



# Aeroelastic Optimization

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METU

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General Electric Corporate Research & Development Center  
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# Presentation Outline

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- Introduction
- Aeroelastic Optimization
  - Linear Static Aeroelastic Optimization
  - Linear Dynamic Aeroelastic Optimization
- Trim Optimization
- Commercial Programs with Aeroelastic Design Capabilities
- Appendix B - Static and Static Aeroelastic Gradients



# Introduction

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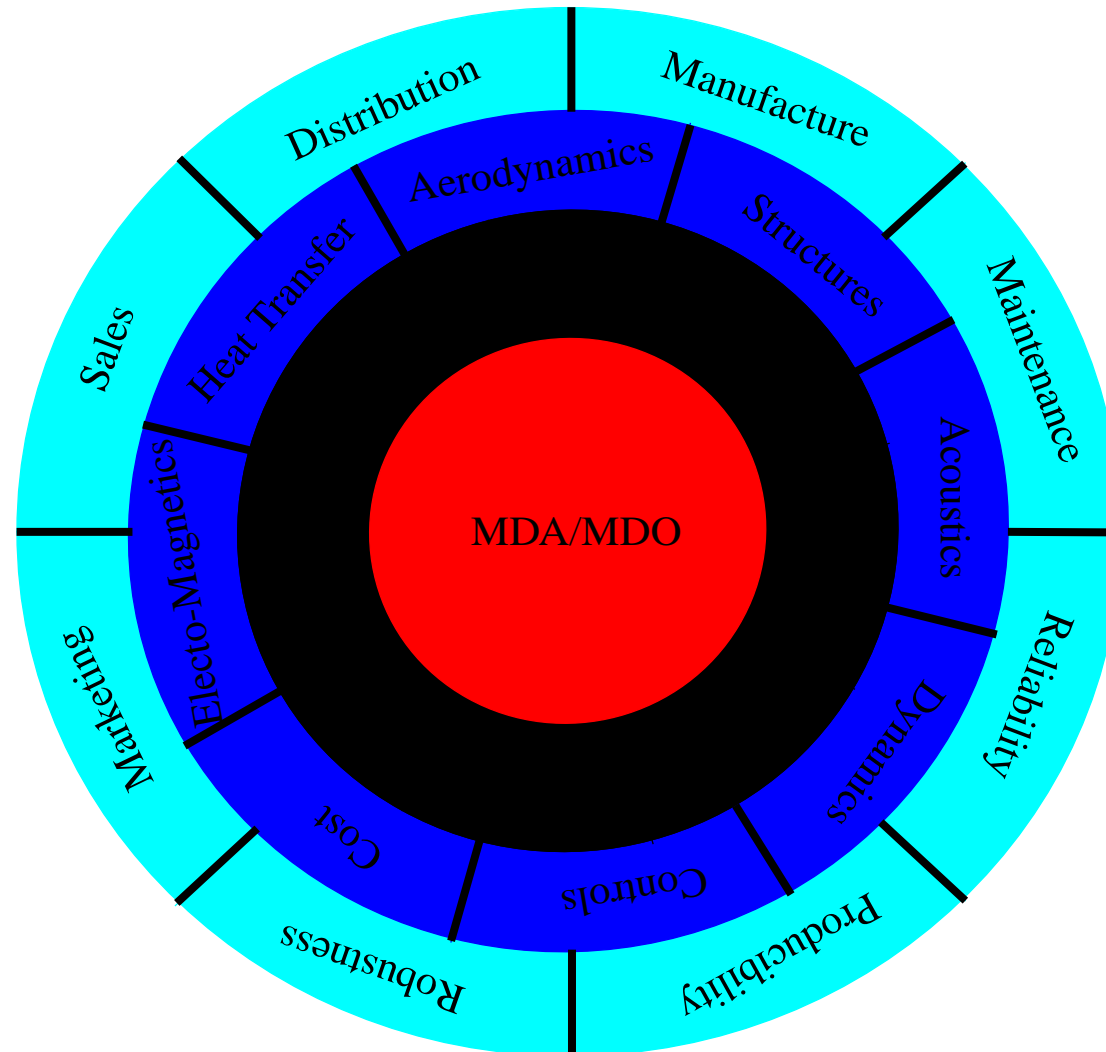
## *Motivation for Optimization*

- Missions of aeronautical and space vehicles are becoming increasingly complex
- Identifying trade-offs among pertinent disciplines is critical in obtaining designs
- Traditional methods may not achieve a design let alone an optimal design
- Optimization also used to evaluate/design modifications to existing systems



# Introduction

## *Aircraft Design Considerations in MDA/MDO*





# Introduction

## *Goal of Aeroelastic Optimization*

- Determine the aerodynamic and structural parameters to satisfy all necessary requirements over system service life
  - Traditionally, weight and performance were main objective functions. That has changed
    - Life cycle cost, manufacturability, maintainability, etc. now equal players
  - Historically, aerodynamic parameters (sweep, planform, etc.) were considered in *conceptual* design
  - Structural parameters considered in *preliminary* design
  - Recent MDO algorithms combining conceptual, preliminary and detailed design variables.
  - With advent of AAW technology/active control (piezoelectrics) must also consider some control design parameters as well (Aeroservoelastic Optimization)
  - Recently nonlinear engineering analysis considered (CFD, nonlinear FEM)



# Aeroelastic Optimization

## *Scope of Discussion- Preliminary Design*

- Assume external geometry fixed
- Determine structural physical properties (such as membrane/shell thicknesses, composite lay-ups, cross-sectional areas of rods and bars) such that the desired aeroelastic performance is met
- Mathematical statement

Minimize/(Maximize  $-F(v_s)$ ) the objective function

$$F(v_s)$$

Subject to the constraint conditions (28)

$$Z_j(v_s) \leq \bar{Z}_j \quad j = 1, 2, \dots, n$$

$$v_s^L \leq v_s \leq v_s^U$$



# Aeroelastic Optimization

$F(v_s)$  - Objective function (weight, lift effectiveness, or any linear/non-linear combination of responses, only requirement: that it reduces to a single scalar value)

$Z_j(v_s)$  - Behavioral constraints (stress, displacement, aeroelastic response, flutter etc.) (can be as many as tens of thousands)

$\bar{Z}_j$  - Allowable value for  $Z_j(v_s)$

$v_s$  - vector of design variables (assumed continuous, 1000 max)

$F(v_s), Z_j(v_s)$  - Typically implicit functions of  $v_s$

Note: Just because considered engineering analyses are linear does not imply that the responses  $Z_j(v_s)$  are linear w.r.t. ( $v_s$ ). In fact, they can be highly non-linear.



# Aeroelastic Optimization

## *A Solution Approach*

Efficient solution to (28), the classical nonlinear mathematical programming problem, can be achieved by gradient based algorithms along with;

- Approximation concepts
- Design variable linking
- Active constraint strategies
- Move limit strategies

*Effective solutions to (28) should require less than 30 detailed Engineering Analyses (including gradient calculations)*



# Aeroelastic Optimization

## *Approximation concepts*

- Single point or multi-point first order (requires only gradients) approximations

- 1st order Taylor Series direct space  $\bar{f} = f_o + \sum_{i=1}^{ndv} \frac{\partial f}{\partial v_i} (v_i - v_{oi})$

- 1st order Taylor Series inverse space

$$x_i = \frac{1}{v_i}, \bar{f} = f_o - \sum_{i=1}^{ndv} \left( \frac{\frac{\partial f}{\partial v_i} (x_i - x_{oi})}{x_{oi}^2} \right)$$

- Second order approximations require Hessian matrix (difficult to evaluate). Two point approximations methods available.



