Aerospace design: a complex task

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Overview

- hierarchical product definition
- hierarchical design
- different design philosophies and methods
- sensitivity analysis

WARNING: I am not a designer, so do I really know what design is about? My aim is to provoke thought and discussion.
Sources of Complexity

- lots of components
- lots of design parameters
- lots of design constraints and requirements
- multidisciplinary

In aerospace this is aggravated by the huge computational cost of detailed analysis.
Hierarchical EPD

Handling geometric complexity requires hierarchical electronic product definition (EPD)

- at lowest level, very simple functional description of major components appropriate to preliminary design
- at higher levels, increasing amount of detail as needed, for example, by CFD and structural analysis packages
Hierarchical EPD

Example: aircraft

<table>
<thead>
<tr>
<th>Level 1</th>
<th>aircraft weight, wingspan, cruising speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 2</td>
<td>wing/fuselage geometry</td>
</tr>
<tr>
<td>Level 3</td>
<td>engines, tail, winglets</td>
</tr>
<tr>
<td>Level 4</td>
<td>high-lift flaps &amp; slats, take-off climb rate</td>
</tr>
<tr>
<td>Level 5</td>
<td>control surfaces, fairings, desired roll rate</td>
</tr>
</tbody>
</table>

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Hierarchical EPD

Example: turbine vane

<table>
<thead>
<tr>
<th>Level 1</th>
<th>number of blades, hub/tip radius, throat area, mass flow, inflow/outflow angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 2</td>
<td>camber/thickness distribution, cooling mass flow</td>
</tr>
<tr>
<td>Level 3</td>
<td>fillets at hub and tip junctions</td>
</tr>
<tr>
<td>Level 4</td>
<td>film cooling holes and slots, temperature of coolant supply</td>
</tr>
<tr>
<td>Level 5</td>
<td>alloy type and thermal properties</td>
</tr>
</tbody>
</table>

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Hierarchical EPD

- parameters at each level of EPD hierarchy form collective design parameters
- altering any parameter, at any level, defines a parametric change which is inherited at higher levels of the EPD system
- grid generator must be able to respond to this to define perturbed grids
- parametric solids-based core to CAD system may be essential to provide this capability

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Handling the very large number of design parameters in an aerospace system also requires a hierarchical approach

- to limit the number of ‘active’ design parameters
- to minimise the computational cost

Each level of design works with the appropriate level of EPD definition.
Hierarchical Design

Preliminary design

- uses very simple modelling of the overall system, with a lot of empiricism from past designs
- considers important trade-offs between different components
- often involves integer design parameters
- often aims to minimise airlines’ operating costs, or maximise manufacturers’ profit
Hierarchical Design

Component design
- uses very detailed mathematical modelling with few approximations
- has to satisfy functional requirements and lots of constraints imposed by preliminary design
- often aims to minimise drag/loss, but maybe not directly
Hierarchical Design

Current system: preliminary design followed by component design

- Preliminary design
  - overall design decisions
  - updated empiricism for future

Component design

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Hierarchical Design

Future: tightly-coupled two-level design

System design

overall system changes

updated component data

Component design

Requires a well-integrated design system, much of which is computer driven.

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Design philosophies

Design parameters: \( \alpha \)

CFD/structural variables: \( U \)

Discrete equations: \( F(U, \alpha) = 0 \)

Equality constraints: \( E(U, \alpha) = 0 \)

Inequality constraints: \( C(U, \alpha) \geq 0 \)
Design philosophies

1) Define an objective function $I(U, \alpha)$ and leave it to a black-box optimiser
   - may be appropriate for preliminary design
   - designer responsible for defining design space, constraints and objective function, and monitoring design evolution
Design philosophies

2) Define more than one objective function and view trade-off curve before choosing optimum
   - puts the designer more in the loop
   - may be appropriate for multidisciplinary applications

Aerospace design: a complex task
3) Design system computes sensitivities with respect to design parameters but designer specifies design changes
   • puts the designer totally in charge
   • allows the designer to keep in mind other constraints not easily quantified
   • design system could aid designer by ensuring some constraints are automatically satisfied
Design methods

Global optimisation in preliminary design: genetic algorithms and other stochastic optimisation methods

- good at finding global optimum not just a local optimum
- well suited to optimisation involving integer parameters
- computational cost acceptable because of low cost of empirical modelling
**Design methods**

Local optimisation in system and component design: gradient-based methods using (approximate) sensitivities

- lots of methods for unconstrained and constrained optimisation
- objective functions will not be smooth (discontinuities and little ‘ripples’) which could cause problems
- computationally less costly than stochastic optimisation (I think)
Design methods

- discontinuities due to changing grid topology
- ripples due to changing shock position relative to grid

Objective function

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One approach to coping with these difficulties is to construct a least-squares approximation by a smooth function, sometimes called a ‘response surface’

Optimising this smooth approximation subject to smoothed constraints would be a relatively easy task.
Sensitivity Calculations

Nonlinear:
- perturb each component of $\alpha$ in turn, compute new solutions and use to get approximate gradient
- easy to implement, trivial to parallelise
- expensive for large numbers of design parameters
Sensitivity Calculations

Linear:
- solve linearised discrete equations, like nonlinear treatment with very small perturbations
- no cost benefits compared to nonlinear treatment in most cases
- additional effort of writing linear code
Sensitivity Calculations

One advantage of direct linear/nonlinear sensitivity approach is Quasi-Newton optimisation for least-squares applications.

Suppose we wish to minimise

\[ I(\alpha) = \sum_n (p(x_n, \alpha) - p_{des}(x_n))^2 \Delta s \]

At a minimum, we require

\[ \frac{\partial I}{\partial \alpha_i} = 2 \sum_n \frac{\partial p}{\partial \alpha_i} (p(x_n, \alpha) - p_{des}(x_n)) \Delta s = 0 \]
Sensitivity Calculations

Solving this set of simultaneous equations using Newton-Raphson gives

\[ A(\alpha^{n+1} - \alpha^n) = -r^n \]

where

\[ r_n^i = \sum_n \frac{\partial p}{\partial \alpha_i} (p(x_n, \alpha) - p_{des}(x_n)) \Delta s \]

and

\[ A_{ij} = \sum_n \left( \frac{\partial p}{\partial \alpha_i} \frac{\partial p}{\partial \alpha_j} + \frac{\partial^2 p}{\partial \alpha_i \partial \alpha_j} (p - p_{des}) \right) \Delta s \]
Neglecting the second-derivative term gives the Quasi-Newton method which converges quickly to the minimum if $p - p_{des}$ is small.

This can also be viewed as minimising the quadratic approximation

$$ I \approx \sum_n \left( p(x_n, \alpha^n) + \frac{\partial p}{\partial \alpha} \Delta \alpha - p_{des}(x_n) \right)^2 \Delta s $$
Sensitivity Calculations

Adjoint method:
- based on linear approach
- reduces number of calculations to one for each objective function and constraint function
- cost of each optimisation step is independent of number of design parameters, so can have lots; however number of steps may increase with number of parameters
Sensitivity Calculations

Sensitivity information can show significance of constraints imposed in preliminary design – feedback is crucial for better preliminary design trade-offs

Also useful in other areas:
- manufacturing tolerances
- risk management
- strategic research planning

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What Would I Recommend?

A hierarchical solution:

- genetic algorithms for black-box optimisation of preliminary design
- for component design, start with few design variables, direct sensitivity analysis and optimisation by the designer (using response surface if necessary)
- for final refinement, add additional design variables and switch to adjoint-based optimisation