Design For Variation

Accelerating Industrial Productivity via Deterministic Computer Experiments and Stochastic Simulation Experiments

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Pratt & Whitney Engineering
A Passion for Innovation

PurePower® PW1000G Engine
Deterministic Design, Uncertain World

Traditional Approach: Empirical Design Margins, Factors of Safety

▲ Manufacturing

▲ Usage

▲ Materials
Design For Variation

A Strategic Initiative at Pratt & Whitney

▲ To Reduce Escapes (Safety)
   – Variation plays a significant role in field problems
   – Cost of finding/correcting problems increases rapidly as product matures

▲ To Improve Producibility (Cost/Competitiveness)
   – Find and focus on important features (few?)
   – Relax requirements on unimportant features (many?)
   – Use Robust Design to reduce sensitivity

▲ To Maximize Rotor Life (Time on Wing)
   – Rotor life depends on max distress / min life airfoil
   – ‘Weakest link’ structure pervasive in gas turbines
   – Reducing variation increases rotor life
Design For Variation (DFV) Strategic Plan

Vision: All Key Modeling Processes will be DFV-enabled

▲ Strategy
- Identify Key Processes
- Define elements of a DFV-enabled modeling process
- Provide Resources under Strategic Initiative

Mechanical Systems and Externals
- Carbon Seal Performance
- Ball & Roller Bearing Design
- FDGS Durability
- Externals: Forced Response Analysis

Combustor and Augmentor
- Combustor pattern factor
- Combustor Liner TMF
- Augmentor Ignition Margin Audit
- Mid Turbine Frame Robust Design

Air Systems
- Thermal Management Model
- Internal Air System Model
- Engine Data Matching

Validation Testing
- Engine Validation Planning

Vehicle Systems
- Probabilistic
- Ambient Temp Distribution

Performance Analysis
- Performance Monte Carlo Risk Assessment
- Engine Test Confidence, Uncertainty
- Uncertainty in Engine System Predictions
- Production Test Data Trending and Analysis

DFV Infrastructure
- (Statistics & Partners)
- Sens / Uncert / Opt Software
- High Perf Computing
- Training
- ESW
- Communications
- Input Data
- Tech Support

Fan & Compressor
- HFB Productivity
- Parametric Airfoil
- Compressor Aero Design

Structures
- Probabilistic HCF
- Parametric Geometry Simulation Model
- Engine Dynamics and Loads

Turbine
- Turbine Blade Durability
- Turbine Vanes and BOAS Durability
- Rotor Thermal Model
- Airfoil LCF Lifing

Black: Legacy Task
Green: 2010 funded
Blue: 2011 funded (new)
Elements of a DFV-Enabled Modeling Process

**Physics-Based Models**

- **Model Preparation**
  1. A robust parametric physics-based model

- **Model Input Variability and Uncertainty Quantification**
  2. Process for retrieving data needed to quantify variability and uncertainty in model inputs
  3. Process for performing statistical analysis/developing statistical model of input data

- **Model Sensitivity Analysis**
  4. Process for generating a matrix of space-filling computer experiments (model runs) for sensitivity analysis
  5. Process for driving matrix of runs through parametric model for sensitivity analysis
  6. Process for
     a. Developing and validating the model emulator
     b. Performing sensitivity analysis

- **Model Calibration**
  7. Process for determining the required model calibration data (amount, design, characteristics to be measured, etc.)
  8. Process for performing Bayesian Model Calibration

- **Uncertainty Analysis**
  9. Process for generating a Monte-Carlo sample accounting for all significant sources of uncertainty and driving it through
     • Parametric model
     • Model emulator
     • Bias corrected and calibrated model

- **Enable Practice**
  10. Local DFV Engineering Standard Work (ESW) and Training, and DFV incorporated as a proficiency in local ESW Proficiency Matrix
Design For Variation

Five Components

- **DEFINE** Customer requirements (probabilistic)