# Aeroelastic Optimization

## *Design Variable Linking*

$$\{t\} = [P]\{v\} \quad (29)$$

- Unique linking - Single value in any given row or column of  $[P]$

$$\begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix} = \begin{bmatrix} P_{11} & 0 & 0 \\ 0 & 0 & P_{23} \\ 0 & P_{32} & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$$

- Group linking - Only one entry per row but may have multiple entries in a given column

$$\begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix} = \begin{bmatrix} P_{11} & 0 & 0 \\ P_{21} & 0 & 0 \\ P_{31} & 0 & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$$

- Shape function linking - Multiple entries in a row and or column

$$\begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$$



# Aeroelastic Optimization

## *Active constraint strategies*

- Pass an “active” subset of the constraints to the approximate problem
  - Retain all violated constraints
  - Retain constraints within 10% of the boundary
  - Don't retain more than 1 or 2 times NDV unless necessary
- Update the “active” set for each new approximate problem
- Calculate gradients for only the “active” set of constraints
  - Results in large computational savings



# Aeroelastic Optimization

## *Move Limit Strategies*

- Using approximations for constraints functions, objective function, constraint function gradients, and objective function gradients must be recognized by imposing constraints on the movement of the design variables for any given approximate problem.

$$\frac{v_{oi}}{\text{movlim}} \leq v_i \leq \text{movlim} \times v_{oi}$$

- movlim is problem dependent, values typically can range anywhere from 1.1 to 2.0



# Aeroelastic Optimization

## *Gradient Calculations*

- Efficient accurate gradient calculations are *essential* to gradient based solutions to (28).
- If at all possible avoid finite difference gradients
  - Costly, and prone to step size problems
- Use analytic or semi-analytic gradients



# Aeroelastic Optimization

## *Gradient Calculations*

- For the current scope, static and dynamic aeroelastic gradients depend on the gradients of  $[M]$ ,  $[K]$ ,  $[B]$  at the elemental level.
- Decompose the elemental matrices into 3 parts
  - Invariant w.r.t. design variable  $\{v\}$  ( $k_{fixed}^{ee}$ ,  $m_{fixed}^{ee}$ ,  $b_{fixed}^{ee}$ )
  - Linear variation w.r.t.  $\{v\}$  ( $k_{factor}^{ee}$ ,  $m_{factor}^{ee}$ ,  $b_{factor}^{ee}$ )
  - Non-linear variation w.r.t.  $\{v\}$  ( $k_{nonlinear}^{ee}$ ,  $m_{nonlinear}^{ee}$ ,  $b_{nonlinear}^{ee}$ )

$$\begin{aligned} [K] &= Ak_{fixed}^{ee} + A \sum_s \sum_i P_{is} k_{factor_i}^{ee} v_s + Ak_{nonlinear}^{ee} \\ [M] &= Am_{fixed}^{ee} + A \sum_s \sum_i P_{is} m_{factor_i}^{ee} v_s + Am_{nonlinear}^{ee} \\ [B] &= Ab_{fixed}^{ee} + A \sum_s \sum_i P_{is} b_{factor_i}^{ee} v_s + Ab_{nonlinear}^{ee} \end{aligned} \quad (30)$$



# Aeroelastic Optimization

$\mathbf{A}$  - the assemble operation for the elemental matrices to global

$ee$  - superscript indicating elemental matrices

$P_{is}$  - being the terms of the design variable linking matrix  $[P]$  in (29)

Differentiating (30) w.r.t.  $v_s$  yields ( $\mathbf{A}$  is an assembly operator)

$$\begin{aligned}\frac{\partial}{\partial v_s}[K] &= \mathbf{A} \sum_i P_{is} k_{factor_i}^{ee} + \mathbf{A} \sum_i P_{is} \frac{\partial k_{nl}^{ee}}{\partial t_i} \\ \frac{\partial}{\partial v_s}[M] &= \mathbf{A} \sum_i P_{is} m_{factor_i}^{ee} + \mathbf{A} \sum_i P_{is} \frac{\partial m_{nl}^{ee}}{\partial t_i} \\ \frac{\partial}{\partial v_s}[B] &= \mathbf{A} \sum_i P_{is} b_{factor_i}^{ee} + \mathbf{A} \sum_i P_{is} \frac{\partial b_{nl}^{ee}}{\partial t_i}\end{aligned}\tag{31}$$



# Aeroelastic Optimization

With  $(\partial k_{nl}^{ee})/(\partial t_i)$ ,  $(\partial m_{nl}^{ee})/(\partial t_i)$ ,  $(\partial b_{nl}^{ee})/(\partial t_i)$  by forward finite difference as

$$\begin{aligned}\left. \frac{\partial k_{nl}^{ee}}{\partial t_i} \right|_n &= \frac{k_{nl}^{ee} \Big|_n(t_i + \Delta t_i) - k_{nl}^{ee} \Big|_n}{\Delta t_i} \\ \left. \frac{\partial m_{nl}^{ee}}{\partial t_i} \right|_n &= \frac{m_{nl}^{ee} \Big|_n(t_i + \Delta t_i) - m_{nl}^{ee} \Big|_n}{\Delta t_i} \\ \left. \frac{\partial b_{nl}^{ee}}{\partial t_i} \right|_n &= \frac{b_{nl}^{ee} \Big|_n(t_i + \Delta t_i) - b_{nl}^{ee} \Big|_n}{\Delta t_i}\end{aligned}\tag{32}$$

$xx_{nonlinear}^{ee} = 0$  fully analytic,  $xx_{nonlinear}^{ee} \neq 0$  semi-analytic  $\nabla$

