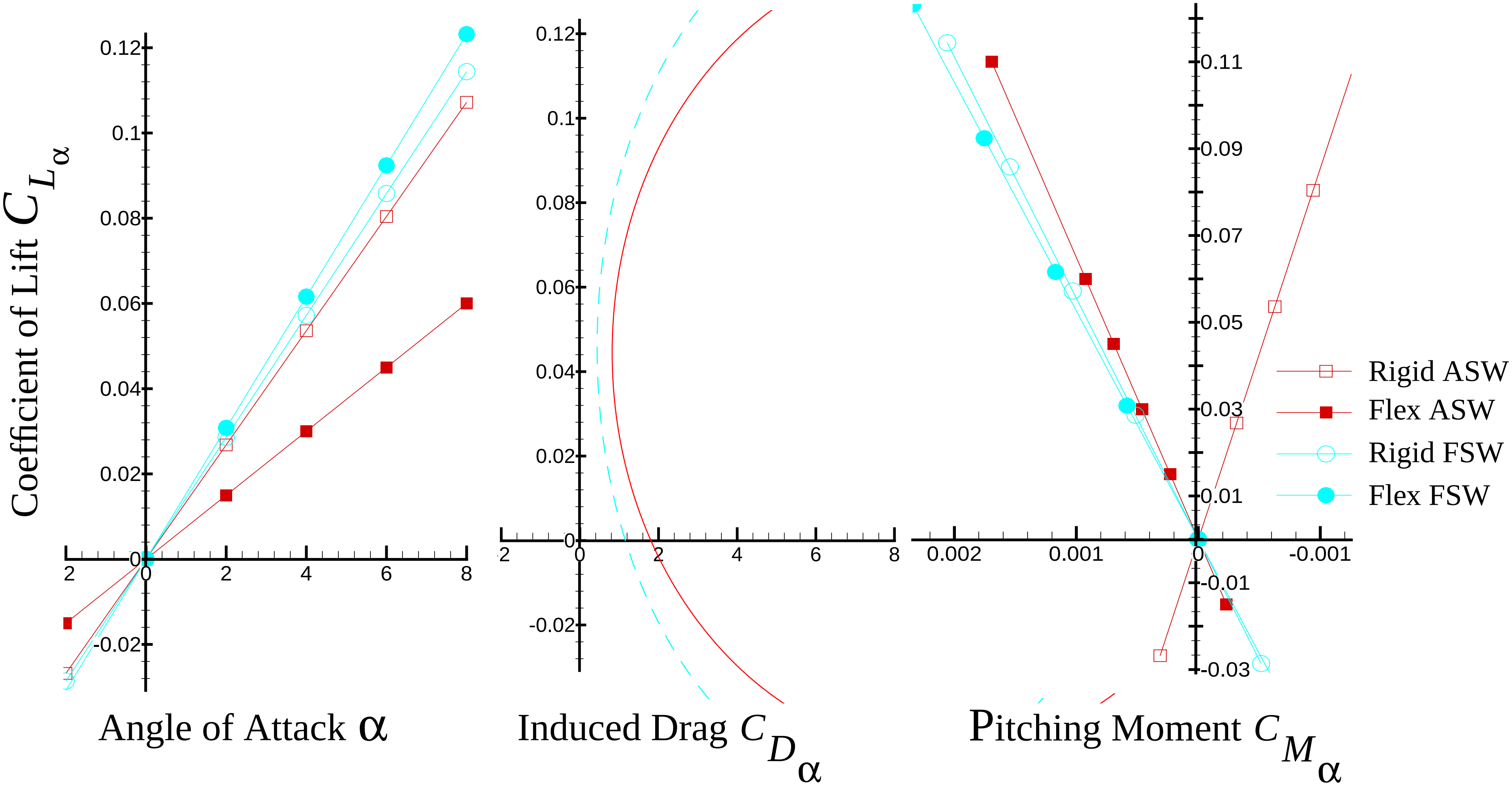
Linear Static Aeroelasticity

Steady Aerodynamic Loads

$$F(u) = \bar{q}[G]^T[AIC][G_s]\{u\} + \bar{q}[G]^T[AIRFRC]\{\delta\}$$

- $\bar{q}$ = Free stream dynamic pressure
- $[G]^T$ - Spline matrix which transforms forces from Aerodynamic DOF (ADOF) to Structural DOF (SDOF). $\{F_s\} = [G]^T\{F_a\}$
- $[G_s]$ - Spline matrix which transforms SDOF (displacements) to ADOF (panel slopes)
- $\{\alpha_a\} = [G_s]\{u\}$
- $[AIC]$ - Aerodynamic Influence Coefficient Matrix. Relates forces on ADOF (panels) due to unit perturbations of the ADOF (slopes)
- $[AIRFRC]$- Unit Rigid body aerodynamic load vectors. One vector for each δ_i
- $\{\delta\}$ - Vector of aerodynamic configuration parameters (angle of attack, elevator angle, aileron deflection, roll rate, pitch rate etc.)

Aeroelastic Effects on Swept Wing Forces and Moments



Linear Static Aeroelasticity

Divergence of a Constrained Vehicle

- When the aerodynamic stiffness $\bar{q}AICS$ becomes greater than the structural stiffness K, the structure fails or diverges.
- The divergence dynamic pressure for a restrained vehicle can be found by solving the eigenvalue problem (static stability)

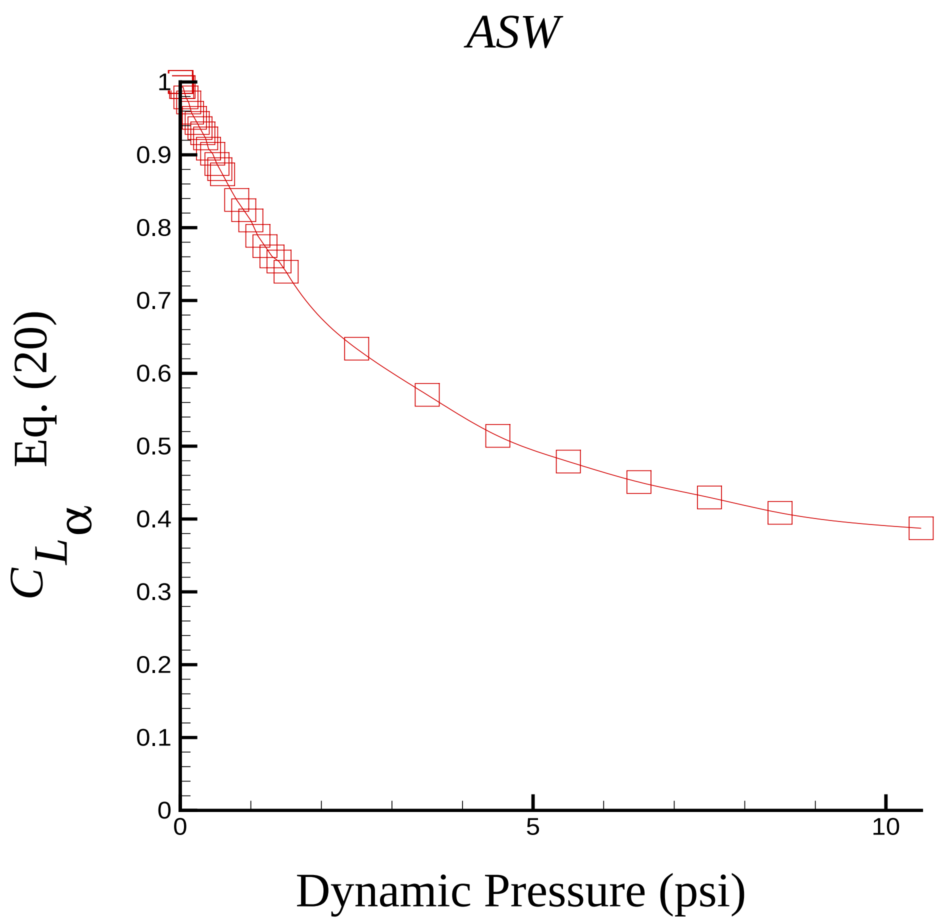
$$[K - \bar{q}AICS]\{u\} = \{0\} \qquad (3)$$

