Aircraft Structural Mass Property Prediction Using Conceptual-Level Structural Analysis

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Summary

- ELAPS is a conceptual-level aircraft structural analysis tool uniquely situated between empirical methods and finite element analysis.
- The ELAPS-based mass property analysis process enables a low cost, high fidelity multidisciplinary approach to conceptual design.
- Stochastic analysis techniques provide a robust and efficient framework for managing uncertainty in conceptual design.
Overview

• Structural mass property prediction
• ELAPS
• ELAPS structural models
• Non-optimal mass
• Stochastic analysis and design
• ELAPS stochastic mass property analysis
• Case study: ERAST Proof-of-Concept
• Summary & Conclusions
Structural Mass Property Prediction

\[
\text{Weight}_{\text{fuselage}} = 1.35 \cdot \left[ X_L \cdot \left( \frac{W_{\text{fuselage}} + D_{\text{fuselage}}}{2} \right) \right]^{1.28} \cdot \\
\left( 1.0 + 0.05 \cdot N_{\text{engine}_{\text{fuselage}}} \right) \cdot \left( 1.0 + 0.38 \cdot W_{\text{cargo}_{\text{fuselage}}} \right) \cdot N_{\text{fuselage}}
\]

(from Mitchell, 1993)

- Empirical equations
- Empirically-augmented physical methods
- Finite Element Analysis (FEA)
- Algorithmic Mass Factoring Method (AM-FM, Boeing)
- Mock-ups & prototypes
ELAPS

- ELAPS = Equivalent LAminated Plate Solution
- FEA elements
- ELAPS segments

- Fast modeling
- Low computational cost
ELAPS Structural Models

- Plane of Symmetry
- Discrete Spar Segments
- Control Surface Segment
- Outboard Wing Segment
- "Smeared" Spar Segments
- Control Surface Segment
- Discrete Rib Segments
- Mass of Bombs and Missiles
Non-Optimal Mass

\[ NOMF = \frac{\text{as-built mass}}{\text{ideal mass}} \]

- Rod Element
- Shell Elements
- Spar Cap
- Pad-up and Splice
- Formed Angles and Adhesive
- Composite Laminates with HC Core

NASA Intercenter Systems Analysis Team
Stochastic Analysis and Design

- Management of uncertainty
- Robustness
- Risk Assessment
- Learning
ELAPS Stochastic Mass Property Analysis

NOMF Uncertainty

ELAPS Calibration Model

NOMF Calibration

NOMF Probability Density Functions

KEY
○ SKIN COVER PANEL / FUSELAGE BEAM
□ DISCRETE SPAR OR WEB
△ CONTROL SURFACE

Non-Optimal Mass Factor, NOMF
ELAPS Stochastic Mass Property Analysis
Monte Carlo Simulation

ELAPS Analysis Model

W as-built = \sum_{i=1}^{W_{\text{Ideal}_i \cdot NOMF_i}} + \sum_{i=1}^{W_{\text{Spar}_i \cdot NOMF_i}} + \sum_{i=1}^{W_{\text{Rib}_i \cdot NOMF_i}} + \ldots

Configuration Roll-up

Monte Carlo Simulation

Histogram

Median Value = 1.04 NW\_wing

Normalized Wing Weight, NW\_wing

Normalized Wing Weight, NW\_wing
Case Study: 
ERAST Proof-of-Concept

Design Proposals

Design Mission:
Subsonic
85k ft cruise altitude
50 fpm R/C at altitude
4 hr endurance at altitude
100 lb payload
Engine: 80 hp at altitude
Case Study: ERAST Proof-of-Concept

ELAPS Calibration Model

Boeing Condor UAV

Static Deflection Comparison

Flutter Mode Comparisons

Group Weight Statement

Component NOMF PDFs

\[ \text{NOMF}_i = f(x) \]
Case Study: ERAST Proof-of-Concept
Aeroelasticity Analysis

Boeing Condor
$C_{\text{wing}}=1.35$

$C_{\text{L}}$ vs Span Location

<table>
<thead>
<tr>
<th>Span Location, in</th>
<th>0</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Wing</td>
<td>▲</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deformed Wing</td>
<td>◇</td>
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</tbody>
</table>

Airfoil Analysis
Lifting Line Analysis
Wing Profile Drag Utility
$\Delta C_{D pw}$
$\Delta C_{D i}$
$C_i$ Distribution
Pressure Loads
$\Delta C_p$ vs $x/c$ vs $C_i$
Airfoil Analysis

ELAPS
Tip deflection, twist

NASA Intercenter Systems Analysis Team
Case Study: ERAST Proof-of-Concept

Mass Property Analysis

ELAPS Model

Structural Sizing

Ideal Mass

\[ \text{NOMF}_i = f(x) \]

As-built Mass

Monte Carlo

Histogram or PDF

0 20 40 60 80 100 120 140 160
0.5 1 1.5 2 2.5

Median Value = 1.12 NW_{wing}

Median Value = 1.04 NW_{wing}

Median Value = 1.01 NW_{wing}
Summary & Conclusions

• ELAPS is a structural analysis tool uniquely suited to multidisciplinary conceptual design
  – Enables high-fidelity structural behavior knowledge early in the design process (including aeroelasticity)
  – Speed of modeling and analysis significantly reduces design and analysis cycle time

• The ELAPS-based stochastic mass property analysis process facilitates weight risk assessment, especially in cases of advanced technology or unusual vehicle configuration