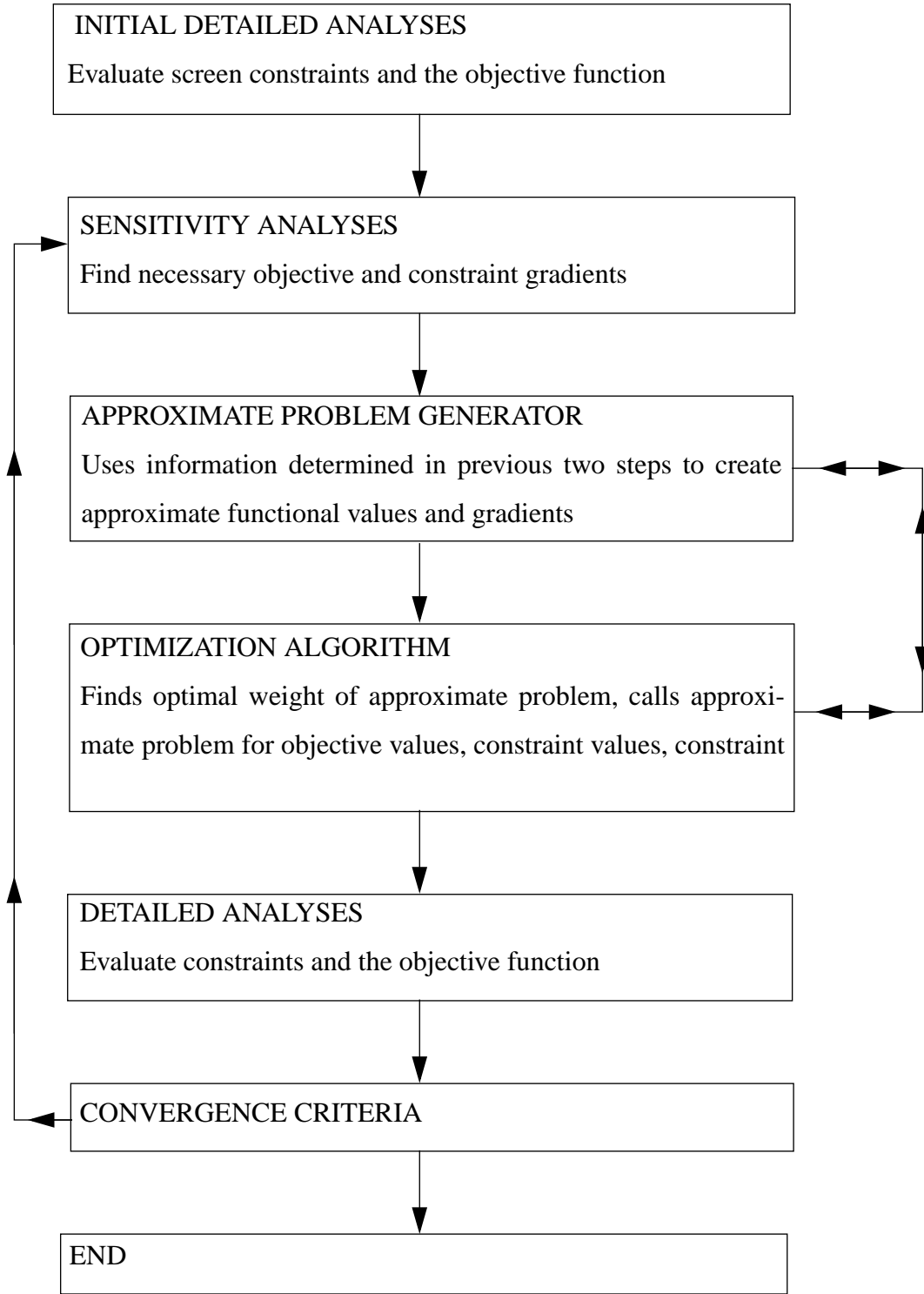


# Aeroelastic Optimization

## *Aeroelastic Constraints Considered*

- Static Aeroelastic Constraints
  - Stress
  - Strain
  - Displacement
  - Flexible stability derivatives (lift effectiveness, control surface effectiveness, etc.)
  - Aileron effectiveness
  - Free trim parameter constraints
- Dynamic Aeroelastic Constraints
  - Flutter

# Optimization Algorithm Flow





# Aeroelastic Optimization

## *Requirements for Optimization Environment*

- Multiple Boundary Conditions considered simultaneously
  - Symmetric
  - Anti-symmetric
  - Asymmetric
  - Store configurations
- Multiple disciplines considered simultaneously
  - Statics
  - Dynamics
  - Static Aeroelasticity
  - Dynamic Aeroelasticity
- Ability to construct constraints and objective functions from available responses



# Static Aeroelastic Optimization

## *Von Mises Stress/Tsai-Hill Constraint*

$$g = \left[ \left( \frac{\sigma_x}{S_x} \right)^2 + \left( \frac{\sigma_y}{S_y} \right)^2 - \frac{\sigma_x \sigma_y}{S_x S_y} + \left( \frac{\tau_{xy}}{F_s} \right)^2 \right]^{\frac{1}{2}} - 1$$

- $\sigma_x, \sigma_y, \tau_{xy}$  - Element normal, transverse, and shear strains
- $S_x, S_y, F_s$  - Normal, transverse and shear allowables.
  - $S_x, S_y$  - each may be  $S_c, S_t$  compression or tension allowables depending on the sign of  $\sigma_x, \sigma_y$
  - $S_c, S_t$  need not be equal



# Static Aeroelastic Optimization

## *Principal Strain Constraint*

$$g_1 = \frac{\epsilon_x}{\epsilon_{all}} - 1$$

$$g_2 = \frac{\epsilon_y}{\epsilon_{all}} - 1$$

with

$$\epsilon_x = \frac{1}{2} \left[ \epsilon_1 + \epsilon_2 + [(\epsilon_1 - \epsilon_2)^2 + \epsilon_{12}^2]^{1/2} \right]$$

$$\epsilon_y = \frac{1}{2} \left[ \epsilon_1 + \epsilon_2 - [(\epsilon_1 - \epsilon_2)^2 + \epsilon_{12}^2]^{1/2} \right]$$

- Fiber and transverse strain constraints often used as well



# Static Aeroelastic Optimization

## *Displacement Constraints*

$$\sum_{j=1}^{ndisp} A_{ij} u_j \leq \delta_{i_{all}}$$

- $A_{ij}$ ,  $\delta_i$  - Weighting factors on  $u_j$  and user specified limit respectively
- Enables specifying limits of the shape of the displacements
  - Wing tip twist constraint

$$- \frac{w_{LE} - w_{TE}}{C_{tip}} \leq 0.04 \text{ radians}$$



# Static Aeroelastic Optimization

## *Aileron Effectiveness Constraint*

$$\varepsilon_{min} \leq \varepsilon_{eff} \leq \varepsilon_{max}$$

With

$$\varepsilon_{eff} = \frac{\left(C_{l_{\delta_a}}\right)^f}{\left(C_{l_{\frac{pb}{2V}}}\right)^f}$$

$C_l$  - Rolling moment about the aircraft centerline

$\delta_a$  - Aileron deflection

$\frac{pb}{2V}$  - Roll rate nondimensionalized by wing span and aircraft velocity

$f$  - Flexibility effects are included in the derivatives

- Steady roll rate achievable for a unit value of aileron deflection.



# Static Aeroelasticity

## *Flexible Stability Derivative Constraint*

$$\left[ \frac{\partial C_F}{\partial \delta_{trim}} \right]_{lower} \leq \frac{\partial C_F}{\partial \delta_{trim}} \leq \left[ \frac{\partial C_F}{\partial \delta_{trim}} \right]_{upper}$$

- Enables constraint of any flexible derivative in any axis for any trim parameter
- For example, lift effectiveness

$$\epsilon_{min} \leq \frac{C_{L\alpha_f}}{C_{L\alpha_r}} \leq \epsilon_{max}$$



# Static Aeroelastic Optimization

## *Trim Parameter Constraint*

- Any FREE parameter in the trim solution can be constrained

$$\delta_{trim} \leq \delta_{trim_{req}} \text{ or } \delta_{trim} \geq \delta_{trim_{req}}$$

- Angle of attack, control surface deflection etc.