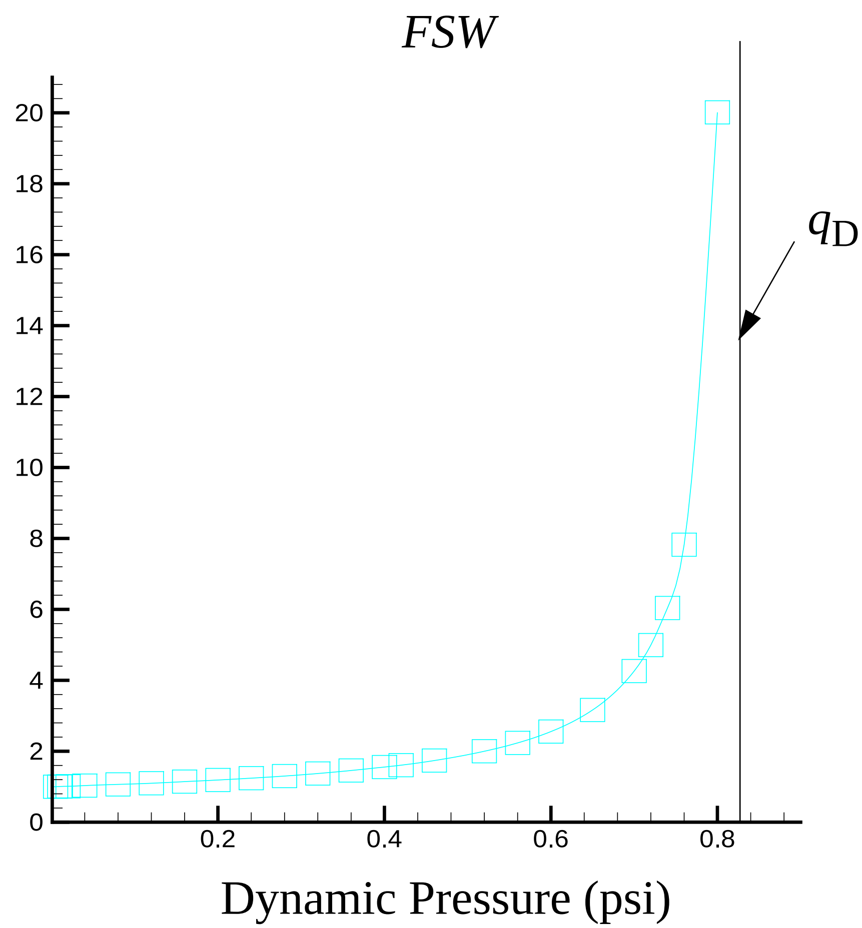
- Lowest eigenvalue $\bar{q}_D$ represents the divergence dynamic pressure
- The eigenvector $\{u_D\}$ represents the divergent shape
- Divergence is independent of initial angle of attack

Linear Static Aeroelasticity

Affect of Sweep on Lift Effectiveness

(M=0.7)





Linear Static Aeroelasticity

Static Aeroelastic Trim Equations

Writing equation (2) in the *f-set* (Reference Appendix A) yields

$$[K_{ff} - \bar{q}AICS]u_f + M_{ff}\ddot{u}_f = P^a_f\delta$$

or (4)

$$K^a_{ff}u_f + M_{ff}\ddot{u}_f = P^a_f\delta$$

Using the procedure in Appendix A for Guyan reduction equation (4) can be cast in the *a-set* as

$$K^a_{aa}u_a + M_{aa}\ddot{u}_a = P^a_a\delta$$

with

$$K^a_{aa} = \bar{K}^a_{aa} - K^a_a G^a_o$$

$$P^a_a = \bar{P}^a_a - K^a_{ao}\left[K^a_{oo}\right]^{-1}P^a_o \qquad (5)$$

$$M_{aa} = \bar{M}_{aa} + M_{ao}G_o + \left[G^a_o\right]^T M^T_{oa} + \left[G^a_o\right]^T M_{oo}G^a_o$$

Linear Static Aeroelasticity

Equation (5) can now be partitioned into the *r-set* and the *l-set* to

$$\begin{bmatrix} \boldsymbol{K}^a_{ll} & \boldsymbol{K}^a_{lr} \\ \boldsymbol{K}^a_{rl} & \boldsymbol{K}^a_{rr} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}_l \\ \boldsymbol{u}_r \end{Bmatrix} + \begin{bmatrix} \boldsymbol{M}_{ll} & \boldsymbol{M}_{lr} \\ \boldsymbol{M}_{rl} & \boldsymbol{M}_{rr} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{u}}_l \\ \ddot{\boldsymbol{u}}_r \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{P}^a_l \\ P^a_l \end{Bmatrix} \delta \qquad (6)$$

As with the inertial relief formulation $\ddot{u}_l = D\ddot{u}_r$ where D is the rigid body transformation matrix. To produce stability derivatives that are independent of the *r-set* (i.e. support point) an orthogonality condition is imposed in the form

$$\begin{bmatrix} D^T & I \end{bmatrix} \begin{bmatrix} \boldsymbol{M}_{ll} & \boldsymbol{M}_{lr} \\ \boldsymbol{M}_{rl} & \boldsymbol{M}_{rr} \end{bmatrix} \begin{Bmatrix} u_l \\ u_r \end{Bmatrix} = 0 \qquad (7)$$

Using the orthogonality condition and $\ddot{u}_l = D\ddot{u}_r$ equation (6) can be cast in the following form

Linear Static Aeroelasticity

$$\begin{bmatrix} \boldsymbol{K}^a_{ll} & \boldsymbol{K}^a_{lr} & \boldsymbol{M}_{ll}\boldsymbol{D} + \boldsymbol{M}_{lr} \\ \boldsymbol{K}^a_{rl} & \boldsymbol{K}^a_{rr} & \boldsymbol{M}_{rl}\boldsymbol{D} + \boldsymbol{M}_{rr} \\ \boldsymbol{D}^T\boldsymbol{M}_{ll} + \boldsymbol{M}_{rl} & \boldsymbol{D}^T\boldsymbol{M}_{lr} + \boldsymbol{M}_{rr} & \boldsymbol{0} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}_l \\ \boldsymbol{u}_r \\ \ddot{\boldsymbol{u}}_r \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{P}^a_l \\ \boldsymbol{P}^a_r \\ \boldsymbol{0} \end{Bmatrix} \delta \qquad (8)$$

Equation (8) can be solved by multiplying the first row by D^T and adding it to the second row. The new second row is interchanged with the third equation to yield the following system of equations.

