Low Order Aeromechanical Modeling
for Conceptual Design of Fuel-Efficient Aircraft

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Motivation – I

Historical trends indicate large future increases in air traffic.

Primary focus of jet transport R&D:

- 1950’s – 1970’s: Range
- 1980’s – 1990’s: Fuel burn (direct costs)
- 2000’s – 2010’s: Fuel burn (direct + indirect costs from emissions)

Reasonable prediction:

With increases in air traffic providing increasing impetus, fuel burn will remain the major R&D focus and design target, for both economic and environmental reasons.
Presentation Outline

• Fuel burn drivers

• Need for low-order models and optimization

• Recent low-order model example (TASOPT)

• General applications: parametric studies

• Specific application: D8 transport aircraft concept
Discipline Interactions Drive Fuel Burn

\[ W_{\text{fuel}} \approx W_{ZF} \times TSFC' \times \frac{D}{L} \times \frac{1}{M} \times \frac{R}{a} \]

(linearized Breguet)

• Fuel weight \( W_{\text{fuel}} \) for fixed range \( R \) is product of:

  \( W_{ZF} \)  Zero-fuel weight at landing (structures)
  \( TSFC' \)  Thrust-specific fuel consumption (propulsion)
  \( D/L \)  Drag/lift ratio (aerodynamics)
  \( 1/M \)  Inverse Mach number (operation)

• Can reduce any one parameter, but others will likely increase

• To reduce net fuel burn, must account for all important discipline interactions
Fuel-Economy Design Space

For any new technology, want to find the new global optimum in Airframe+Engine+Ops design space, possibly outside current practice.
Importance of Global Optimization

Free Design Variables
( sweep, CL, AR, altitude, FPR, BPR, Tt4, ... )

Global optimization adjusts all free design variables after a design parameter change

→ Essential to maximize benefit of a new technology
Requirements for Low-Order Modeling – I

• Global detail-design space is enormous — cannot optimize:
  CAD model parameters
  FEA input parameters for all critical load cases
  CFD input parameters for all operating points
  Engine-deck definition, parameters for all operating points

• Low-order design space is manageable (∼20 variables):
  \[ \Lambda \] wing sweep
  \[ t/c_i \] airfoil thickness at wing station \( i = 1 \ldots N \)
  \[ \lambda_i \] relative chord \( c_i/c_0 \) at wing station \( i = 1 \ldots N \)
  \[ r_{c_i} \] relative \( c_i/c_{l_0} \) at wing station \( i = 1 \ldots N \)
  \[ OPR_{D} \] design overall pressure ratio
  \[ FPR_{D} \] design fan pressure ratio
  \[ BPR_{D} \] design bypass ratio
  \[ T_{t4_{TO}} \] takeoff turbine inlet temperature
  \[ T_{t4_{CR}} \] cruise turbine inlet temperature
  \[ h_{CR} \] start-of-cruise altitude
  \[ C_{L_{CR}} \] cruise lift coefficient
Low-Order Design-Point Closure with Optimization

Objectives:
1. Design Inputs:
   - ~80 Design Parameters
     - Range, Nmax, Payload, Fstress, Mach, Tmetal, CMfuse, IBFmax, OPR, ...
   - ~20 Design Variables
     - (Sweep, CL, AR, Altitude, FPR, BPR, Tt4, ...)

2. Optimization:
   - ~500 optimization steps
   - ~25 iterations to machine zero

3. Design Closure:
   - Surface spans, areas
   - Loads, Shears, Moments
   - Structural gauges
   - Volumes and Weights
   - Drag, Engine size + weight
   - Trajectory, Fuel Weight
   - Total Weight converged?

