Pezhman Mardanpour and Dewey H. Hodges
Georgia Institute of Technology

Air Force Research Laboratory through Bihrle Applied Research, Inc.
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Effect of Engine Placement on Aeroelastic Trim and Stability of Flying Wing Aircraft

Introduction & Theory

- **Flying wings**
- High performance
  - Drag reduction due to a smooth outer surface and the lack of a vertical tail
- Directional instability (yawing instability)
  - Rotation of the aircraft in the horizontal plane
- Aeroelastic instability (body-freedom flutter)
  - Symmetric first elastic bending and torsion modes coupled with the aircraft short-period mode
- A high-aspect-ratio flying wing
  - Undergo large deformation, geometrically nonlinear behavior
  - Inaccuracy of linear aeroelastic analysis, the importance of nonlinear aeroelastic analysis
  - **NATASHA** (**N**onlinear **A**eroelastic **T**rim **A**nd **S**tability of **HA**LE Aircraft)

- **NATASHA is formulated based on Nonlinear Composite Beam Theory**
- Fully Intrinsic Beam Equations (no displacement or rotation in the formulation – no singularities)

$$F_B' + \widetilde{K}_B F_B + f_B = \dot{P}_B + \widetilde{\Omega}_B P_B$$

$$M_B' + \widetilde{K}_B M_B + (\widetilde{e}_1 + \widetilde{\gamma}) F_B + m_B = \dot{H}_B + \widetilde{\Omega}_B H_B + \widetilde{V}_B P_B$$

- Structural Constitutive Equations

$$\begin{Bmatrix} \gamma \\ \kappa \end{Bmatrix} = \begin{bmatrix} R & S \\ S^T & T \end{bmatrix} \begin{Bmatrix} F_B \\ M_B \end{Bmatrix}$$

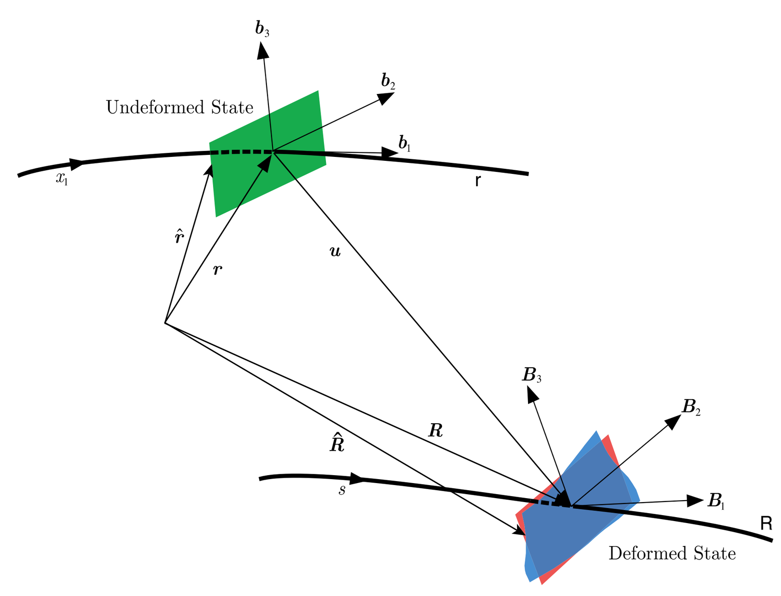
- Inertial Constitutive Equations

$$\begin{Bmatrix} P_B \\ H_B \end{Bmatrix} = \begin{bmatrix} \mu\Delta & -\mu\widetilde{\xi} \\ \mu\widetilde{\xi} & I \end{bmatrix} \begin{Bmatrix} V_B \\ \Omega_B \end{Bmatrix}$$