$$\begin{bmatrix} \boldsymbol{K}^a_{ll} & \boldsymbol{K}^a_{lr} & \boldsymbol{M}_{ll}\boldsymbol{D} + \boldsymbol{M}_{lr} \\ \boldsymbol{D}^T\boldsymbol{M}_{ll} + \boldsymbol{M}_{rl} & \boldsymbol{D}^T\boldsymbol{M}_{lr} + \boldsymbol{M}_{rr} & \boldsymbol{0} \\ \boldsymbol{D}^T\boldsymbol{K}^a_{ll} + \boldsymbol{K}^a_{rl} & \boldsymbol{D}^T\boldsymbol{K}^a_{lr} + \boldsymbol{K}^a_{rr} & \boldsymbol{m}_r \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}_l \\ \boldsymbol{u}_r \\ \ddot{\boldsymbol{u}}_r \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{P}^a_l \\ \boldsymbol{0} \\ \boldsymbol{D}^T\boldsymbol{P}^a_l + \boldsymbol{P}^a_r \end{Bmatrix} \delta \qquad (9)$$

Linear Static Aeroelasticity

Where $\boldsymbol{m}_r = D^T M_{ll} D + D^T M_{lr} + \overline{M}_{rr}$ is defined as the rigid body mass matrix. Using a simplifying notation equation (9) becomes

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}_l \\ \boldsymbol{u}_r \\ \ddot{\boldsymbol{u}}_r \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{P}_l^a \\ \boldsymbol{0} \\ \boldsymbol{D}^T \boldsymbol{P}_l^a + \boldsymbol{P}_r^a \end{Bmatrix} \qquad (10)$$

Solving the first row of equation (10) for u_l and substituting in the second and third rows we obtain the trim equations in the form

$$\begin{bmatrix} \boldsymbol{K}_{11} & \boldsymbol{K}_{12} \\ \boldsymbol{K}_{21} & \boldsymbol{K}_{22} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}_1 \\ \boldsymbol{u}_2 \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{P}_1 \\ \boldsymbol{P}_2 \end{Bmatrix} \{\delta\} \qquad (11)$$

with

Linear Static Aeroelasticity

$$\begin{aligned}
K_{11} &= R_{22} - R_{21}R_{11}^{-1}R_{12} \\
K_{12} &= R_{23} - R_{21}R_{11}^{-1}R_{13} \\
K_{21} &= R_{32} - R_{31}R_{11}^{-1}R_{12} \\
K_{22} &= R_{33} - R_{31}R_{11}^{-1}R_{13} \\
P_1 &= -R_{21}R_{11}^{-1}P_l^a \\
P_2 &= D^T P_l^a + P_r^a - R_{31}R_{11}^{-1}P_l^a \\
u_1 &= u_r \\
u_2 &= \ddot{u}_r
\end{aligned} \tag{12}$$

Solving equation (11) for u_1 and u_2 the rigid body displacements and accelerations respectively yields

Linear Static Aeroelasticity

$$u_1 = K_{11}^{-1}[P_1\delta - K_{12}u_2] \tag{13}$$

$$[K_{22} - K_{21}K_{11}^{-1}K_{12}]u_2 = [P_2 - K_{21}K_{11}^{-1}P_1]\delta$$

or

$$[LHSA]\{u_2\} = [RHSA]\{\delta\} \tag{14}$$

or

$$[L]\{u_2\} = [R]\{\delta\}$$

Equation (14) is the basic equation for static aeroelastic trim analysis. There is one equation for each rigid body degree of freedom (6 DOF trim). $\{u_2\}$ is the vector of structural accelerations at the support point and $\{\delta\}$ is a vector of trim parameters. Partitioning equation (14) into free or unknown (subscripts *f*,*u*) values and known or set (subscripts *k*,*s*) values and gathering all unknown values to the left yields

Note: System can be over-specified producing trim optimization problem.

Linear Static Aeroelasticity

$$\begin{bmatrix} L_{ff} & -R_{fu} \\ L_{kf} & -R_{ku} \end{bmatrix} \begin{Bmatrix} u_{2f} \\ \delta_u \end{Bmatrix} = \begin{bmatrix} -L_{fk} & -R_{fs} \\ -L_{kk} & -R_{ks} \end{bmatrix} \begin{Bmatrix} u_{2k} \\ \delta_s \end{Bmatrix} \qquad (15)$$

Potential values for u_{2k} and δ are given in equation (16)

$$u_2 \in \begin{bmatrix} \text{NX - longitudinal acceleration} \\ \text{NY - lateral acceleration} \\ \text{NZ - vertical acceleration} \\ \text{PACCEL - roll acceleration} \\ \text{QACCEL - pitch acceleration} \\ \text{RACCEL - yaw acceleration} \end{bmatrix} \qquad \delta \in \begin{bmatrix} \text{BASE - reference state} \\ \text{ALPHA - angle of attack} \\ \text{BETA - yaw angle} \\ \text{PRATE - roll rate} \\ \text{QRATE - pitch rate} \\ \text{RRATE - yaw rate} \\ \{\delta_{sym}\}\text{- symmetric surfaces} \\ \{\delta_{anti}\}\text{- antisymmetric surfaces} \\ \{\delta_{asym}\}\text{- asymmetric surfaces} \end{bmatrix} \qquad (16)$$

Linear Static Aeroelasticity

Rigid Trim Equations

From equation (9) considering only rigid body accelerations and loads yields

$$\mathrm{LHSA}_{rigid} = R_{33} = m_r$$
$$\mathrm{RHSA}_{rigid} = \bar{P}_2 = D^T P_l^a + P_r^a \qquad (17)$$

and the rigid trim equations as

$$[LHSA_{rigid}]\{\ddot{u}_r\} = [RHSA_{rigid}]\{\delta\} \qquad (18)$$

Linear Static Aeroelasticity

Stability Derivatives

Using equation (14) and using an identity vector for $\{\delta\}$ and employing the rigid body mass matrix $\boldsymbol{m}_r$ forces due to unit parameter values can be determined as

$$\boldsymbol{F} = \boldsymbol{m}_r \left\{ [\boldsymbol{K}_{22} - \boldsymbol{K}_{21}\boldsymbol{K}_{11}^{-1}\boldsymbol{K}_{12}]^{-1} [\boldsymbol{P}_2 - \boldsymbol{K}_{21}\boldsymbol{K}_{11}^{-1}\boldsymbol{P}_1] \right\} \quad (17)$$

$$F \in \begin{Bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} = \begin{Bmatrix} \text{Thrust/Drag} \\ \text{Side Force} \\ \text{Lift} \\ \text{Roll Moment} \\ \text{Pitch Moment} \\ \text{Yaw Moment} \end{Bmatrix} \quad (18)$$

Stability Derivatives

Based on equation (18) non-dimensional stability derivatives are

Surface Parameters	Rate Parameters
$C_D = \frac{F_x}{\bar{q}S}$	$C_D = \frac{F_x}{\bar{q}Sc}$
$C_S = \frac{F_y}{\bar{q}S}$	$C_S = \frac{F_y}{\bar{q}Sb}$
$C_L = \frac{F_z}{\bar{q}S}$	$C_L = \frac{F_z}{\bar{q}Sc}$
$C_l = \frac{M_x}{\bar{q}Sb}$	$C_l = \frac{M_x}{\bar{q}Sb^2}$
$C_m = \frac{M_y}{\bar{q}Sc}$	$C_m = \frac{M_y}{\bar{q}Sc^2}$
$C_y = \frac{M_z}{\bar{q}Sb}$	$C_y = \frac{M_z}{\bar{q}Sb^2}$

(19)

- Note: These are "*unrestrained*" stability derivatives (free-free)

Linear Static Aeroelasticity

Example Stability Derivatives for α

From equations (14) and (17)

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{Bmatrix}_\alpha = [m_r][\mathrm{LHSA}]^{-1}[\mathrm{RHSA}]\begin{Bmatrix} \delta_0 = 0 \\ \delta_\alpha = 1.0 \\ \delta_\beta = 0 \\ \delta_{\mathrm{PRATE}} = 0 \\ \delta_{\mathrm{QRATE}} = 0 \\ \delta_{\mathrm{RRATE}} = 0 \\ \{\delta\}_{surface} = 0 \end{Bmatrix} \qquad (20)$$

Yielding $C_{D_\alpha}, C_{S_\alpha}, C_{L_\alpha}, C_{l_\alpha}, C_{M_\alpha}$ etc.