4. Design Outputs:
   - Weights
   - Gauges
   - Engine size
   - Noise
   - T/O perf
   - Sweep, CL, AR, Altitude, ...

Objective is to calculate Design Outputs = f (Design Inputs) for optimized aircraft
Typical exhaustive low-order model design study:

- 25 design-closure iterations
- 20 design variables (objective-gradient components)
- 100 optimization-descent steps
- \( \times 200 \) independent-parameter combinations (technology, config., etc)

\[ \text{Total evaluations} = 10 \text{ million} \]
Requirements for Low-Order Modeling – III

Conclusions:

• High-order models are too slow for global optimization
• Computational speed is crucial even with low-order models, but . . .
• To give correct trends, low-order models must capture all relevant interactions between disciplines:
  – structural weight
  – aerodynamic performance
  – propulsion performance
  – trim and stability requirements
  – cruise altitude
  – takeoff distance
Requirements for Low-Order Modeling – IV

• A key requirement is reliable weight prediction
• Historical weight correlations are questionable:

\[
\frac{W_{\text{empty}}}{W} = 0.32 + 0.66W^{-0.13}\ AR^{0.3}\ \left(\frac{T}{W}\right)^{0.06}\ \left(\frac{W}{S}\right)^{-0.05}\ M_{\infty}^{0.05}
\]

Not trustworthy for unconventional concepts, new technologies, extreme parameter ranges.

→ Primary structure should be sized by first-principles structural models
Requirements for Low-Order Modeling – V

- A key requirement is reliable drag (or power dissipation) prediction
- Wetted-area drag models are often inadequate:

\[
C_{D_p} = \frac{A_{\text{wet}}}{S} C_f(Re_l) \left[ 1 + 1.5 \left( \frac{d}{l} \right)_{\text{eff}}^{3/2} + 7.0 \left( \frac{d}{l} \right)_{\text{eff}}^3 \right]
\]

Not suitable for unusual fuselage shapes (what is \((d/l)_{\text{eff}}\)?), inadequate for modeling boundary layer ingestion, etc.

→ Potential + viscous flow calculation methods are preferable
Requirements for Low-Order Modeling – VI

- A key requirement is reliable engine performance prediction
- Empirical engine performance models are questionable:

\[
\frac{TSFC_{\text{min}}}{TSFC} = 0.10\left(\frac{F}{F_{\text{max}}}\right) + 0.24\left(\frac{F}{F_{\text{max}}}\right)^{0.8} + 0.66\left(\frac{F}{F_{\text{max}}}\right)^{-0.8}
\]

\[
+ 0.1M_{\infty}\left(\frac{F_{\text{max}}}{F} - \frac{F}{F_{\text{max}}}\right)
\]

Not trustworthy for extreme OPR, BPR, \(T_{t4}\), new technologies, etc.

→ Component-based engine simulation is preferable
Example: Transport Aircraft System OPTimization

A collection of *physics-based*, coupled, low-order models for

- Primary structure
- Aero
- Engine
- Trim, stability
- Flight trajectory (Ops)

sequenced in a sizing loop, wrapped by an optimization loop.
TASOPT Summary – II

TASOPT does not use

- Historical correlations for primary structure weights
- Wetted-area × form-factor methods for drag prediction
- Fixed wing airfoils
- Assumed engine parameters and performance
- Assumed trim conditions

→ These cannot be trusted for “outside the box” designs
Primary Structure — Fuselage

- pressure vessel with added bending and torsion loads
- bending loads from distributed payload, tail

\[ N(W_{\text{pay}} + W_{\text{padd}} + W_{\text{shell}} + W_{\text{window}} + W_{\text{insul}} + W_{\text{floor}} + W_{\text{seat}}) \]

added bending stringers

\[ M(x) \]

\[ M_v(x) \]

\[ M_h(x) \]
Primary Structure — Fuselage

- single-bubble or double-bubble pressure vessel
- skin also takes torsion loads from vertical tail
- added longeron area for bending loads

→ Pressurization, Loads fully size all structural elements
Primary Structure — Wing or Tail Surface

- Multiple linear-taper planform, with or without strut
- Aero loading $p(\eta)$ with center and tip rolloffs
- Weight loading $w(\eta)$ from structure, fuel, engine

\[ \eta = \frac{2y}{b} \]

\[ \Delta L_o \]

\[ \Delta L_t \]

\[ NW_{\text{inn}} \]

\[ NW_{\text{out}} \]

\[ w(\eta) \]

\[ \eta = \frac{2y}{b} \]
Wing or Tail Surface Cross-Section

- Box beam: bending caps with shear webs
- Non-structural LE/TE fairings, slats, flaps, spoilers
- Box interior defines maximum fuel volume
- Spanwise-constant material stresses