# Dynamic Aeroelastic Optimization

## *Frequency Constraints*

$$f_i \leq f_{high} \Rightarrow g = 1 - \frac{4\pi^2 f_{high}^2}{\lambda_i}$$

$$f_i \leq f_{high} \Rightarrow g = \frac{4\pi^2 f_{low}^2}{\lambda_i} - 1$$

- Constraint actually on the eigenvalue  $\lambda_i$  (improves accuracy of approximation)



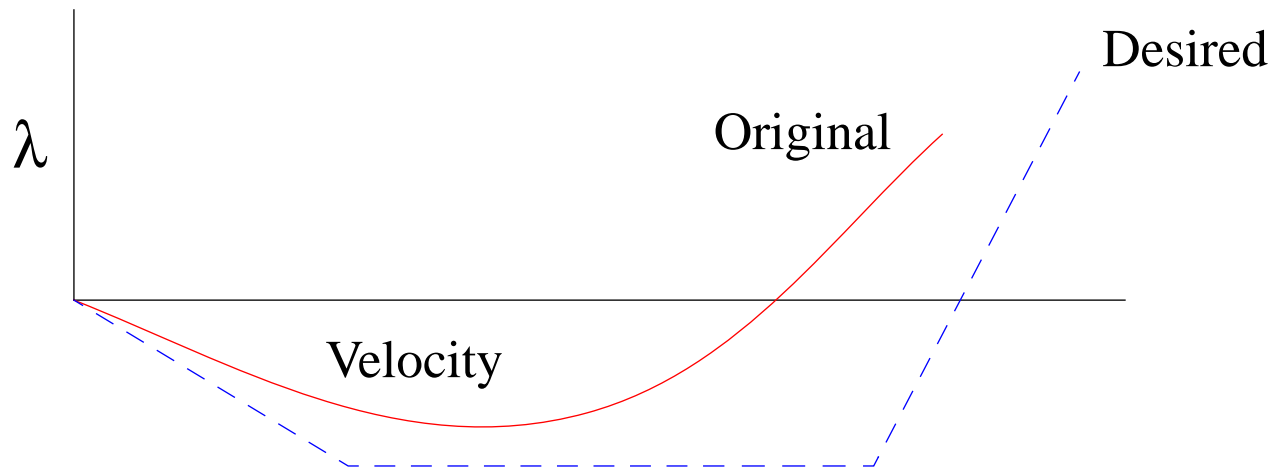
# Dynamic Aeroelasticity

## *Flutter Constraint*

- Constraint is formulated in terms of satisfying requirements on the modal damping values at a series of specified velocities

$$(\gamma_{ij} \leq \gamma_{jREQ}) \quad j = 1, 2, \dots, nvel$$

- Advantages of constraining damping
  - No need to calculate flutter velocity
  - Able to capture “hump” modes
- Disadvantage
  - modal damping is only estimated away from the axis for P-K solution





# Static Aeroelasticity

## *Rectangular Wing Example*

### Material Properties

$E = 10.E06$  psi

Poisson's Ratio = .3

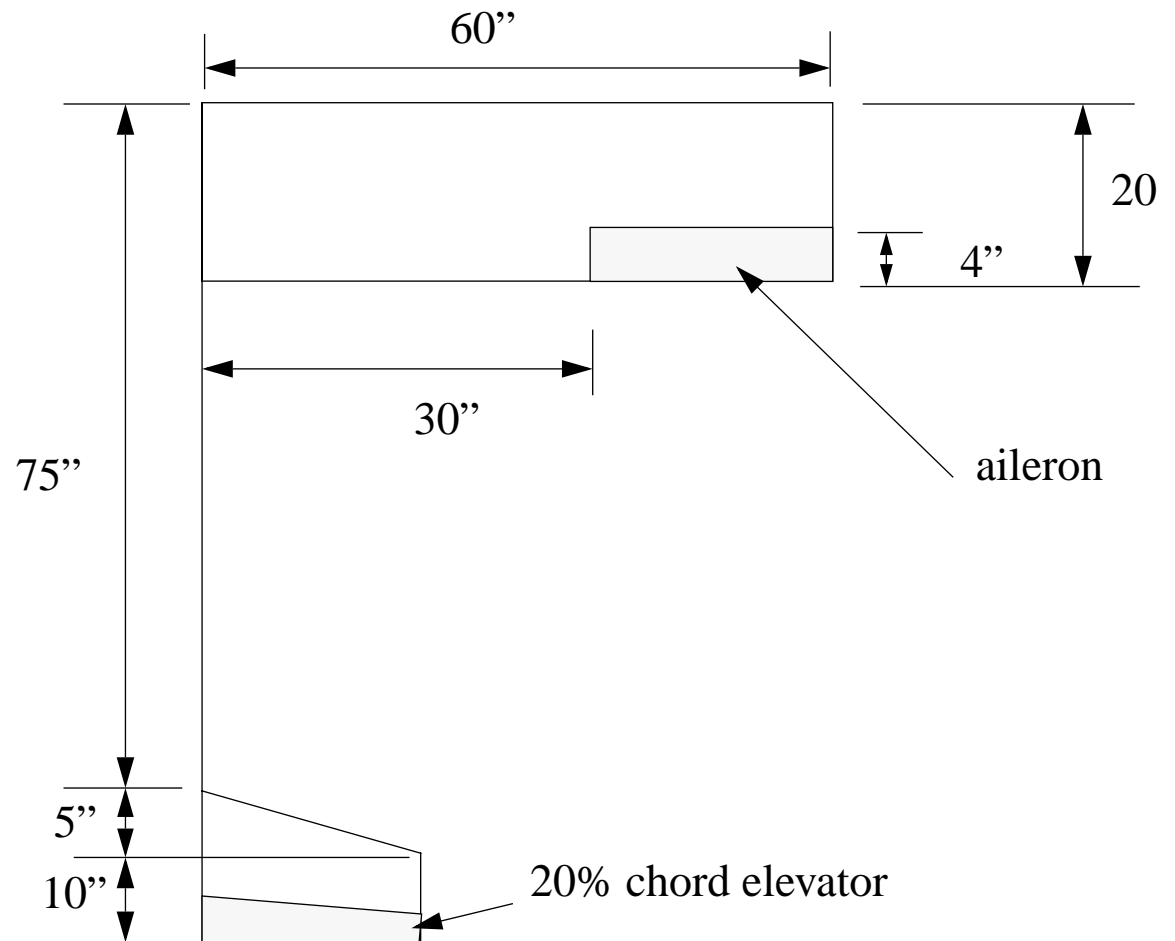
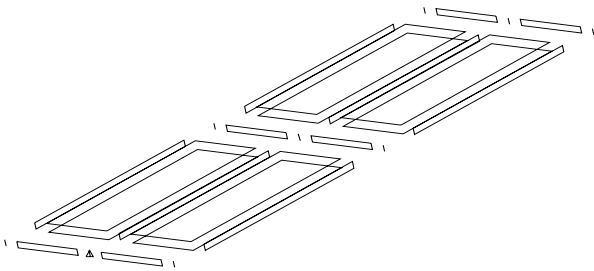
Weight Density  $0.1$  lb/in<sup>3</sup>