Linear Static Aeroelasticity

Stability Derivative Types

- There are four varieties of *flexible* stability derivatives

  - *Unrestrained* (orthogonality and inertia relief included)
  - *Restrained* (orthogonality, no inertial relief)
  - *Supported* (no orthogonality, but inertial relief)
  - *Fixed* (no orthogonality, no inertial relief)

- For wind tunnel comparison use either *Restrained* or *Fixed*

Make sure you know which type of stability derivatives a given program produces

Linear Static Aeroelasticity

Lift Trim Analysis

- For straight and level flight i.e. $\{u_2\} = \mathrm{NZ}$ equation (14) produces a single equation with one free parameter (say α)

$$\mathrm{LHSA} \times \mathrm{NZ} = \mathrm{RHSA} \times \alpha$$

$$\alpha = \frac{(\mathrm{LHSA} \times \mathrm{NZ})}{\mathrm{RHSA}}$$

or in terms of stability derivatives

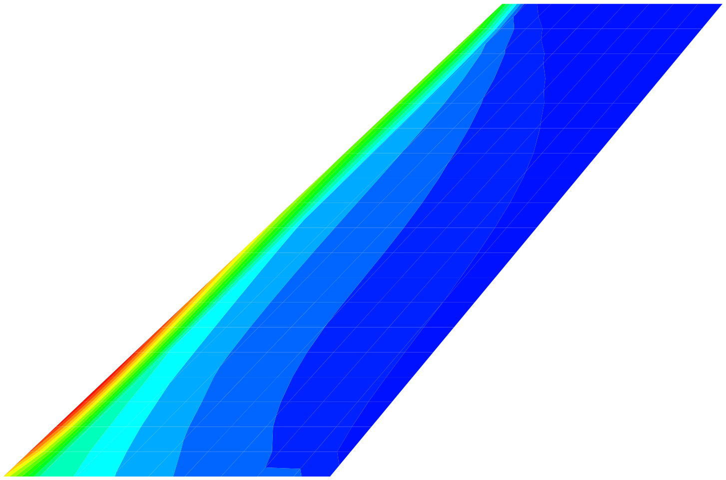
$$m_r \times \mathrm{NZ} = \alpha \bar{q} S C_{L_\alpha}$$

$$\alpha = \frac{(m_r \times \mathrm{NZ})}{\bar{q} S C_{L_\alpha}}$$

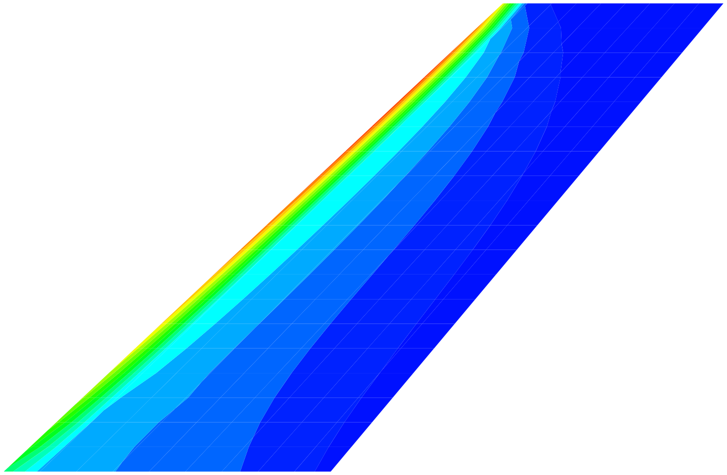
Linear Static Aeroelasticity

Aeroelastic and Rigid Trimmed Pressures

(M = 0.7, q = 5.04 psi, nz = 1g)



Aeroelastic Trim (α = 2.61°) Eq. (14)

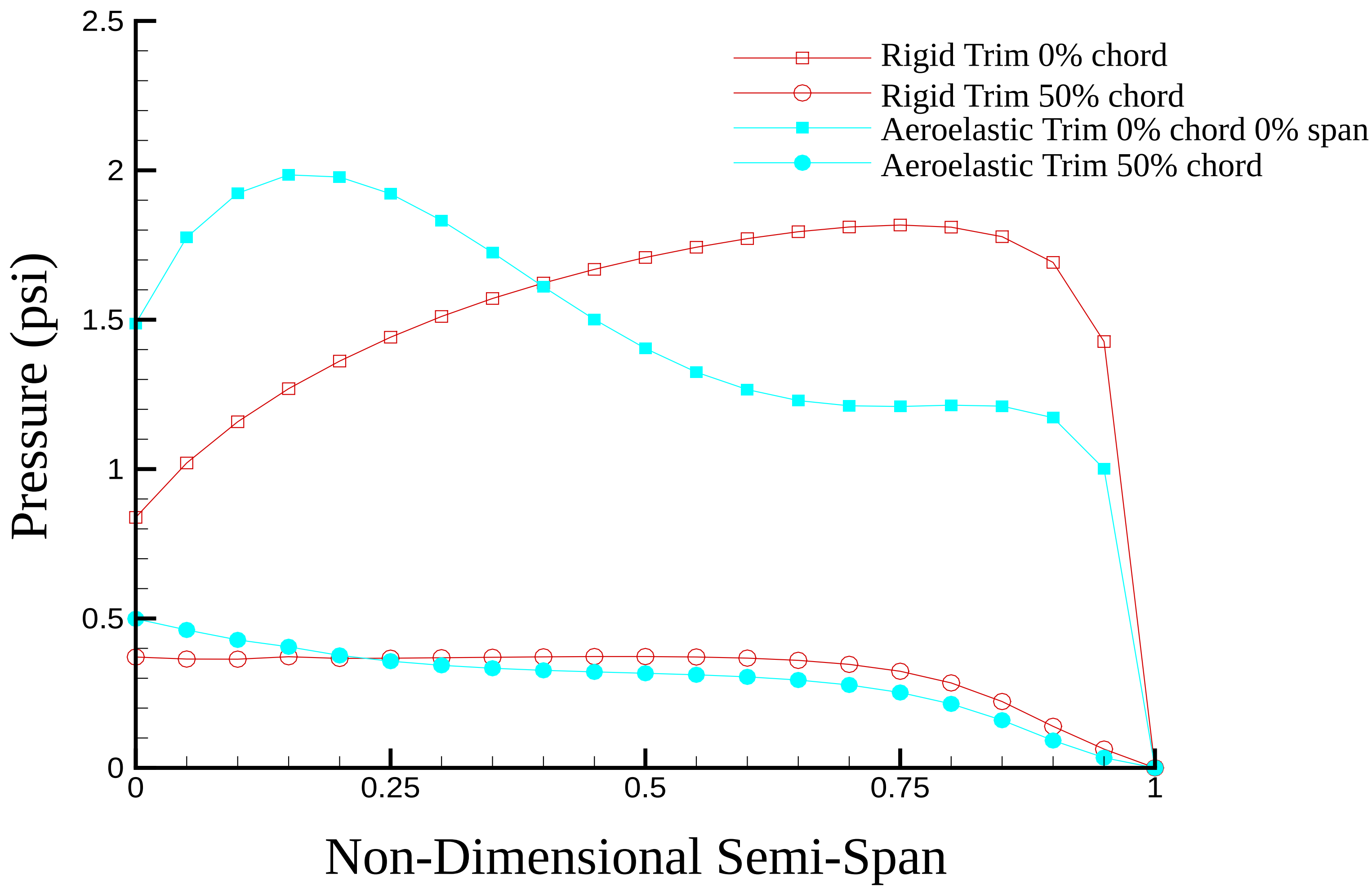


Rigid Trim (α = 1.29°) Eq. (18)

