Low-Order Aero-Structural Analysis Using OpenVSP and ASWing

Erik Olson, Ph.D.
NASA-Langley Research Center
Quinten Henricks, B.S.
Ohio State University

OpenVSP Workshop 2017
Outline

• Background & Motivation
• Methodology
• B737-200 Example
• Parametric Analysis
• Conclusions and Future Work
Background (1/2)

- Flight Optimization System (FLOPS) has shortcomings in weights estimation
  - Current state-of-the-art aircraft aspect ratios beyond FLOPS’ weights database
  - Weights equations based on conventional configurations and in-service technologies

- Updates to current empirical/semi-empirical regressions desired
  - Use physics-based analysis capabilities to capture new weight trends
  - New trends can be used to modify/replace current wing weight equations
  - Capability to analyze unconventional vehicles and advanced technologies

- Ongoing development under Higher-Order Design Environment (HOrDE) and Layered Extensible Aircraft Performance System (LEAPS) efforts
  - HOrDE seeks to develop multi-disciplinary and multi-fidelity design methodologies to enable higher-order analysis
  - Interaction with LEAPS team created a common baseline vehicle and associated load cases for consistent analyses
Background (2/2)

• Existing Low-Order Methods
  – Flight Optimization System (FLOPS) weight equations
  – Preliminary Design of Cylindrical Structures (PDCyl)
  – Equivalent Laminated Plate Solution (RELAPS)
  – AMMIT

• Finite-Element Based Methodologies Under Development
  – HCDStruct (Gern, Quinlan)
  – FEM-ready geometry (Li)
  – M4 Engineering PBWeight
  – Multi-fidelity structural analysis framework (Ga Tech, Laughlin)
  – Multi-fidelity aeroelastic modeling (UAlabama)
Motivation

• **Motivation**: Methodologies under development are relatively high-order and/or lack a full set of features (flutter, full-body flexible dynamics, gust response, time-domain calculations). There remains a niche for a full-featured, lower-order conceptual methodology.

• **Goal**: develop full-featured, low-order structural sizing methodology which is more applicable to more modern structures (e.g. high-AR wings) and unconventional concepts (e.g. truss-braced wing) than existing weight equations, by leveraging existing tools.
Outline

- Background & Motivation
- Methodology
- B737-200 Example
- Parametric Analysis
- Conclusions and Future Work
OpenVSP Degenerate Geometry

Surface

Plate

Point

Stick
Example for an analysis method based on the degenerate Stick model
ASWing Aero-Structural Analysis

Equivalent-beam structure + lifting-line aero

Degenerate Stick Properties of Interest

Properties calculated at each spanwise node:

- **Shell**
  - Center of mass: \( \mathbf{x}_{cg} \)
  - Moments of inertia: \( \bar{I}_{11}, \bar{I}_{22}, \bar{I}_{12} \) (for uniform unit wall thickness)
  - Perimeter: \( p \)

- **Solid**
  - Center of mass: \( \mathbf{x}_{cg} \)
  - Moments of inertia: \( I_{11}, I_{22}, I_{12} \)
  - Area: \( A \)
Preparing Degenerate Model for ASWing

- **Stick models**, specify spanwise variation of:
  - material moduli $E$, $G$
  - shell thickness (constant-thickness cross section)
  - shell density (structural material)
  - solid density (fuel or payload)

- **Point models**, specify:
  - density (point masses)
  - internal pressure (fuselage pressurization)
Assume (1) thin-walled structure, with (2) constant $E$, $G$, and $t$ at each cross section. For each cross section, define:

- **Stiffness Matrix**
  - $(EI)_{cc} = Et\bar{I}_{11}$
  - $(EI)_{nn} = Et\bar{I}_{22}$
  - $(EI)_{cn} = Et\bar{I}_{12}$
  - $GJ = Gt(\bar{I}_{11} + \bar{I}_{22})$
  - $EA = Etp$
  - $(EI)_{cs} = (EI)_{sn} = (GK)_{cc} = (GK)_{nn} = 0$

- **Mass Moments of Inertia**
  - Shell (structural material)
  - Solid (payload, fuel, etc.)