→ Bending Moments, Shears, fully size wingbox elements
Load Cases

Each primary-structure element is sized at its critical load case:

Wing: Net load at $N_{\text{lift}}$

Tails: Max aero load at never-exceed speed $V_{\text{NE}}$

Tailcone: Max torsion from vertical tail load at $V_{\text{NE}}$

Body skin: Pressurization + Max vertical-tail torsion at $V_{\text{NE}}$

Longerons: Payload loading + Tail loads, at $N_{\text{land}}$, $V_{\text{NE}}$
Secondary Structure and Equipment Weights

Other weights obtained via densities or fractions:

\[ W_{\text{fix}} \] fixed pilots, cockpit, instrumentation weight
\[ W'_{\text{window}} \] window weight/length
\[ W''_{\text{insul}} \] insulation weight/area
\[ f_{\text{padd}} \] attendants, seats, galleys, IFE, etc. weight/payload
\[ f_{\text{gear}} \] landing gear weight/MTOW
\[ f_{\text{hpesys}} \] hydraulics, pneumatics, electrical weight/MTOW
\[ f_{\text{flap}} \] flaps, ailerons weight/wingbox-weight
Transonic Airfoil Family

- Airfoil family designed offline for good transonic drag rise
- Viscous/Inviscid CFD database for any $\frac{t}{c}, c_\ell, M_\perp, Re_c$
- Dispenses with wetted-area drag prediction methods
- Provides “rubber airfoil” for optimizer

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Parametric Airfoil Performance Model

Typical $C_p(x), M(x, y)$ at one $(\frac{t}{c}, c, M_\perp, Re_c)$ point
Parametric Airfoil Performance Model

Sweep theory with root corrections gives 3D wing profile drag

\[ C_{D_{\text{wing}}} = \mathcal{F}(C_L, M_\infty, \Lambda, \frac{t}{c}, Re_c) \]
Induced Drag Model

- Trefftz Plane analysis with wake contraction by fuselage
- Includes tail load from trim calculations

\[ D_i = -\frac{1}{2} \rho \sum_k \Gamma_k w_{nk} \Delta s_k \]
Fuselage Drag Model

- Viscous/Inviscid calculation for any area, perimeter $A(x), \, b_0(x)$
- Dispenses with wetted-area drag prediction methods
- BL state at engine inlet is known for proper BLI accounting

$$D_{\text{fuse}} = \rho V^2 \Theta_\infty$$
Engine Performance Model

- Complete 1D flowpath simulation, with turbine cooling and accounting for any Boundary Layer Ingestion (BLI), for...
  - sizing at cruise design point,
  - operation at off-design takeoff, climb, descent, static.
- Dispenses with engine-performance correlations
- Provides “rubber engine” for optimizer
Operation Models — Mission Profiles

- Each design “flown” over specified total range mission to
  - size fuel weight
  - evaluate takeoff performance
- Provides “rubber trajectory” for optimizer

\[
W_{\text{MTO}} - W_{\text{burn}}
\]

\[
W_{\text{reserve}}
\]

\[
W_{\text{dry}} = W_{\text{MTO}} - W_{\text{fuel}}
\]
### TASOPT Calibration/Verification

#### B737-800  Sizing, Airframe+Ops Optimization

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- √ Sizing procedure returns nearly the actual B737-800
- √ Optimization only slightly modifies the actual B737-800
Example Applications

• Influence of technology parameters
  – materials: specific stress
  – engines: $OPR, T_{metal}$

• Examination of novel configurations
  – D8 concept
Improved Materials

- Chosen material parameter is allowable-stress / density
- Modeled as “stress factor”, representing technology
- B737-class aircraft is examined
Improved Materials – B737 Maximum Weight

