Robust design and optimization

Key methods and applications

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Rolls-Royce
Content

- Rolls-Royce
- Process and key tools
- Case study
- Summary
- Outlook
Rolls-Royce

Reliability, integrity, innovation

A. Karl, Rolls-Royce, January 2011
Rolls-Royce proprietary information
Key statistics

Underlying Group revenue £10.1 billion

- Civil aerospace: 44%
- Defence aerospace: 20%
- Marine: 26%
- Energy: 10%

<table>
<thead>
<tr>
<th>Services</th>
<th>49%</th>
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<tbody>
<tr>
<td>Original equipment</td>
<td>51%</td>
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- Underlying profit: £915m
- Order book: £58.3bn
- Employees: 38,500
- Operating from 50 countries
Our current installed base

Group-wide 54,000 gas turbines in service globally

**Civil aerospace**
- *World No.2*
  - 650 airlines, freight operators and lease companies
  - 4,000 corporate and utility operators

**Defence aerospace**
- *World No.2*
  - 160 defence customers
  - US Department of Defense is largest defence customer

**Marine**
- *World No.1*
  - 2,000 commercial customers
  - 70 navies served

**Energy**
- *A substantial position in oil and gas pumping and compression*
  - Customers in over 120 countries
  - Over 45,000MW of delivered electric power
What is robust design?
Robust design methodology

**Define**
- Understand what is important to the customer and translate into engineering language
- Choose design concepts with variation in mind

**Characterize**
- Generate measurable Critical-to-Quality (CTQ's) criteria for each level
- For each CTQ:
  - Understand the sources of variation
  - Measure the effects of variation

**Optimize**
- For each CTQ:
  - Choose and implement a strategy to reduce the effects of variation

**Verify**
- Use knowledge of variation and its effects in construction and design verification plan
Robust design and the design process

DCOV methodology used as design framework
Basic principles of parameter and tolerance design as part of robust design

Provided the inputs (x’s) are statistically independent, the Taylor series expansion gives the

Variation transmission equation

\[
\sigma_y^2 \approx \sigma_{x_1}^2 \left( \left. \frac{\partial Y}{\partial X_1} \right|_{x_1 = \mu_{x_1}} \right)^2 + \sigma_{x_2}^2 \left( \left. \frac{\partial Y}{\partial X_2} \right|_{x_2 = \mu_{x_2}} \right)^2 + \ldots = \sum_{j=1}^{k} \sigma_{x_j}^2 \left( \left. \frac{\partial y}{\partial x_j} \right|_{x_j = \mu_{x_j}} \right)^2
\]

Tolerance design \quad Parameter design
Case study: RR500 front support anti-ice system

- **Purpose**
  - To increase the metal temperature of the RR500 front support to prevent the build up of ice in extreme climates

- **Challenges**
  - Determining the best anti-ice configuration for both cost and performance

- **Goal**
  - Use robust design tools and methodology to minimize anti-ice air flow rate and manufacturing cost while satisfying product requirements
Analysis workflow

Automated process includes:

- 1-D flow solver
- 3-D thermal finite element analysis
- Manufacturing cost model

Response surface models to describe the relationship between customer requirements and key input variables
Assessing the design space

Main customer requirements:
metal temperature at key locations and required air flow rate

Axis values are key input parameters identified in the first steps of the robust design process (normalized with an arbitrary reference value)
Initial design selection

- Optimization methodology applied to surrogate responses to generate optimal design configuration
  - Bullet nose holes: 94% dia. min
  - Radial aft passage: 96% dia. min
  - Axial TE holes: 102% dia. min
  - Number of axial TE holes: 7

Sample visualization of optimization process:

Step 1: Determine number of axial TE holes (least number of TE holes and lowest L/D minimizes manufacturing cost)

Step 2: select axial TE hole diameter to satisfy temperature requirement

Step 3: use other response surface models to determine the other parameters

Strut Trailing Edge Metal Temperature
Minimum value needs to be achieved
Assessing the design robustness and selecting a nominal design

- Step 1: Collect manufacturing data and map onto the response model outputs (grey rectangle)
- Step 2: Ensure that the whole range is in the feasible area
- Step 3: Select the nominal design to sit in the middle of the manufacturing variation range (black dot)
Summary

- Optimization and automated design help achieving better design by focusing the work on the key levers.
- Simulation driven design allows a thorough design assessment early in a development program.
- Robust design allows the consideration of variation in the design process and the appropriate selection of the nominal design point.
Outlook

- Process integration, automation and robust design will be growing rapidly in the next few years
- Further developments and improvements in the available integration and optimization tools and methods will support this trend
  - The software and methods must be usable by the end user and not just by specialized methods and tool development areas.
  - The software and methods must offer a simple integration of key tools (CAD, FEA, cost, post processing, meshing, statistics, etc) used in industry
  - The software and methods must integrate with the emerging simulation data management tools to extend the principles currently used in the geometry world (data storage, versioning, workflows, etc.) into the analysis and simulation world