- **ANALYZE** DFV-enable modeling process, model emulation, model sensitivity analysis, calibration, and uncertainty analysis

- **SOLVE** Identify ‘optimum’ design that satisfies requirements

- **VERIFY/VALIDATE** Variability/Uncertainty model

- **SUSTAIN** Stable system of causes of performance variation
Design For Variation

ANALYZE Identify root causes of performance variation and uncertainty and their effects
Design For Variation

Infrastructure: Enabling Design For Variation

▲ Develop/Maintain Software
  - Emulation, Sensitivity Analysis, Model Calibration
  - Statistical Analysis, Monte Carlo Simulation, Optimization

▲ Provide High Performance Computing Resources

▲ Develop/Deliver Training
  - Introduction
  - Practitioners I: Sensitivity Analysis, Emulation, And Experimental Design
  - Practitioners II: ISIGHT-FD For Sensitivity And Uncertainty Analysis
  - Practitioners III: Bayesian Model Calibration And Uncertainty Analysis

▲ Project Management Assistance

▲ Write Engineering Standard Work

▲ Communication
  - Wiki, Meetings

▲ Input Data Quality and Availability
  - Process Capability, Material Properties
  - Systems Performance, Mission Analysis

MATLAB

Infrastructure:

Enabling Design For Variation
Bayesian Model Calibration

Applied to Beam Deflection Problem (Small Problem, High Pedagogic Value)

Bayesian Model Calibration will be used to calibrate a code\(^1\) that predicts large deflections of a steel beam with rectangular cross-section (cantilever) under a uniformly distributed load \(w\) and a vertical concentrated load \(F\) applied at the free end

- \(x\) (variable input) = Concentrated load, \(F\)
- \(\theta\) (calibration input) = Material elastic modulus, \(E\)
- \(y(x), \eta(x,\theta)\) = beam deflection (measured, predicted)

Bayesian Model Calibration

How is Prior Chosen?
Understand Nuances (High Posterior $\theta / \delta$ Correlation)

What if Discrepancy Function is Significant?
Applications

▲ Engineering
- Reliability improvement, Problem avoidance
- Robust Design
- Cost reduction
- Subsystem design

▲ Manufacturing
- Process Control
- Proactive manufacturing
- What (not) to measure

▲ Service
- On-board health monitoring and life prediction
- Self-calibrating models
Described below is a Bayesian High-Cycle Fatigue (HCF) risk assessment system for turbine engine blades. Hierarchical models are employed to capture engineering knowledge of the factors important for assessing HCF risk. The model accounts for engine-to-engine, run-to-run, and blade-to-blade variability as well as uncertainty in material capability, usage (flight conditions, time at resonance), and steady and vibratory stresses. Other models (thermal, FOD, etc) are added as required.
Design For Variation / Design For Six Sigma

Challenges

▲ Computational issues in Bayesian model calibration
  – Establishment of ‘Gold Standard’ numerical methods
  – Lack of commercial software availability

▲ High dimensional data visualization

▲ Probability models for variation in internal/external structures with complex geometry
  – Data: 40k+ measurements per part
  – Also need to be predictive (model the manufacturing process that forms the part)

▲ ‘Optimal’ design of physical experiments for model calibration

▲ Large transient model calibration

▲ What if only sub-models can be calibrated?

▲ Discrepancy root cause investigation structure
  – Sometimes instrumentation technology can rival model technology

▲ Robust design optimization

▲ Computational challenges in making the probabilistic system larger (e.g. include geometry) and larger (grow to sub-systems) and larger (system engineering)

▲ Lack of textbooks, engineering methods and applications papers

▲ Non-technical issues: Cost, resistance to change
Design For Variation

▲ Goal: quantify, understand, and control the risk of not meeting design criteria or exceeding thresholds

▲ “The revolutionary idea that defines the boundary between modern times and the past is the mastery of risk: the notion that the future is more than a whim of the gods and that men and women are not passive before nature.”
   − Peter Bernstein, “Against the Gods: The remarkable story of risk”