- **Center of Mass, Elastic Axis, Tension Axis**
  - $\mathbf{x}_{ea} = \mathbf{x}_{ta} = \mathbf{x}_{cg}$ (follows from thin-walled assumption)

- **Sectional aero (lifting surfaces)**
  - $c_{\ell_0}, c_{\ell_\alpha}, c_{\ell_{max}}, c_{d_0}, c_{m_0}$, control derivatives

---

Resultant Moments and Forces

Moments

Forces

\[ M_n \]
\[ M_s \]
\[ M_c \]

\[ F_n \]
\[ F_s \]
\[ F_c \]

Post-Processing for Stresses

- **Stick stresses** (constant over cross section)
  - Torsional shear:
    \[
    \tau_{Ms} = \frac{M_s}{2A_{solid}}
    \]
  - Extensional stress:
    \[
    \sigma_{Fs} = \frac{F_s}{pt}
    \]
  - Pressurization:
    \[
    \sigma_p = \frac{PR}{t}
    \]

- **Surface stresses**
  - Bending about c:
    \[
    \sigma_{Mc} = -\frac{M_{cI_{nn}}-M_{nI_{cn}}}{I_{ccI_{nn}}-I_{cn}^2} \Delta n
    \]
  - Bending about n:
    \[
    \sigma_{Mn} = \frac{M_{nI_{cc}}-M_{cI_{cn}}}{I_{ccI_{nn}}-I_{cn}^2} \Delta c
    \]
  - Transverse shear along c:
    \[
    \tau_{Fc} = -\frac{F_{cI_{cc}}}{I_{ccI_{nn}}-I_{cn}^2} t \int_0^p \Delta c \ ds + \tau_{c_0}
    \]
  - Transverse shear along n:
    \[
    \tau_{Fn} = -\frac{F_{nI_{nn}}}{I_{ccI_{nn}}-I_{cn}^2} t \int_0^p \Delta n \ ds + \tau_{n_0}
    \]
Principal and von Mises Stresses

• Combined Stresses
  – Total direct stress:  \( \sigma_{TOT} = \sigma_{Mc} + \sigma_{Fs} + \sigma_{Mn} \)
  – Total shear stress:  \( \tau_{TOT} = \tau_{Fc} + \tau_{Ms} + \tau_{Fn} \)
  – Principal stresses:  \( \sigma_{1,2} = \frac{1}{2} \left( \sigma_{TOT} \pm \sqrt{\sigma_{TOT}^2 + 4\tau_{TOT}^2} \right) \)
  – Von Mises stress:  \( \sigma_v = \sqrt{\sigma_1^2 - \sigma_1 \sigma_2 + \sigma_2^2} \)

• Max. Surface Stress
  – maximum principal and von Mises stresses over all load cases, including separate pressurization case

• Max. Stick Stress
  – maximum principal and von Mises stresses over each cross section over all load cases
Integrated Analysis/Sizing Process

Design Variables
- Flight conditions
- Target lift distribution (elliptical)

Design wing twist to match target lift distribution

Iterate wing box structural thickness for fully stressed wing

ModelCenter® model
Twist Optimization Process

- Formulate a matrix equation $Ax = b$, where
  - $A_{ij}$ is the change in the spanwise loading coefficient ($ccℓ$) at reference station $i$ due to a change in twist basis coefficient $j$, and
  - $b_i$ is the residual at reference station $i$. Therefore,
  - $x_j$ is the change in coefficient $j$ required to match the target lift distribution

- Calculate influence matrix, $A$, by individually perturbing the coefficients and calculating the resulting change at the set of reference stations.

- Solve for $x$ using a pseudo-inverse (least-squares).
Structural Thickness Optimization Process

• Choose an initial structural thickness distribution
• Calculate the corresponding maximum von Mises stress distribution
• At each spanwise reference station, update the structural thickness by the ratio of the allowable and maximum stresses:

\[ t_{new} = t_{old} \frac{\sigma_{\text{allowable}}}{\sigma_{\text{vmax}}} \]

• Impose minimum gauge
• Iterate to convergence
Outline

• Background & Motivation
• Methodology
• B737-200 Example
• Parametric Analysis
• Conclusions and Future Work
• Wing and tail torsion boxes created using duplicate wing components that are truncated at forward and rear spar.
• Weight items with easily definable locations represented by blanks with a specified mass (from FLOPS)
### Distributed Weight Components

Shell and volume densities calibrated to match FLOPS weight estimates

<table>
<thead>
<tr>
<th>Location in Model</th>
<th>FLOPS Weight Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing box shell</td>
<td>wing structure</td>
</tr>
<tr>
<td>Horiz. tail box shell</td>
<td>horiz. tail structure</td>
</tr>
<tr>
<td>Vert. tail box shell</td>
<td>vert. tail structure</td>
</tr>
<tr>
<td>Fuselage shell</td>
<td>fuselage structure</td>
</tr>
<tr>
<td>Wing box volume</td>
<td>mission fuel, tanks &amp; plumbing, hydraulics, anti-ice, unusable fuel</td>
</tr>
<tr>
<td>Fuselage volume</td>
<td>passengers, instruments, electrical, avionics, a/c, crew, baggage, pax service, cargo containers, cargo</td>
</tr>
<tr>
<td>Nacelle volume</td>
<td>engines, thrust reversers, engine oil</td>
</tr>
</tbody>
</table>
Sectional Aero (DATCOM)