- Kinematical Partial Differential Equations

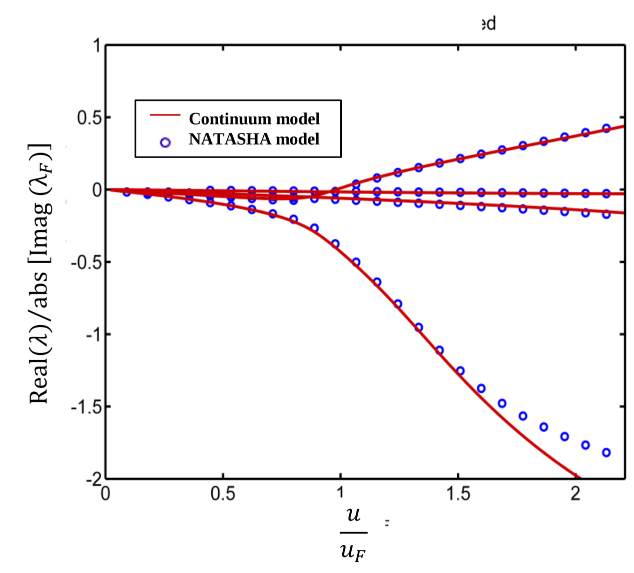
$$V_B' + \widetilde{K}_B V_B + (\widetilde{e}_1 + \widetilde{\gamma}) \Omega_B = \dot{\gamma}$$

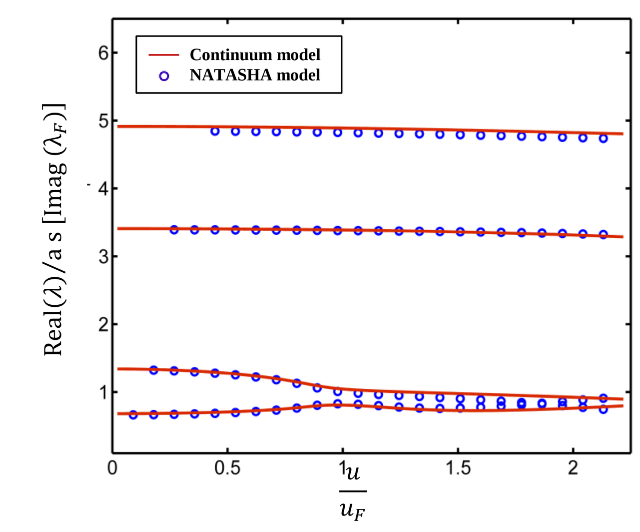
$$\Omega_B' + \widetilde{K}_B \Omega_B = \dot{\kappa}$$



NATASHA Validation

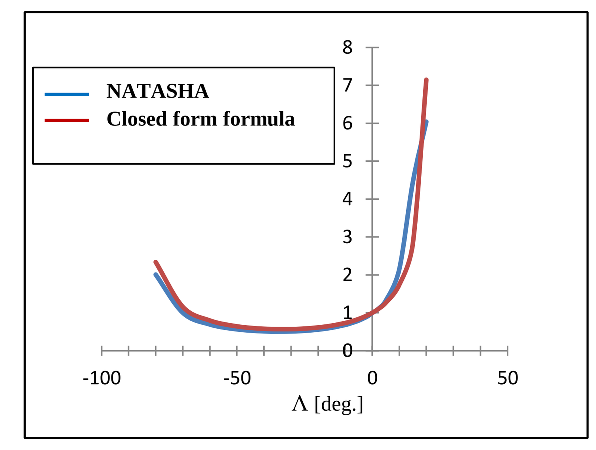
- **Validation for pre- and post-instability**
  (using classical Goland cantilevered wing)
- First four modes
- Continuum aerodynamics (Balakrishnan) vs. Peters aerodynamics model



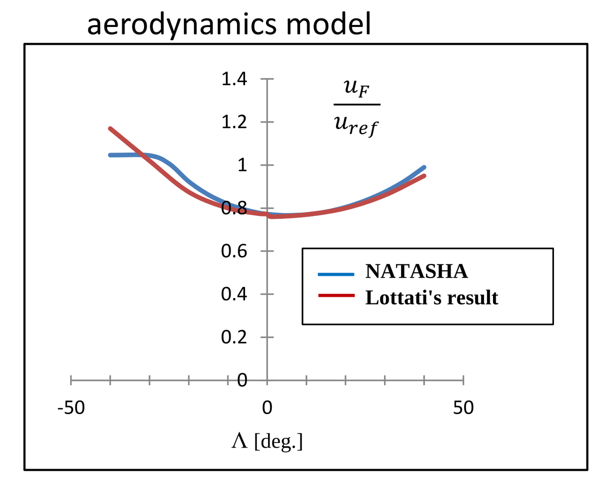


- **Validation for sweep effect**
  (using classical Goland cantilevered wing)
- Divergence
  - Closed form formula, Hodges *et al*

$$\frac{q_D}{q_{D_0}} = \frac{1 + \tan^2(\Lambda)}{1 - \frac{3\pi^2}{76}\frac{GJ}{EI}\frac{l}{e}\tan(\Lambda)}$$