Tensile Strength =  $20.0$  ksi

Compressive Strength  $15$  ksi

Shear Strength  $12.0$  ksi

### Structural Model





# Static Aeroelastic Optimization

## *Rectangular Wing Example*

- Flight Conditions

- Symmetric

$$M = 0.8, q = 6.5 \text{ psi}, n_z = 8.0g, \text{QRATE} = 15.7 \text{ deg/sec}$$

$$\alpha = \text{FREE}, \text{ELEV} = \text{FREE}$$

- Anti-symmetric

$$M = 0.8, q = 6.5 \text{ psi}, \text{aileron} = 1.0 \text{ deg}, \text{QACCEL} = 0.0$$

$$\text{PRATE} = \text{FREE}$$

- Constraints

- Maximum Tip Rotation (Degs)- 1.0

- Maximum Lift Effectiveness - 1.60

- Minimum Aileron Effectiveness.30

$$\sigma_T \leq 20 \text{ ksi}$$

- $\sigma_C \leq 15 \text{ ksi}$

$$\tau_{xy} \leq 12 \text{ ksi}$$

- Design Variables

- Inboard top skins

- Inboard bottom skins

- Outboard top skins

- Outboard bottom skins

- Objective Function

- Weight



# Static Aeroelastic Optimization

## *Rectangular Wing Example*

- Four Design Cases Run

Constraint	Case			
	A	B	C	D
Maximum Tip Rotation	1.0	1.0	--	1.0
Maximum Lift Effectiveness	--	1.6	--	1.6
Minimum Aileron Effectiveness	--	--	0.30	0.30
Stress Constraints Applied	yes	yes	no	yes



# Static Aeroelastic Optimization

## *Rectangular Wing Example*

- Design Run Results

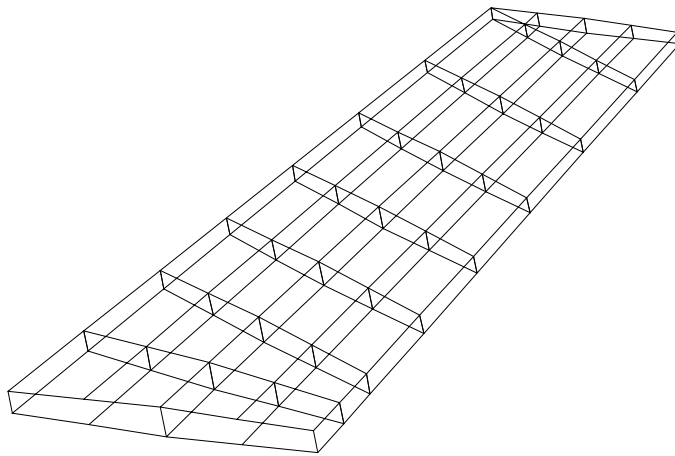
Parameter	Case			
	A	B	C	D
Inboard Top Skin Thicknesses	0.13377	0.18559	0.1166	0.18559
Inboard Bottom Skin Thicknesses	0.13377	0.18532	0.1166	0.18532
Outboard Top Skin Thicknesses	0.08254	0.05274	0.06910	0.05274
Outboard Bottom Skin Thicknesses	0.08256	0.05276	0.06910	0.05276
Structural Weight (lb)	22.71	22.98	22.35	22.98
Tip Rotation (deg)	1.0	1.0	1.68	1.0
Lift Effectiveness	1.92	1.60	2.09	1.60
Aileron Effectiveness	0.312	0.314	0.30	.314
Trimmed Angle of Attack (deg)	1.03	1.30	0.933	1.30
Trimmed Elevator Setting (deg)	-2.03	-2.13	-1.96	-2.13