$\sigma/\rho \sim 1$

$\sigma/\rho \sim 1.25$

$\sigma/\rho \sim 1.5$

$W_{MTO}/W_{MTO_1}$

Allowable specific stress

span unconstrained

span < 118 ft
Improved Materials – B737 Lift/Drag Ratio

\[
\sigma/\rho \sim 1 \\
\sigma/\rho \sim 1.25 \\
\sigma/\rho \sim 1.5
\]

\[L/D\]

Allowable specific stress
Improved Materials – B737 Fuel Burn

- Up to 13% fuel savings with 50% stronger material
- Span constraint has little effect on fuel burn
Engine Technology

1. Overall pressure ratio ($OPR$)
   - Determines ideal Brayton-cycle thermal efficiency
   - Limited by compressor stability, materials

2. Turbine metal temperature ($T_{metal}$)
   - Limits max turbine inlet temperature ($T_{t4}$)
   - Biases $T_{t4}$ / cooling tradeoff

Complex interactions with aircraft characteristics require global optimization for maximum exploitation of improved $OPR$, $T_{metal}$
Engine Technology – Fuel Burn vs. OPR, Tmetal

\[ W_{\text{fuel}} / W_{\text{fuel,1200,30}} \]

- OPR = 30
- OPR = 35
- OPR = 40
- OPR = 45
- OPR = 50
- OPR = 55

→ OPR and \( T_{\text{metal}} \) improvements are highly synergistic
D8.x Aircraft for NASA’s N+3 Program

NASA Goal: Identify concepts and technologies needed for 70% (!) reduction in Fuel / PAX-mile by 2035
D8 Fuselage Concept

737–800

D8.x

D8.x

737–800
D8.x Configuration (vs B737)

Lifting nose, rear flat fuselage

- increased fuselage carryover lift → smaller wing
- built-in nose-up moment from nose lift → smaller tail
D8.x Configuration (vs B737)

Wide double-bubble fuselage

- partial span loading via 216” wide fuselage (vs 154”)
- reduced floor-beam weight via center floor support
- shorter landing gear and load path
D8.x Engine/Tail Configuration

- Rear fuselage and tails double as flow-aligning nacelles
  - only minimal nacelles needed
  - shield fan faces from ground observers

- Provides Boundary Layer Ingestion (BLI)
  - local potential flow $M \approx 0.6$ matches fan requirement
  - no additional BL diffusion – no streamwise vorticity into fan

- Fin strakes synergystically exploited:
  - function as pylons carrying engine loads and tail surface loads
  - shield fan faces from ground observers
Low-Order Modeling Objective

For the new given shape and aerodynamic/weight/balance properties of the D8 fuselage . . .

- Find best possible wing+tail+engine+ops combination
- Evaluate fuel-burn benefits relative to current B737-800
- Determine sensitivity to future forecast material, aerodynamic, engine technologies
D8.x Designs for B737-800 Replacement

**D8.1 (Aluminum)**
- 0.72 Mach
- 22.0 L/D
- 130k MTOW
- 5000 ft field

**D8.5 (Composite)**
- 0.74 Mach
- 24.9 L/D
- 100k MTOW
- 5000 ft field

**B737–800**
- 0.80 Mach
- 15.2 L/D
- 166k MTOW
- 8000 ft field

-70% Fuel Burn

-45% Fuel Burn

-49% Fuel Burn
Breguet Parameter Comparison

\[ W_{\text{fuel}} = W_{ZF} \left[ \exp\left( \frac{TSFC}{M} \frac{D}{L} \frac{R}{a} \right) - 1 \right] \approx W_{ZF} \left( \frac{TSFC}{M} \frac{D}{L} \frac{R}{a} \right) \]

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D8 Concept Experimental Confirmation

D8.1 Low-Speed Wind Tunnel Model (20:1 scale, 2.3 m span)
$L/D = 16.1$ for tripped case

$L/D = 22.8$ with $C_{D_p}$ correction to full-scale $Re$

$L/D = 21.0$ predicted by TASOPT for transonic D8.1
Summary

• Importance of low-order modeling
• Low-order model example (TASOPT)
• Global optimization for evaluation of new technologies
• Global optimization for maximum exploitation of new technologies
• Example applications
  – Materials and engine technology evaluation
  – D8 concept optimization