Linear Static Aeroelasticity

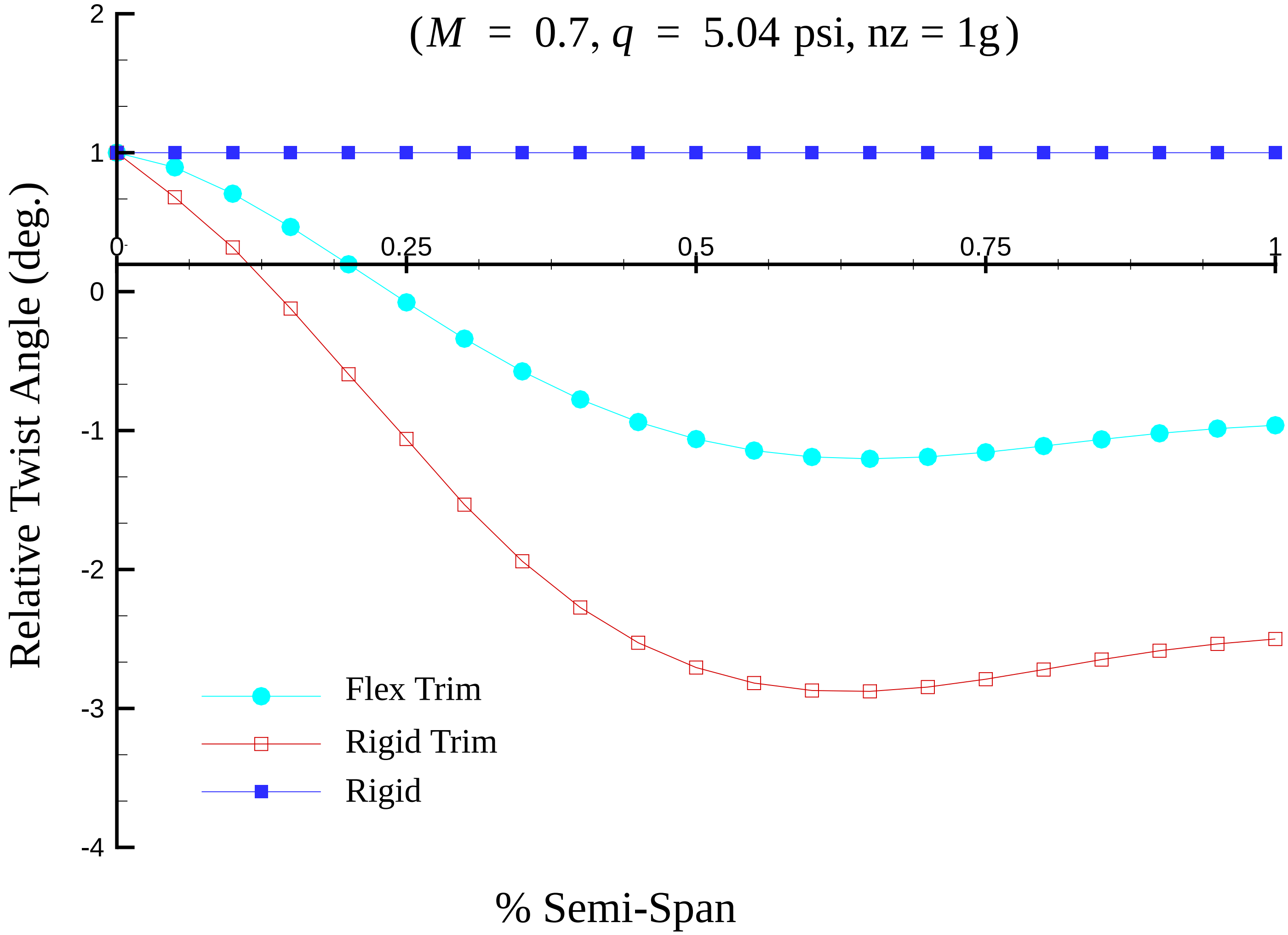
Rigid and Aeroelastic Trim Pressures vs. Span

(M = 0.7, q = 5.04 psi, nz = 1g)