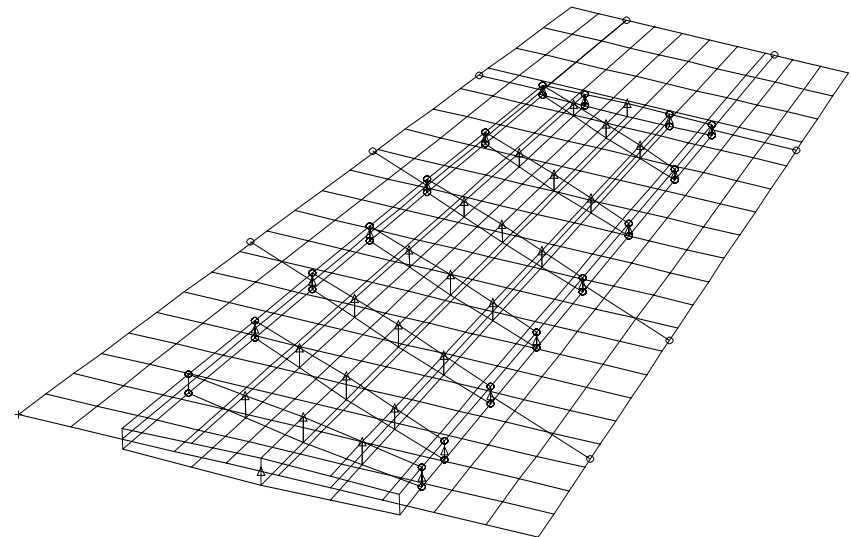
# Aeroelastic Optimization

## *Intermediate Complexity Wing (ICW) Example*

Structural Model



Structures and Aerodynamics Models





# Aeroelastic Optimization

## • Material Properties

### Orthotropic Material

$$E_1 = 19.9E6 \text{ psi}$$

$$E_2 = 1.5E6 \text{ psi}$$

$$\nu_{12} = 0.32$$

$$G_{12} = 0.85E6 \text{ psi}$$

$$\rho = 0.055 \text{ lb/in}^3$$

$$\text{Ply } t_{min} = 0.04 \text{ in.}$$

$$\epsilon_T \leq 4500\mu$$

$$\epsilon_C \leq 3200\mu$$

### Isotropic Material

$$E = 10.5E6 \text{ psi}$$

$$\nu = 0.30$$

$$\rho = 0.10 \text{ lb/in}^3$$

$$t_{min} = 0.04 \text{ in.}$$

$$\sigma_T \leq 45 \text{ ksi}$$

$$\sigma_T \leq 45 \text{ ksi}$$

$$\tau_{xy} \leq 45 \text{ ksi}$$

## • Constraints/D.V.

### Stress Constraints

110 Von Mises Stress (rods&shear panels)

256 TSAI Wu (Composite skins)

### Displacement Constraints

$$u_{z_{tip}} \leq 7.8 \text{ in.}$$

### Flutter Constraints

$$V_f \geq 18270 \text{ in/sec}$$

### Design Variables

153 design variables

Upper & lower surface linked for each ply orientation

## • Flight Conditions

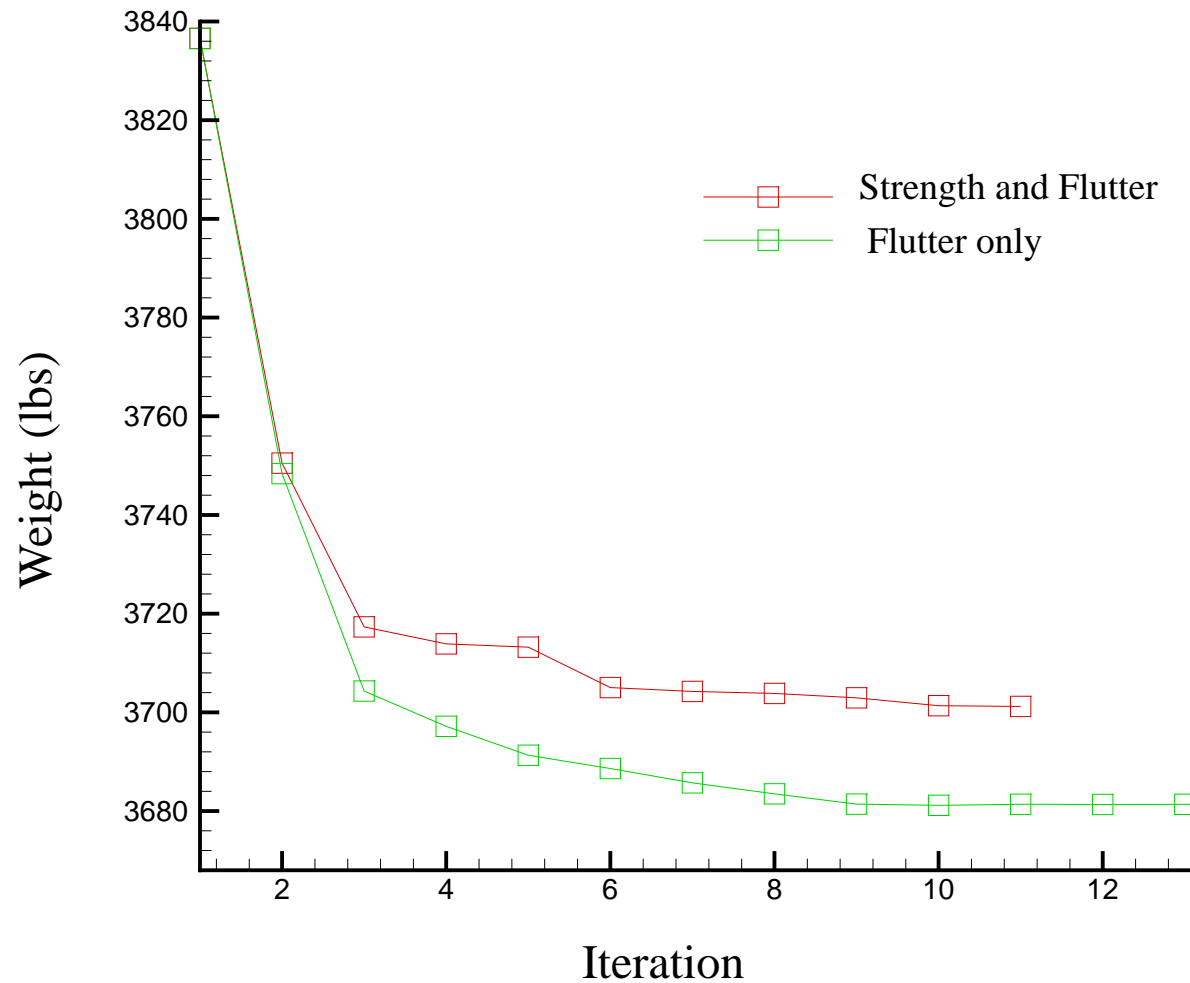
Flutter  $M = 0.8$  sea level

Symmetric 9g pull-up  
 $M=0.8$ , 7.86 psi.