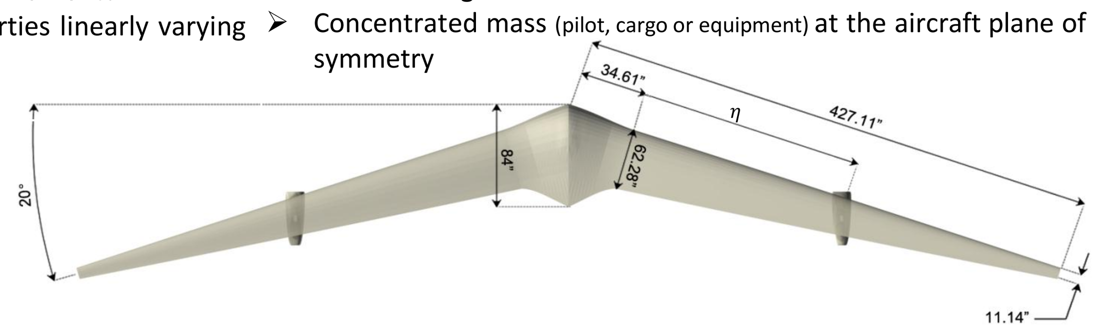


- Flutter
  - Lotatti used Theodorsen unsteady aerodynamics model



Minimum Kinetic Energy & Effect of Sweep Backward

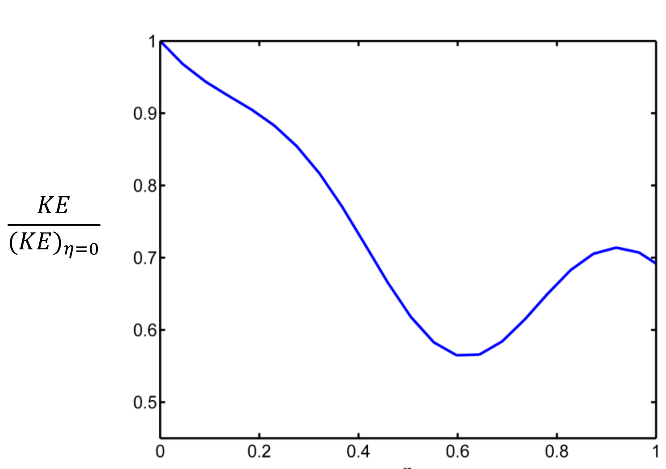
- **Case Study**
- Model
  - Geometry: similar to Horten IV
  - Two engines with mass and angular momentum
  - Structural and aerodynamics properties linearly varying from root to tip of the wing
  - Fuselage modeled as rigid body; mass and inertial properties same as wing roots
  - Concentrated mass (pilot, cargo or equipment) at the aircraft plane of symmetry



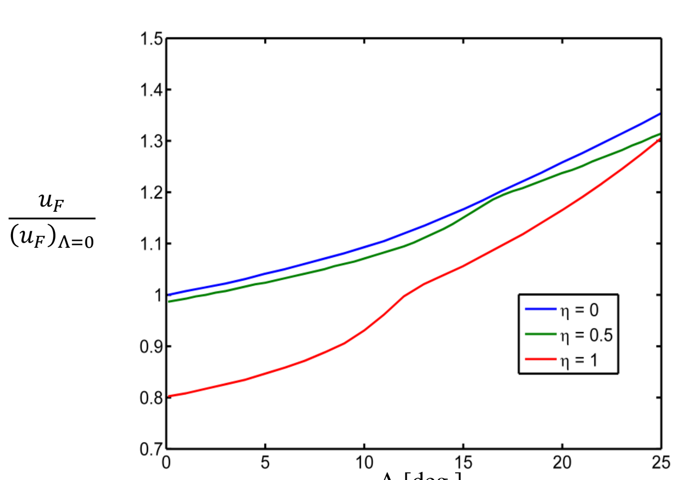
- **Aeroelastic result**
- For the case of clean wing (η =0)

