Tow Steered Wing Structure Design

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Outline

- Motivation and Research Goals
- Background
- Analytical Approach
- Numerical Implementation
- Current Challenges
- Summary and Future Work
Motivation and Research Objectives

• Motivation
  – Enable airframe definition to keep pace with rapidly evolving configurations
  – Identify efficient structural concepts during conceptual design
  – Access to computational geometry and coupled analyses

• Objectives
  – Develop analysis method for variable stiffness wing box structures
    • Static, Vibration, Buckling
    • Aeroelastic response
  – Demonstrate an efficient sizing framework
    • Ability to trade off speed, fidelity and level of detail
Conventional and Steered Laminates

Conventional Multi-Zone Laminates
- Discrete zones of constant properties
- 0/+45/-45/90 ply angles throughout
- Tailored by ply percentages and stack
- Zones are typically sized for worst case point condition -> conservative
- Well established design and analysis

Fiber Steered Laminates
- Stiffness and strength tailored by varying both fiber angle and ply stack
- Fiber paths are in-plane curvilinear
- Design and analysis is more complex
- Offers potential for significant performance improvements
AFP Manufacturing Flexibility & Challenges

**Tow Steering: Challenges & Concerns**
- Current AFP design approach uses traditional methods
- Tow steering exceeds engineering design practice - the concept of fiber steering is not addressed and potential weight and performance advantages are unrealized
- Design/Analysis concerns: fiber path modeling, variable stiffness/strength and certification
- Fabrication concerns: steering limits, gaps/overlaps & quality
Curvilinear Fiber Path Definition

• Linear Fiber Path Model: \( \theta(x') = \phi + (T_1 - T_0) \frac{|x'|}{d} + T_0 \)

• Ply angle \( \theta \) varies linearly over distance \( d \) from \( T_0 \) to \( T_1 \) along \( x' \)

• Laminate designation: \( \phi \pm <T_0|T_1> \) e.g. \([\pm<45|45>]\)

(Gurdal and Olmedo 1993)
(Tatting and Gurdal 2002)
Wing Geometry and Construction

- VSP wing geometry exported to DegenGeom format
- Wing planform modeled as an assembly of quadrilateral segments
• Reference plane: represents the equivalent plate surface
• Wing skin covers: orthotropic laminate or single isotropic layer
• Linearly varying 0° reference fiber path: \( \theta (y') = \phi + \left(T_1 - T_0\right) \frac{y'}{s} + T_0 \)
• Constrained ply orientations: [0/+45/-45/90] relative to reference fiber path
• Variable laminate stiffness: \( Q = Q(x, y) \)
Wing Substructure Cross Section

- Substructure: Ribs and spars or solid material
- Section variables
Analytical Approach

• FSDT: Reissner-Mindlin and Legendre basis functions
• Ritz numerical solution
Buckling Panel Definitions

- Panels derived from rib-spar intersections
- Ritz buckling analysis:
  - Reference: AIAA 2016-1975
  - Good correlation with Nastran FEM
Overview of Analytical Approach

- Mindlin plate theory: \([u, v, w, \phi_x, \phi_y]\)
- Linear fiber path model: \(\theta = \theta(x, y)\)
- Lamination theory: \(\tilde{Q}_{ij} = \tilde{Q}_{ij}(x, y)\)
- Ritz and Legendre polynomials
- Energy transformation: \(\Pi = \Pi(\xi, \eta)\)
- Numerically integrate energy equations
- MATLAB implementation
- Optional NASTRAN solution

Inputs
- Geometry
- Fiber Paths
- Loads, BCs
- Parameters

Matrix Equations
- \([K]\{q\} = \{F\}\)
- \([K - \lambda M]\{q\} = 0\)
- \([K - \lambda G]\{q\} = 0\)

Solve and Post-processing
- Eigenvalues/vectors
- Displacement vector
- Strain recovery

Verification
- NASTRAN
  - SOL 101
  - SOL 103
  - SOL 105

\[
\begin{align*}
\theta(x, y, z, t) &= \theta_0(x, y, t) + \sum_i \frac{\partial \phi}{\partial z} \\
\phi_x &= \frac{\partial u}{\partial z}, \quad \phi_y = \frac{\partial v}{\partial z} \\
\end{align*}
\]

\[
[K_c] = \sum_{i=1}^{M_g} \sum_{j=1}^{N_g} g_i g_j K_{mn}(\xi_i, \eta_j)
\]

\[
K_{mn} = \left[ [C]^T [T_e]^T [D] [T_e] [C] ] / l \right] (\xi_i, \eta_j)
\]

\[
g_i g_j = \text{Gauss weights}
\]
Numerical Implementation

Solve Matrix Equations
- $[K]\{q\} = \{F\}$
- $[K - \lambda M]\{q\} = 0$
- $[K + \lambda G]\{q\} = 0$

• MATLAB single Ritz element of order $N_p$ and $M_g \times M_g$ integration points
• NASTRAN finite element model QUAD4 mesh density = $M_g \times M_g$
Finite Element Solution

- Desired: Ability to create in VSP
- Nastran FEM created automatically and solved in parallel
- Provide calibration of Ritz solutions
- Higher fidelity + ability to increase level of detail
- Managing product structure (TMP/Vision-Viewsets)
- Managing results (TMP/Slim DB)
Current Challenges: VSP Geometry to Analysis

- Interpolating integration points on VSP wing surfaces
- Modeling and extracting rib and spar geometry
Current Challenges: VSPAero Loads Interface

- How to acquire pressure distributions
- Mapping/interpolating pressures from aero to structural mesh (Ritz or FEM)
- Some desired capabilities
  - Recovering results programmatically (pressure distribution, …)
  - Capability to configure and access massive numbers of runs
  - Ability to submit deformed geometry for analysis
Summary & Future Work

• A high order Ritz solution using Legendre polynomials developed to model quadrilateral VAT plates for static, vibration and buckling analyses
• Methodology is being extended to model tow-steered wing structures
• Ritz and FEM solutions have demonstrated good agreement
• Future plans
  – Demonstrate a sizing framework
  – Explore parallelized solution strategies
Thank You and Questions