$C_{\ell 0}, C_{\ell \alpha}, C_{\ell \text{max}}, C_{d0}$

Lift-curve Slope, deg⁻¹

Spanwise Distance, ft

Horizontal tail
Wing
## Load Cases

<table>
<thead>
<tr>
<th>Name</th>
<th>N</th>
<th>Sideslip (deg)</th>
<th>H. tail (deg)</th>
<th>Elevator (deg)</th>
<th>Rudder (deg)</th>
<th>Aileron (deg)</th>
<th>Thrust</th>
<th>Roll rate (deg/s)</th>
<th>Pitch rate (deg/s)</th>
<th>$U_z$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise</td>
<td>1.0</td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5-g Pull-up</td>
<td>2.5</td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0-g Pushover</td>
<td>-1.0</td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taxi bump</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Dynamic over-swing</td>
<td>1.0</td>
<td>5</td>
<td>trim</td>
<td></td>
<td>-27</td>
<td>trim</td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rudder reversal</td>
<td>1.0</td>
<td>5</td>
<td>trim</td>
<td></td>
<td>27</td>
<td>trim</td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial roll+</td>
<td>1.0</td>
<td>trim</td>
<td></td>
<td>trim</td>
<td>-20</td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial roll-</td>
<td>1.0</td>
<td>trim</td>
<td></td>
<td>trim</td>
<td>20</td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked roll+</td>
<td>1.0</td>
<td>trim</td>
<td></td>
<td>trim</td>
<td>20</td>
<td>trim</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked roll-</td>
<td>1.0</td>
<td>trim</td>
<td></td>
<td>trim</td>
<td>-20</td>
<td>trim</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial pitch+</td>
<td>1.0</td>
<td></td>
<td>-17</td>
<td></td>
<td></td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial pitch-</td>
<td>1.0</td>
<td></td>
<td>17</td>
<td></td>
<td></td>
<td>trim</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked pitch+</td>
<td>1.0</td>
<td></td>
<td>17</td>
<td></td>
<td></td>
<td>trim</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked pitch-</td>
<td>1.0</td>
<td></td>
<td>-17</td>
<td></td>
<td></td>
<td>trim</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
B737-200 Sized Wing-Box Thickness

Max. Stress

Max. von Mises Stress, psf

Structural Thickness, ft

Spanwise Fraction

Transformation Tools and Technologies Project --- Higher-Order Design Environment
B737-200 Stress and Deflection

Maximum von Mises Stress for All Load Cases

Wing Deflection (2.5-g Pull-up)

Maximum von Mises Stress: 6.1 ft
Outline

• Background & Motivation
• Methodology
• B737-200 Example
• Parametric Analysis
• Conclusions and Future Work
Parametric Study Setup

- Full-factorial parametric study to check robustness
  - Vertex points of design space
  - Used as a troubleshooting device
  - Variable sensitivity check

- Central-composite design study
  - Used to create wing weight equation
  - Nearly-linear response to design variables makes quadratic model suitable
Wing Weight Equation Fit Metrics

\[ R^2 = 0.9985 \]

- Predicted Weight (Kips)
- Actual Weight (Kips)
- Approximate Error (lbs)
Comparison of Wing Weight Trends

- Aspect Ratio vs. Predicted Wing Weight, lb
- Wing Area, ft² vs. Predicted Wing Weight, lb
- t/c Factor vs. Predicted Wing Weight, lb
- Fuel Weight, lb vs. Predicted Wing Weight, lb
Effect of Minimum Gauge

\[ t_{\text{min}} = 0.01 \text{ ft} \]

\[ t_{\text{min}} = 0.02 \text{ ft} \]
Outline

• Background & Motivation
• Methodology
• B737-200 Example
• Parametric Analysis
• Conclusions and Future Work
Conclusions

• Parametric analysis shows expected physical trends
• Wing weight more sensitive to aspect ratio than FLOPS
• Trend lines are sensitive to choice of minimum gauge
Future Work

• Adjust allowable stress to match expected deflections
• Examine calibration strategies
• Separate thicknesses for front/rear spars, upper/lower skins
• Additional load cases
  – Crash loads
  – Dynamic taxi bump
  – Dynamic gust loads
• Unconventional configurations (hybrid wing-body, truss-braced wing)
• Advanced materials
• Flutter analysis and sizing
Acknowledgements

This work was conducted as part of the NASA Transformational Tools and Technologies Project, led by Michael Rogers (acting), within the Multi-Disciplinary Design, Analysis and Optimization element, led by Patricia Glaab.

Thanks to Jason Welstead, Jess Quinlan (NASA) and Gregory Wrenn (AMA) for 737-200 models and data.