Speed (MPH)	Frequency	Mode
all	0.05 (rad/s)	non-oscillatory yawing instability
85.5	2.9 (Hz)	body freedom flutter (first bending and torsion mode coupled with aircraft short period mode)

- **Minimum Kinetic Energy**
- In the absence of
  - Engines
  - Aerodynamic force (ρ = 0)
  - Gravitational force (g =0)
- Kinetic energy per unit length of the aircraft symmetric free-free mode
  - Lowest region at 60% of the span
  - Increase in modal frequency ~ 3.5 Hz

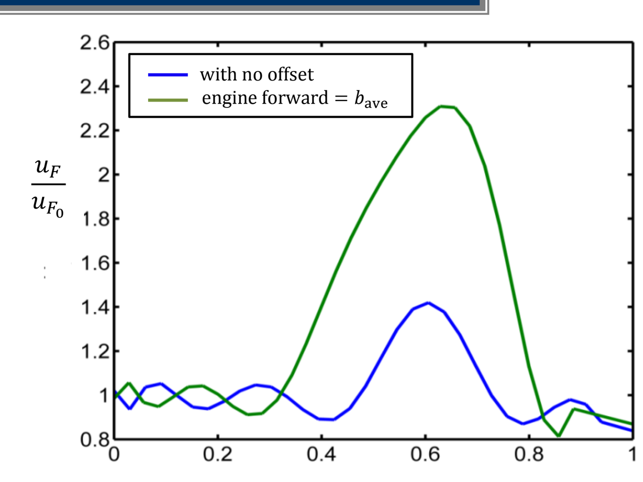


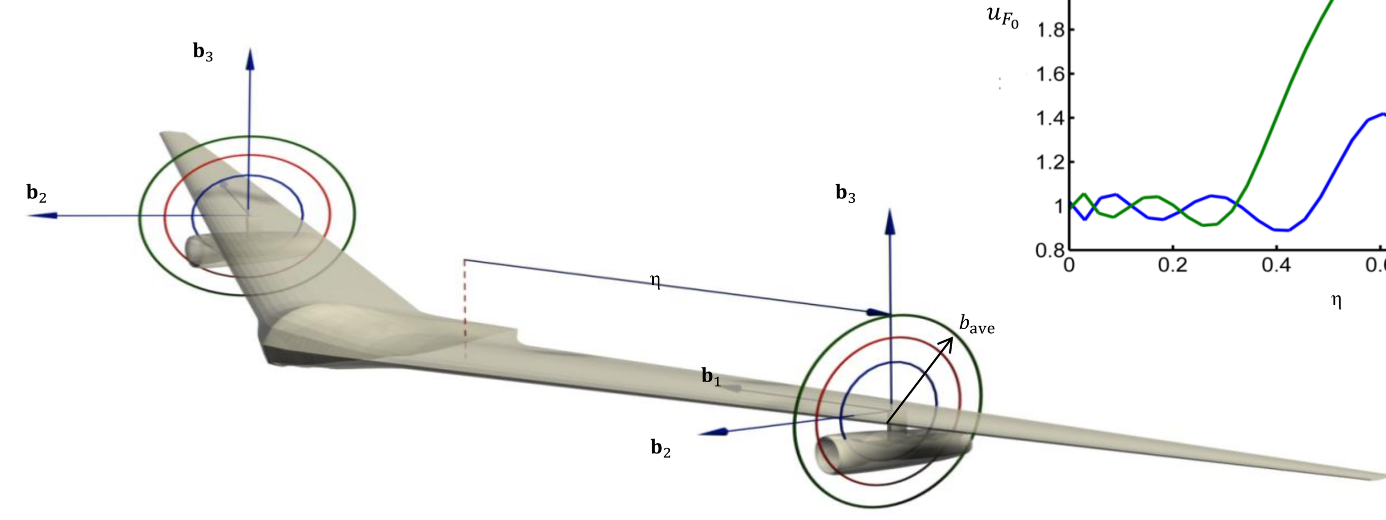
- **Effect of Sweep Backward**
- Engines at
  - Root, middle and tip of the wings (η = 0 , 0.5 and 1)
  - No offset from elastic axis of the wing
  - B.F.F with 2.8 Hz