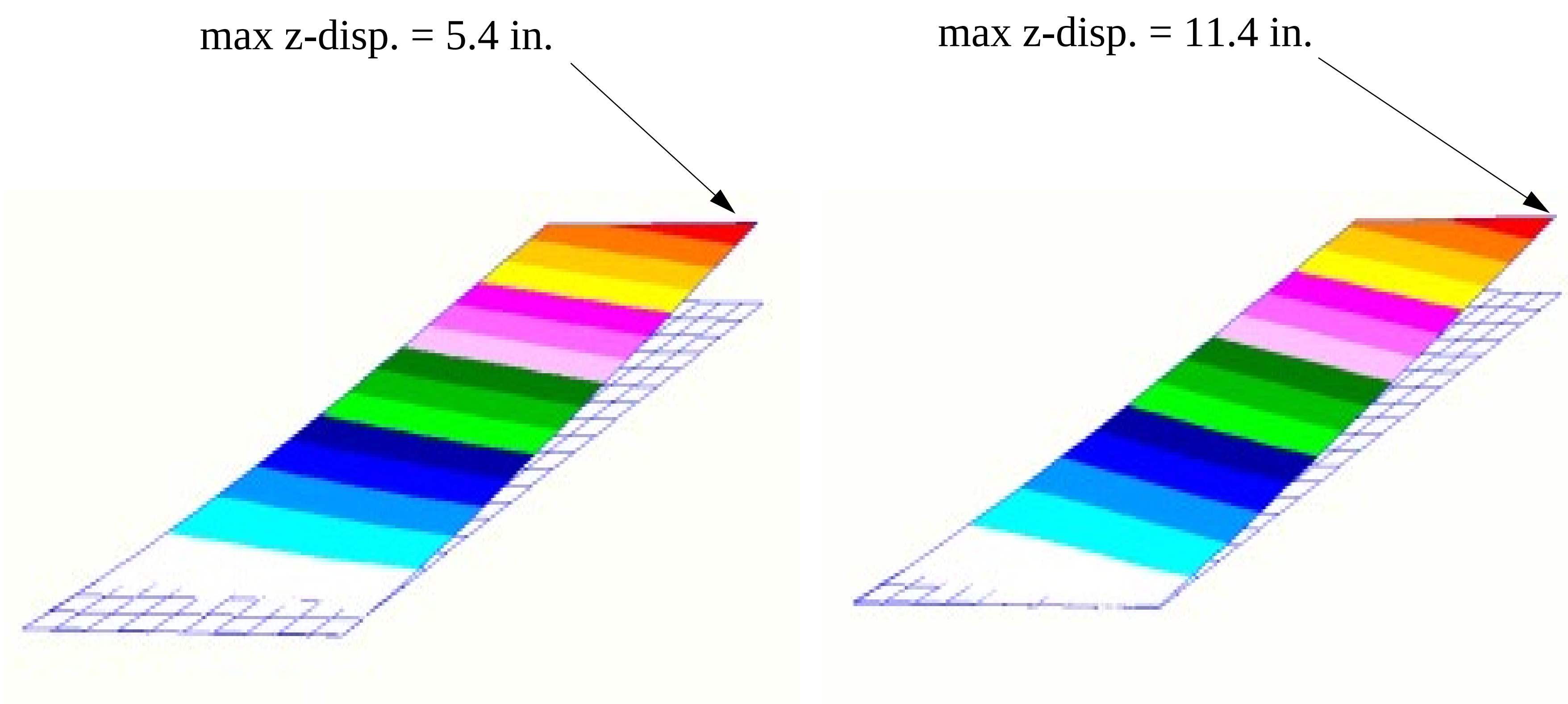
Linear Static Aeroelasticity

Spanwise Twist Due to Swept Wing Deformations



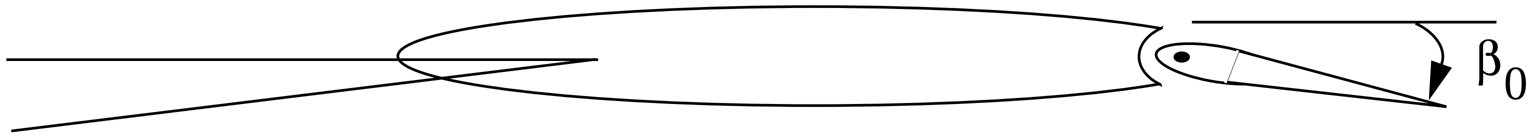
Linear Static Aeroelasticity

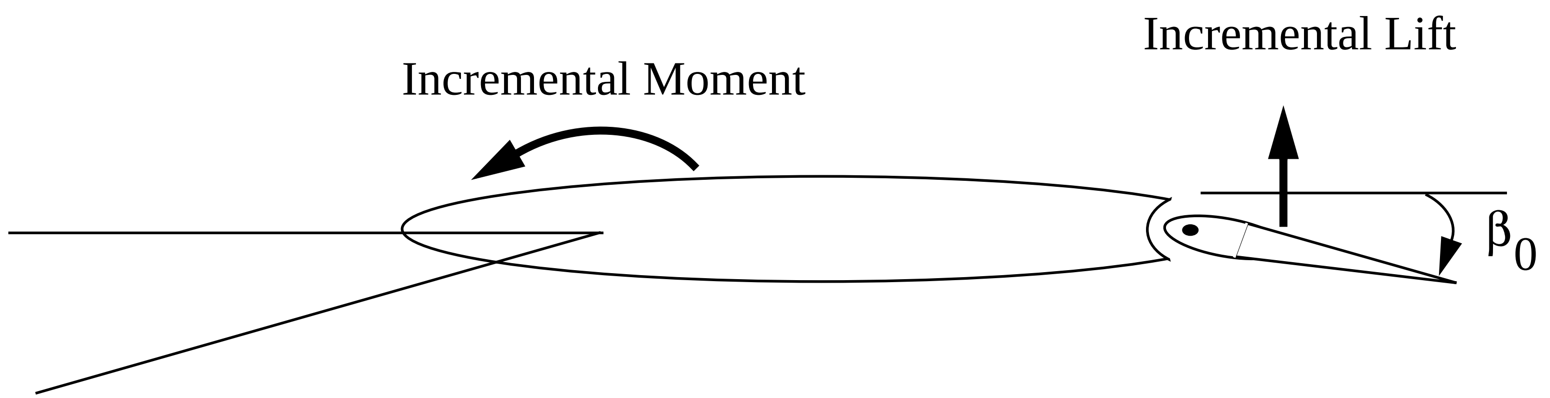
Swept Wing Aeroelastic Effects on Trimmed Displacements



Aeroelastic Trimmed Displacements Rigid Trimmed Displacements

Control Surface Effects





Linear Static Aeroelasticity

Roll Trim Analysis (wing with aileron)

Steady state roll (PACCEL = 0) for given β (aileron deflection)

$$\mathrm{LHSA}_{44} \times \mathrm{PACCEL} \;=\; \mathrm{RHSA}_{43} \times \beta + \mathrm{RHSA}_{44} \times \mathrm{PRATE}$$

$$\mathrm{PRATE} \;=\; \frac{\mathrm{RHSA}_{43} \times \beta}{\mathrm{RHSA}_{44}}$$

or in stability derivative form

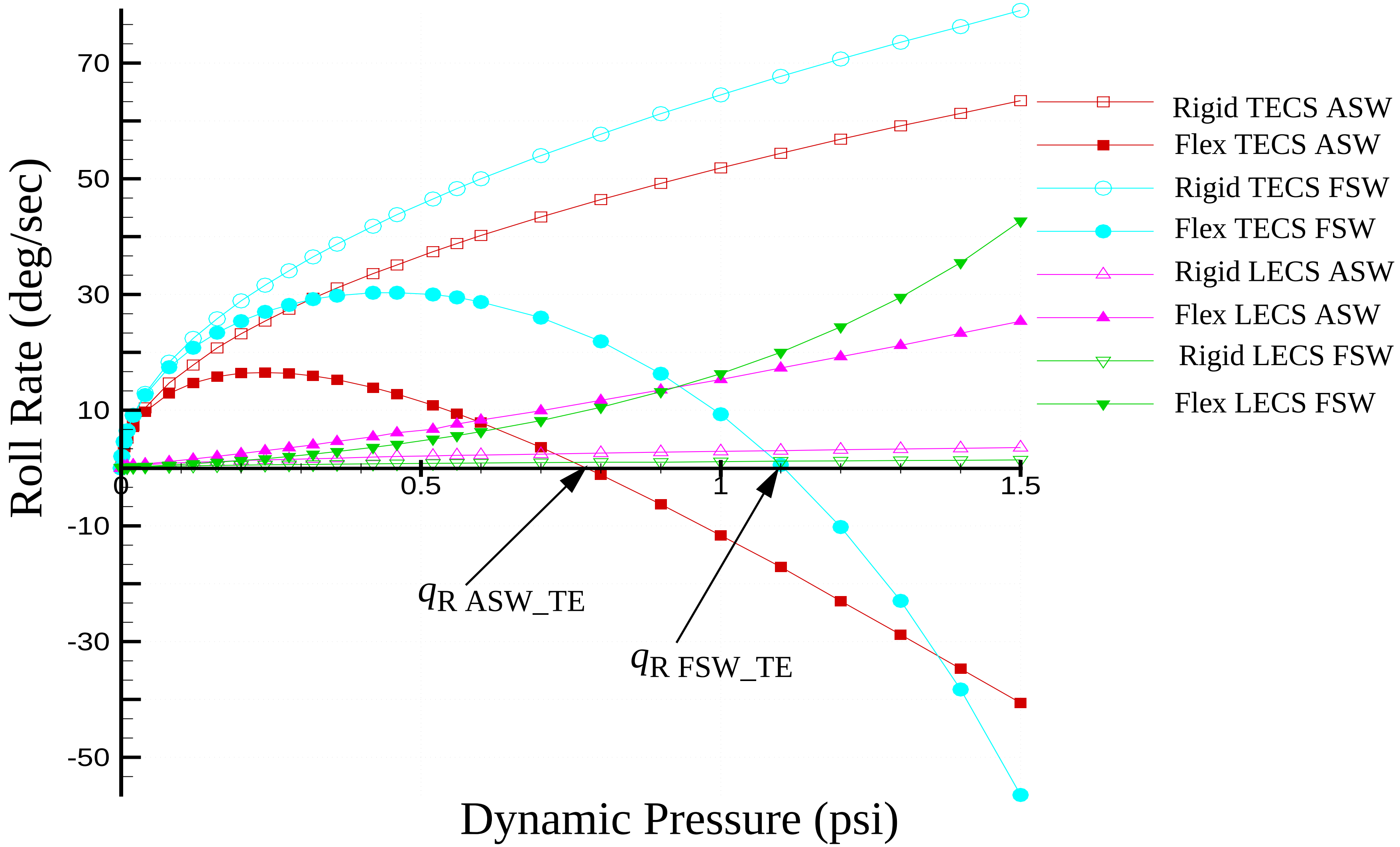
$$\bar{q}Sb\left[C_{l_\beta}\beta + C_{l_{\frac{pb}{2V}}}\mathrm{PRATE}\right] \;=\; I_{\mathrm{roll}}\mathrm{PACCEL}$$