# Aeroelastic Optimization

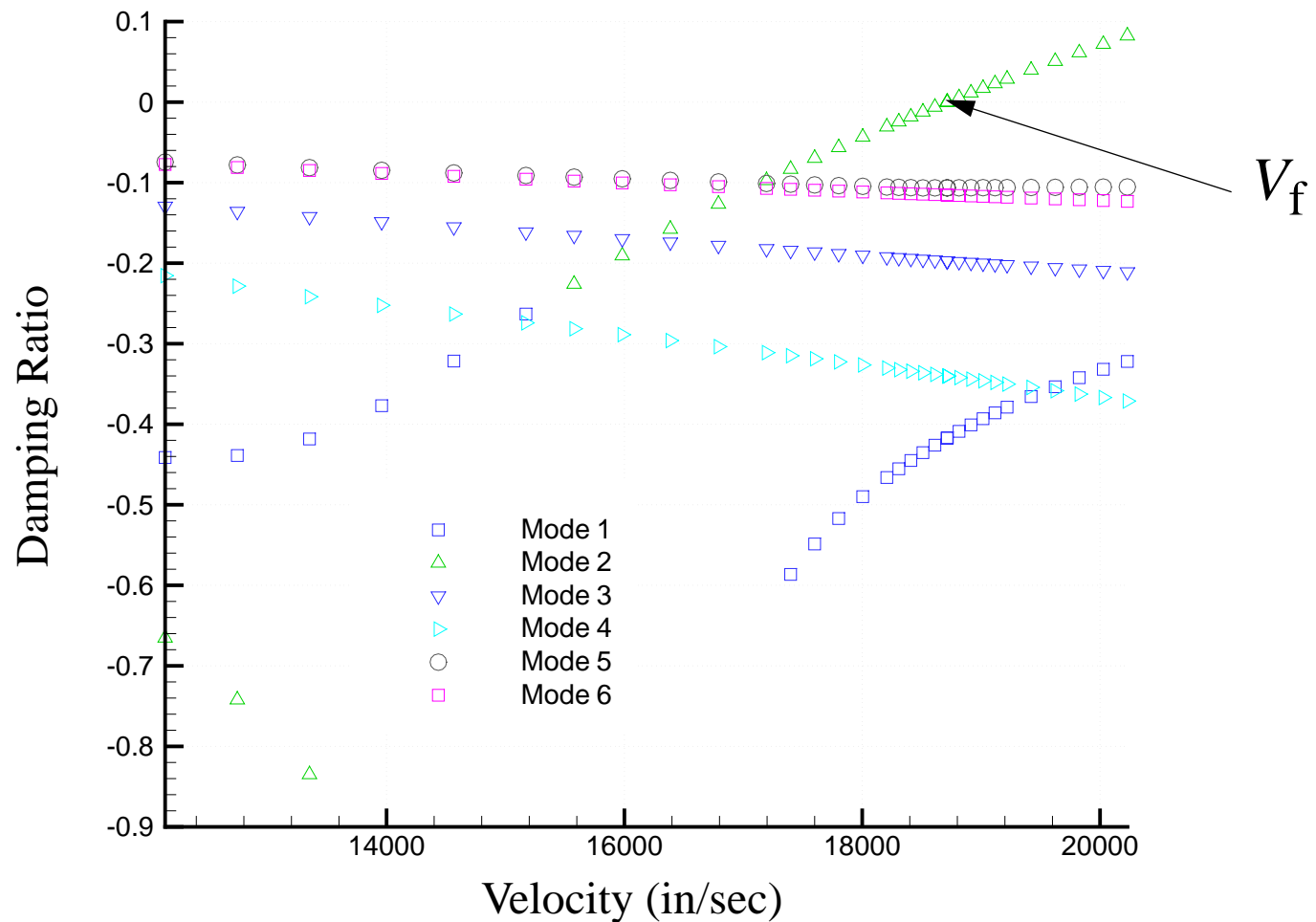
## *Design History for ICW*





# Aeroelastic Optimization

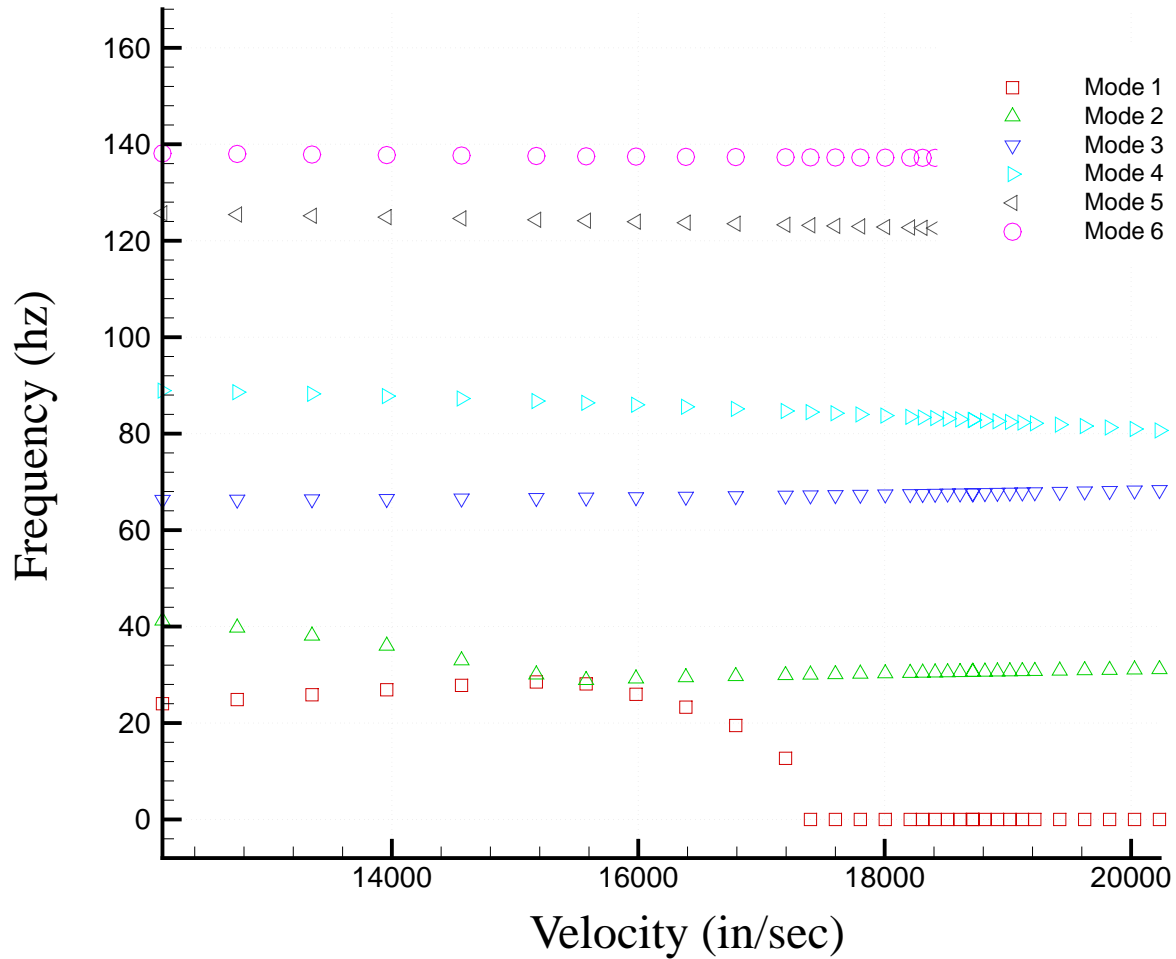
*ICW Final Design V vs. Damping*





# Aeroelastic Optimization

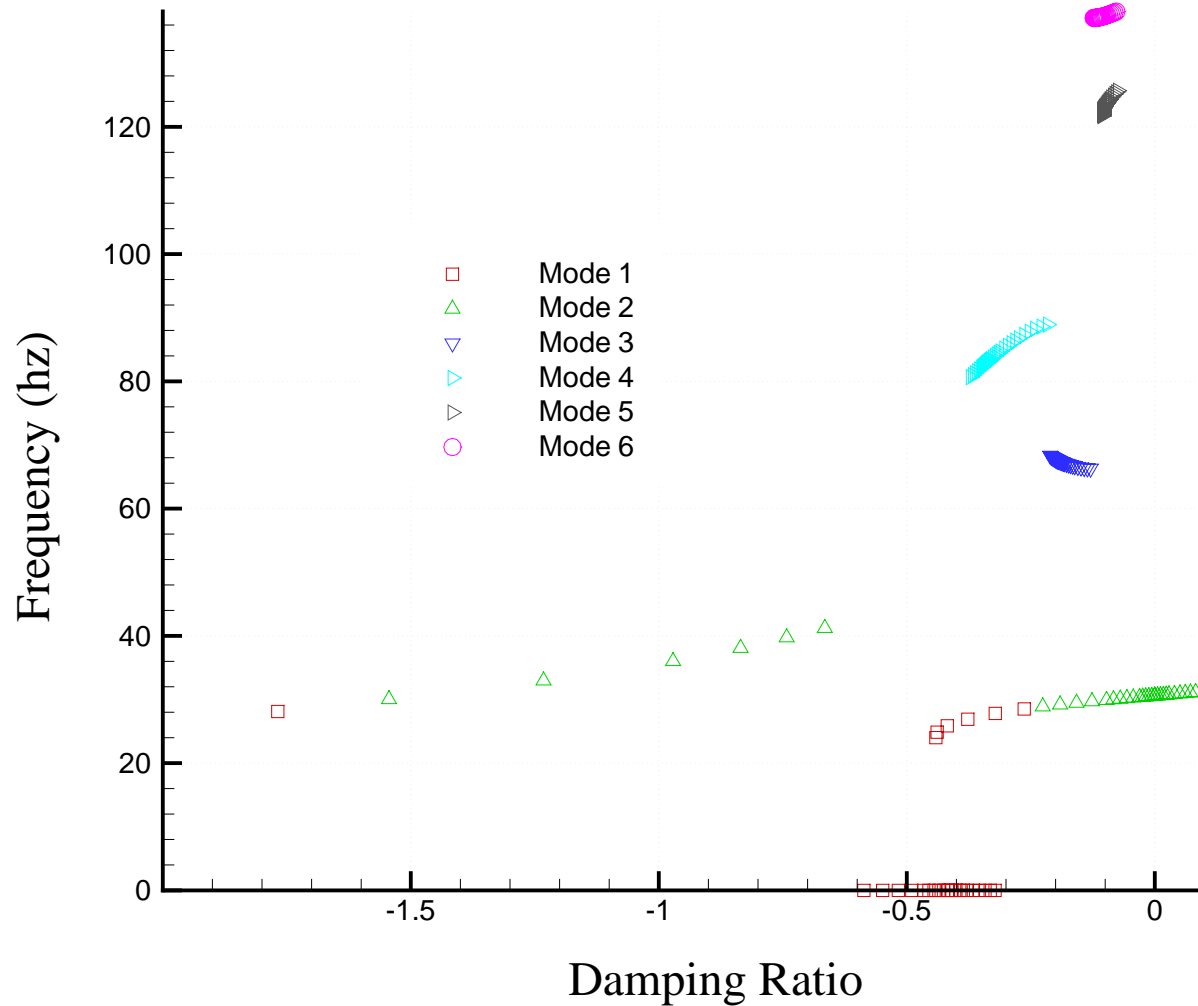
*ICW Final Design Frequency vs. Damping*





# Aeroelastic Optimization

*ICW Final Design Damping vs. Frequency*





# Aeroelastic Optimization

## *Trim Optimization*

- Number of FREE aerodynamic parameters  $>$  Number of trim DOF
- Allows redundant control surfaces
- Objective function based on trim parameters/trim DOF and calculated responses (integrated maneuver loads, hinge moments etc.)
- Constraints based on trim parameters/trim DOF (integrated maneuver loads, hinge moments etc.)