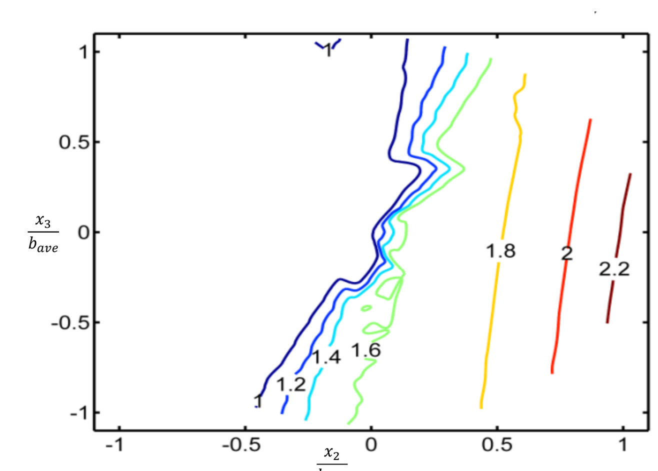
Effect of Engine Placement

- **Effects of Engine Placement**
- Engines with known mass, moment of inertia and angular momentum
- offset from plane of symmetry of the aircraft, η
- offset from elastic axis, ξ , in the order of mean semi-chord

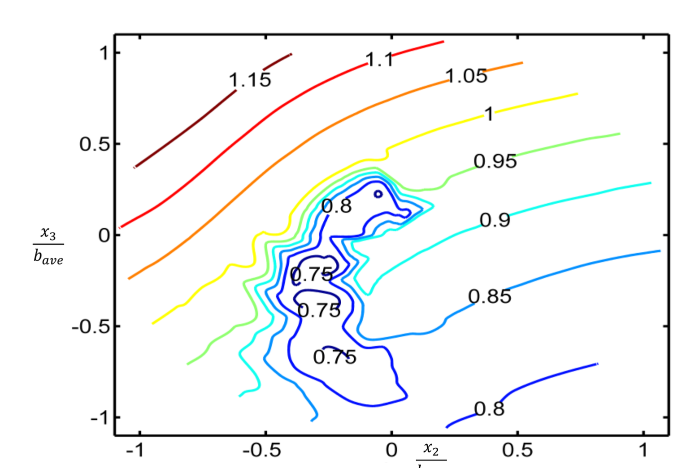




- **Engine Placement at 60% Span**
- Flutter speed
  - Higher flutter speed at forward and above e.a.
  - Flutter speed is the highest at this location

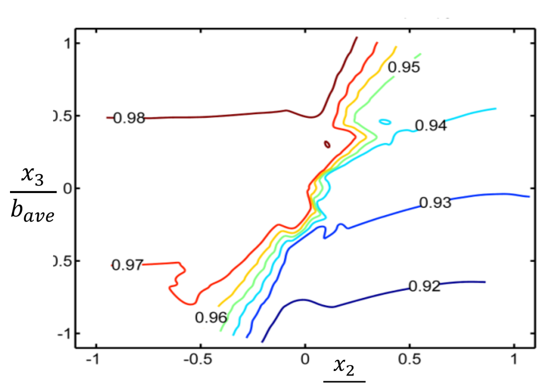


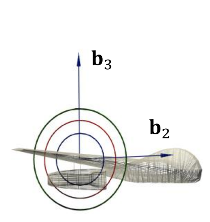
- **Engine Placement at the Tip of the Wings** (η = 1)
- Flutter speed
  - Higher flutter speed at aft and above e.a.
  - The most lowest flutter speed for entire placements
  - Engines at the farthest distance from e.a.
    - another sym. bending mode , on the stability boundary with 0.08 Hz, with no apparent regularity