for steady roll and a given β

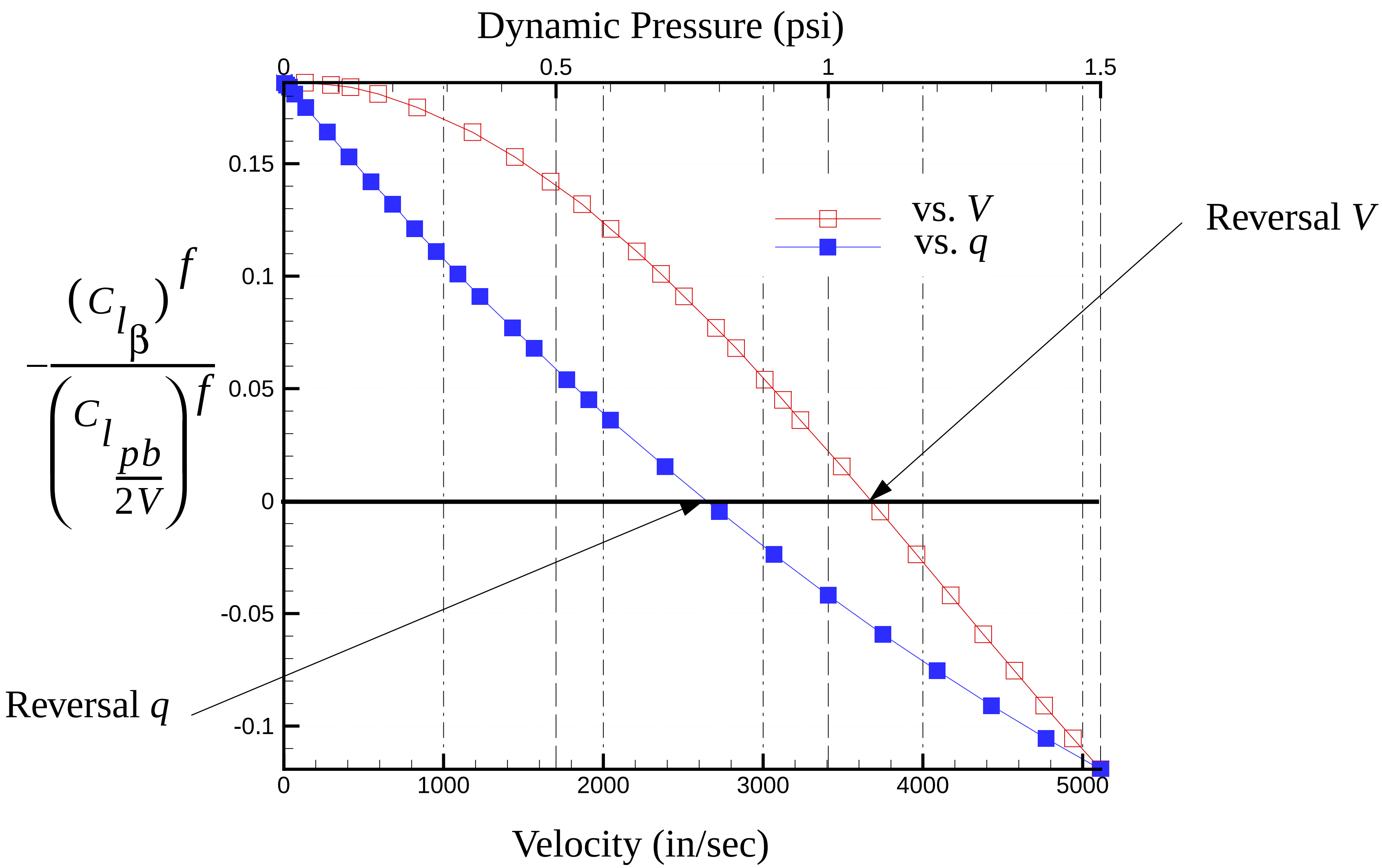
$$\mathrm{PRATE} \;=\; \frac{C_{l_\beta}\beta}{C_{l_{\frac{pb}{2V}}}}$$

Linear Static Aeroelasticity

Roll Rate vs. Dynamic Pressure for $\beta = 1.0°$



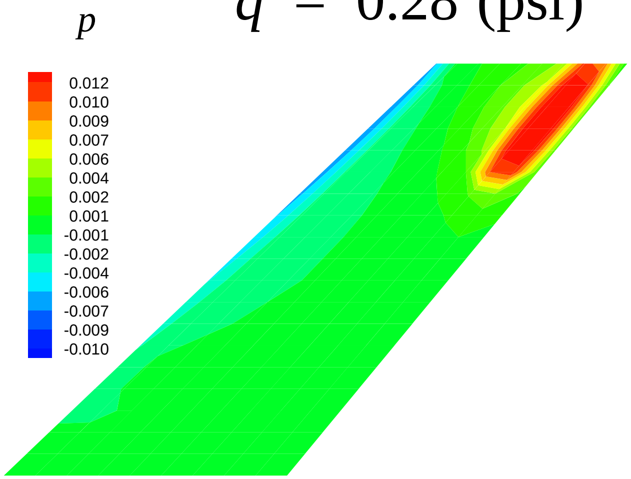
Aileron Effectiveness



Linear Static Aeroelasticity

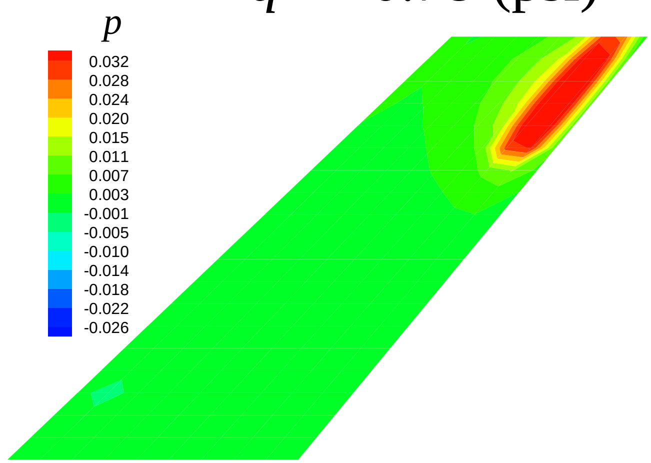
Aeroelastic Effects on Roll Rate Pressures