# Aeroelastic Optimization

## *Trim Optimization Problem*

- Problem is formulated as nonlinear mathematical programming problem

Minimize/(Maximize  $-F(v_s)$ ) the objective function

$$F(v_s)$$

Subject to the constraint conditions

$$g_j(v_s) \leq 0 \quad j = 1, 2, \dots, n_{con}$$

$$v_s^L \leq v_s \leq v_s^U$$

- With  $v_s$  a vector of control effectors (control surfaces, thrust, user defined controllers, smart structures)
- Design constraints and objectives are control effector limits, integrated maneuver loads, and maneuver performance (e.g. roll rate)
- The procedure uses the redundant control effectors and trim parameters ( $\alpha$ ,  $\beta$  etc.) to drive the trim state to a constrained minimum for the objective and constraints defined



# Aeroelastic Optimization

## *Trim Optimization*

- The basic trim equations (Equation 14) are used as constraints to enforce equilibrium
- These two set of constraints state that the imbalance of forces and moments at the support point must be less than a specified tolerance

$$\begin{Bmatrix} g_1 \\ \dots \\ g_{nr} \end{Bmatrix} = (Lu_2 - R\delta) - \begin{Bmatrix} 1 \\ \dots \\ 1 \end{Bmatrix} \text{tolerance}$$

$$\begin{Bmatrix} g_{nr} \\ \dots \\ g_{2 \times nr} \end{Bmatrix} = (R\delta - Lu_2) - \begin{Bmatrix} 1 \\ \dots \\ 1 \end{Bmatrix} \text{tolerance}$$

- Other potential constraints
- ABS function - has singularity at 0
- Squared function - non-linear gradients

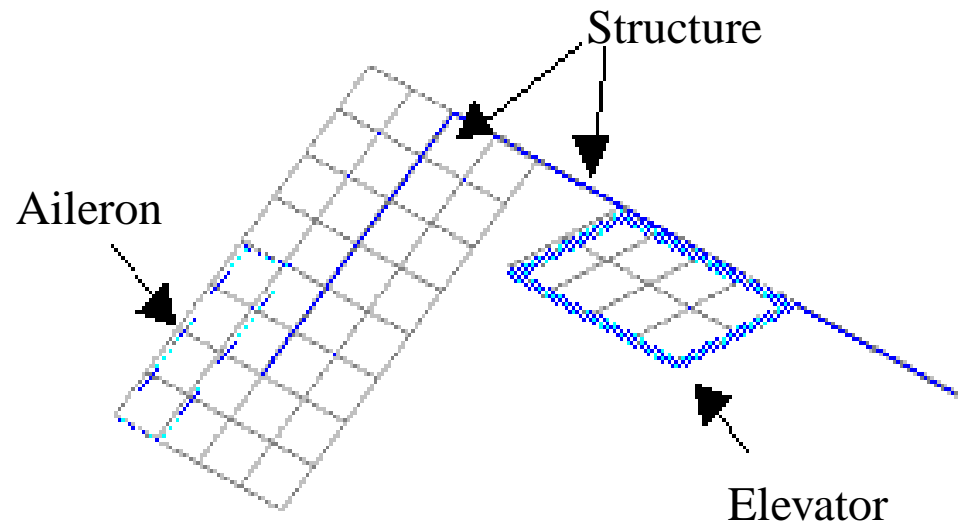


# Aeroelastic Optimization

## *Trim Optimization*

### Forward Swept Wing Example [7]

- Minimize - ( $N_z + 100 \times \text{PRATE}$ )
- Subject to: Vehicle Imbalance
  - Lift  $< 1$  lb
  - Pitch  $< 1$  in-lb
  - $N_z < 10$  g's
  - PRATE  $< 286$  deg/sec
- RESULTS - TRIMMED SOLUTIONS



From Feasible Space - 30 Function Evals & 7 Gradients

From Infeasible space - 182 Function Evals & 32 Gradients



# Aeroelastic Optimization Software

## *Global Aeroelastic Design Software*

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



# Aeroelastic Optimization Software

## *MSC/NASTRAN*

- General Modeling/Analysis Environment
  - Multiple boundary conditions
  - Multiple disciplines per boundary condition
  - Selectable aerodynamic models
  - Optimization solvers (MMFD, SLP, SQP)
- Design variables
  - Element properties, shape
  - Design variable linking (physical, group, shape)
- Objective Functions
  - User definable based on available responses (linear/nonlinear combinations)
- Static Aeroelastic Constraints
  - Stress
  - Strain
  - Displacement
  - Buckling (Panel, Euler column)



# Aeroelastic Optimization Software

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- Flexible Stability derivatives (lift effectiveness, control surface effectiveness, etc.)
  - Free trim parameter constraints
- 
- Trim Optimization
    - Balance Forces due to hinge moment and deflection constraints
  - Generic Control
    - Blends redundant control surfaces based on most effective surfaces
  - Dynamic Aeroelastic Constraints
    - Flutter damping (P-K method)
    - Frequency constraints
  - Pre-Post Processing
    - Extensive Flight Loads pre/post processing functionality in PATRAN environment



# Aeroelastic Optimization Software

## *UAI/ASTROS Aeroelastic Capabilities*

- General Modeling/Analysis Environment
  - Multiple boundary conditions
  - Multiple disciplines per boundary condition
  - Selectable aerodynamic models
  - MPC's set selectable
  - Optimization solvers (FSD, MMFD( $\mu$ Dot))
- Design variables
  - Element properties
  - Design variable linking (physical, group, shape)
- Objective Functions
  - User definable based on available responses (linear/nonlinear combinations)
- Constraints
  - User definable based on available responses (linear/nonlinear combinations)
  - Static Aeroelastic Constraints
    - Stress
    - Strain



# Aeroelastic Optimization Software

- Displacement
- Buckling (Panel, Euler column)
- Flexible Stability derivatives (lift effectiveness, control surface effectiveness, etc.)
- Aileron Effectiveness
- Free trim parameter constraints
- Integrated maneuver loads (BMST)
- Dynamic Aeroelastic Constraints
  - Flutter damping (P-K method)
  - Frequency constraints
- Trim Optimization
  - Formal mathematical programming formulation
  - Allows redundant control surfaces
  - Objective function based on trim parameters/trim DOF and calculated responses (integrated maneuver loads, hinge moments etc.)
  - Constraints based on trim parameters/trim DOF (integrated maneuver loads, hinge moments etc.).
- Nonlinear Trim
  - Rigid load vectors are interpolated/extrapolated based on available set
  - Loop on trim solution until each control surface schedule converges



# Aeroelastic Optimization Software

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- Very easy to add user defined functionality and tailor the system
- Pre-Post Processing
  - Bulk data input 90% compatible with NASTRAN
  - Database accessible with SQL type interface and API



# References

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