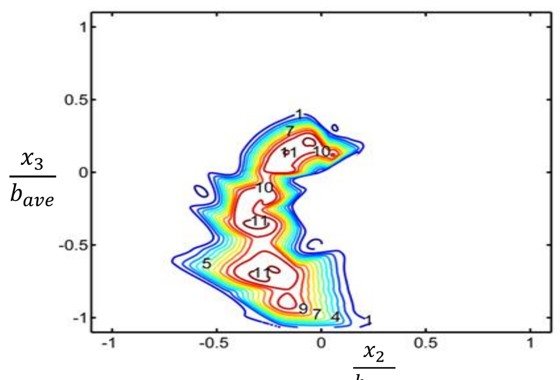
Effect of Engine Placement

- **Engine Placement at 60% Span**
- Flutter frequency

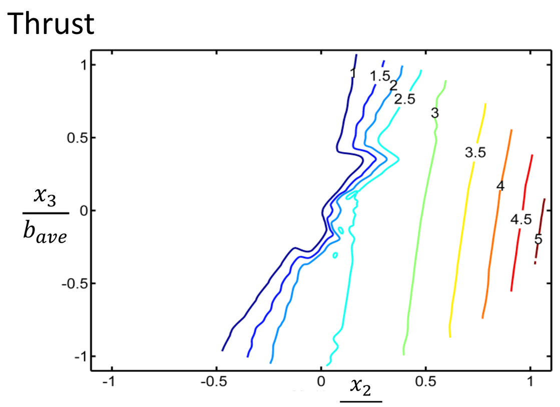




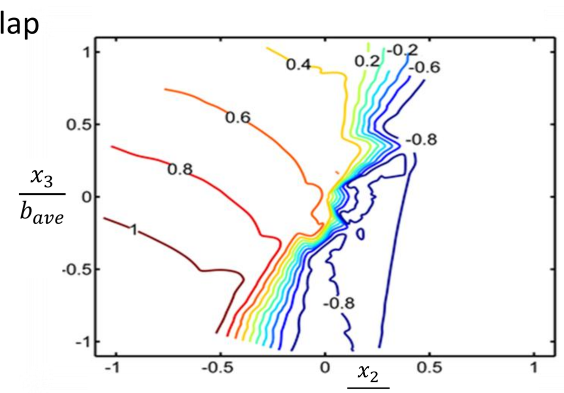
- **Engine Placement at the Tip of the Wings** (η = 1)
- Flutter frequency



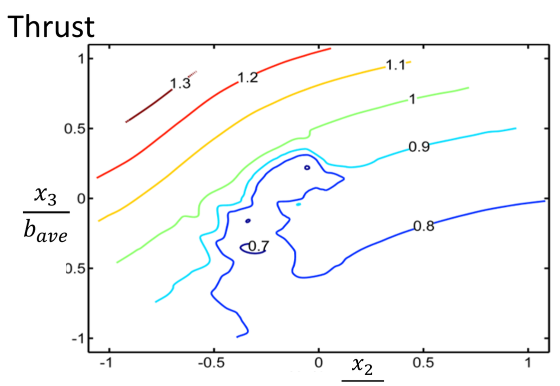
- **Aircraft Controls at Flutter with Engines at 60% Span**
- Thrust



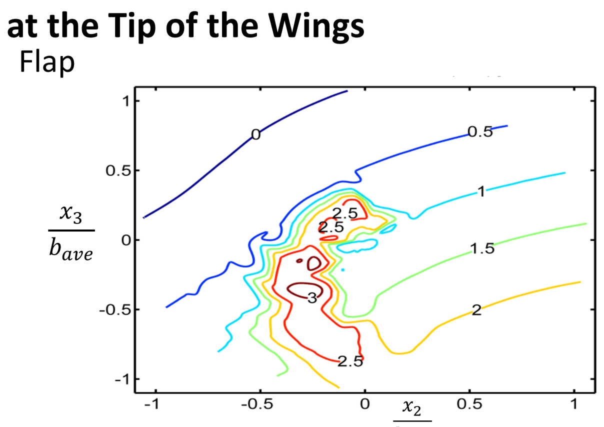
- Flap



- **Aircraft Controls at Flutter while the Engines are at the Tip of the Wings**
- Thrust