$\bar{q} = 0.28$ (psi)



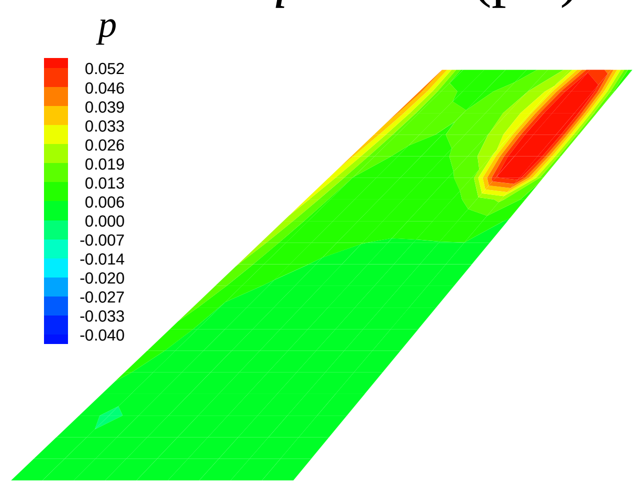
q_{rigid} = 27 (deg/sec)

$\bar{q} = 0.78$ (psi)

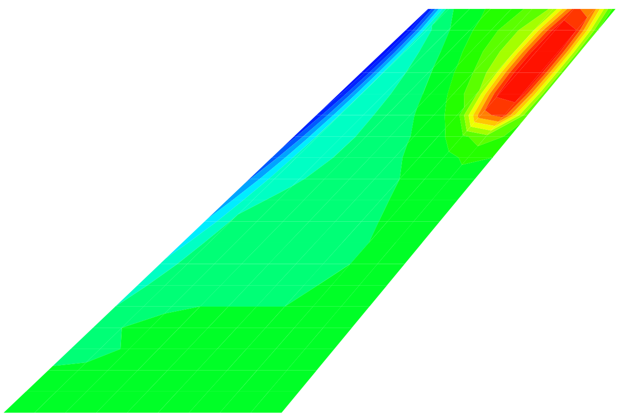


q_{rigid} = 46 (deg/sec)

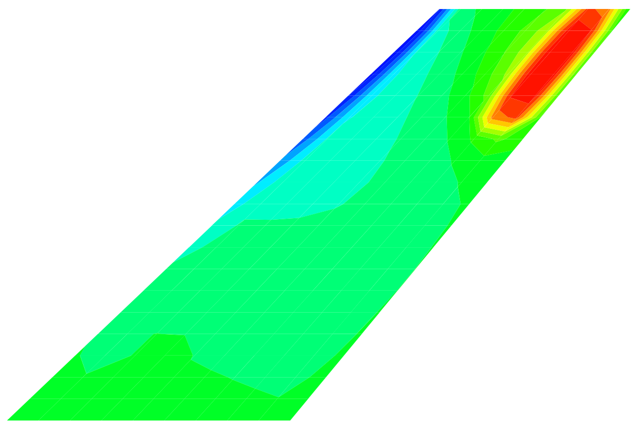
$\bar{q} = 1.5$ (psi)



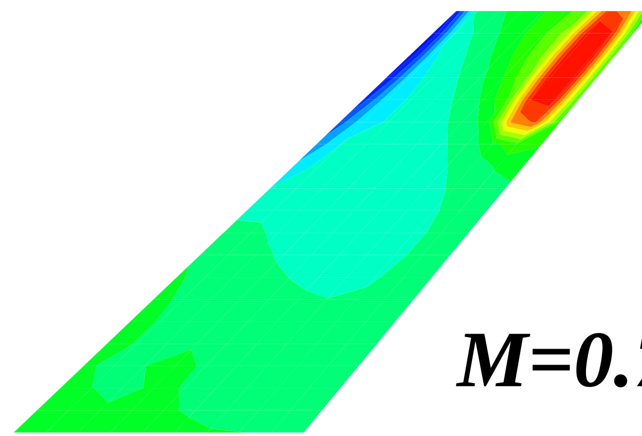
q_{rigid} = 59 (deg/sec)



q_{rigid} = 16 (deg/sec)



q_{rigid} = 0 (deg/sec)



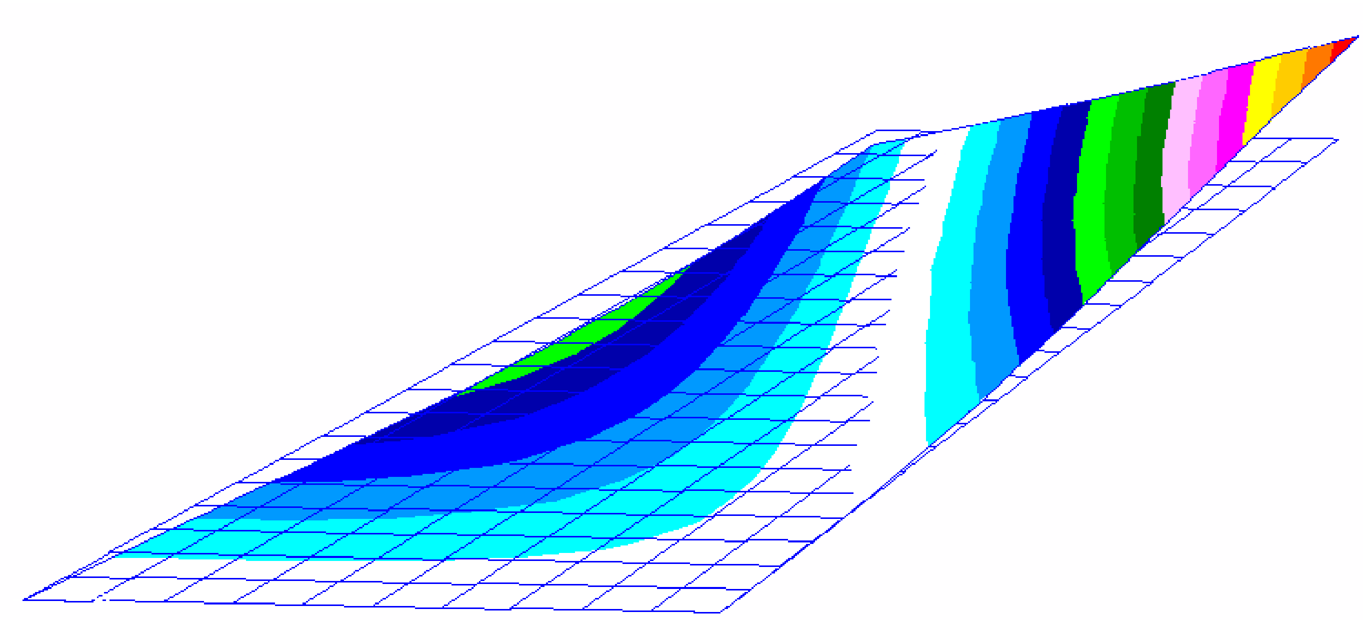
M=0.7

q_{rigid} = -28 (deg/sec)

Linear Static Aeroelasticity

Rolling Wing Deformations

$$M = 0.7, \bar{q} = 1.5 \text{ psi}$$



CRD

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