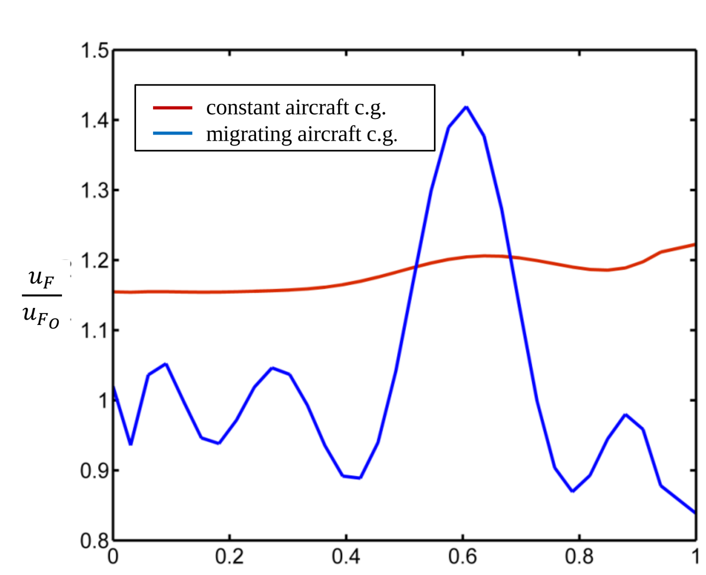


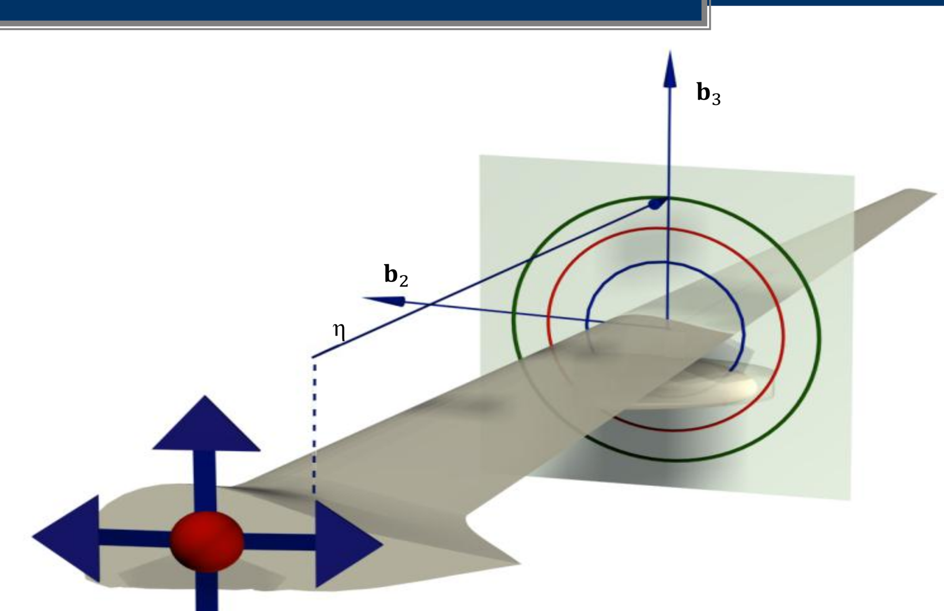
- Flap



Effect of Constant Aircraft C.G.

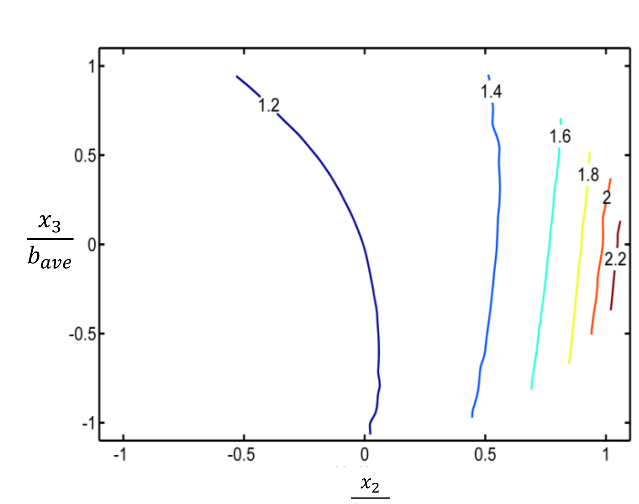
- **Aircraft mass balance**
  - keep the flap deflections in the linear range
  - smoothed out variations in the flutter speed
  - increasing flutter speed along the span





Displacement of a concentrated mass to counteract the effect of aircraft mass imbalance due to engine displacement

- **Engines are at 60% Span**



- **Engines are at the Tip of the Wings**