Uncertainty Management & Quantification for Aircraft Industry

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[[Mécanique déterministe ou incertitudes : Où en est-on avec \( F = M y \) ? - Ça passe ou ça casse ?]]

Penser & innover ensemble
Outline

• Definition and Measurements of Uncertainties
• Uncertainty Quantification
• Design under uncertainties
• Conclusion
Aircraft Maker Point of View

• Uncertainty is an upper bound between:
  – The estimate of aircraft characteristics at a certain stage of its development
  – Characteristics of the aircraft once in service

• This Uncertainty can be the consequence of:
  – The quality of the means used during the development phase to estimate these characteristics
  – An inaccurate knowledge of the final definition of the aircraft

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Uncertainties evolution

- Definition Uncertainty
- Measurement Uncertainty

Performance

- Objective Performance
- Engagement Performance

Time

- Serial Production

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Measurements uncertainties

• For a given Definition, the ways to measure aerodynamic characteristics are the following:
  – Modelization, CFD (digital twin)
  – Wind Tunnel Testing
  – Flight Tests

• These ways are very different in terms of:
  – Design Cycles and Cost
  – Analysis Capacities
  – Validity Range

• Each way is associated to a degree of precision for the estimated aerodynamic characteristics, named here "Measurement Uncertainties"
CFD Uncertainties

• **Geometry:**
  - Details: discontinuities, protuberances (antennas …) …
  - Permeability: engines, bleed …
  - Aeroelastic deformation, icing, …
  - Change of geometry during the lifetime of the aircraft (damage …)
  - Tolerance resulting from the manufacturing process …

• **Atmospheric conditions - Operating conditions:**
  - Temperature, density, pressure, wind …
  - Weight of the aircraft, center of gravity …

• **Modelization**
  - Potential, Euler, Navier-Stokes, boundary layer, turbulence modeling, transition …
  - Steady / Unsteady
  - Mesh quality
  - Body or far field integration for the drag
  - Programming errors, round off (double precision …), convergence level of the iterative process (criteria …) …
Wind Tunnel Testing Uncertainties

- Wind Tunnel effect
  - Wall (porosity ...), fixing support of the mockup
  - Total pressure and temperature conditions
  - Homogeneity of the flow in the tunnel

- Mockup effect
  - Mockup scale / Reynolds number
  - Mockup representativeness
    - Details: discontinuities, roughness, protuberances ...
    - Tolerance resulting from the manufacturing process
    - Boundary layer transition
    - Control surfaces positioning, mass flow ratio
    - Aeroelastic deformations

- Instrumentation and measurement post processing
  - Global or partial weighting
  - Wake measurements ...
Flight test Uncertainties

- Validity (sampling …) of the exchange rate Thrust - Fuel Consumption
- Weight of the aircraft, center of gravity, control surface positioning
- Atmospheric conditions, wind
- Aeroelastic deformation
- Measurement precision (altimeter, airspeed indicator, …)
- Differences between aircraft in service and serial definition
- Tolerance resulting from the manufacturing process …
Dream … and Real Life

Aeroelasticity

Icing

Accretion

Atmospheric conditions
Dream ... and Real Life

Steps and gaps
Outline

• Definition and Measurements of Uncertainties
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UQ and RDO Workshops
2015-2016
Falcon Jet
Industrial Challenge 3 (IC-03)

Gilbert Rogé, Ximun Loyatho, Dassault Aviation
• Falcon Jet, IC-03 Test Case (Industrial Challenge)

• Innovative database for UQ: Industrial relevant external flow test case. Database incorporating modelization (turbulence), numerical error (mesh), operational (aoa) and geometrical (wing spanwise twist distribution) uncertainties.

• 5 Partners:
  • Alenia Aermacchi (Italy)
  • INRIA (France)
  • NUMECA (Belgium)
  • TU Delft (Netherlands)
  • Dassault Aviation (France)
- Test case: Generic Falcon Jet
  - Mach number = 0.80
  - Angle of attack = 2°
  - Altitude = 40000 ft
  - RANS; Turbulence modeling: Spalart Allmaras
  - FEM; unstructured tetrahedral mesh (7.17M nodes)
• Uncertainties. Geometric parameters.
  – Wing spanwise twist angle distribution ($x/c=0.25$; rotation / control section plane)
  – 8 control sections: $0.999y + 0.008z = 1240.614; 2205.710; 3131.413; 3848.613; 5293.181; 6628.500; 8074.377; 9244.835$ mm.
  – Bounded, asymmetric beta PDF distributions (Holland approach)
  – Delta twist angle min = -0.5 deg
  – Delta twist angle max = 0.2 deg
  – Most likely value for Delta twist angle = 0.01 deg
• Propagation study (for geometrical and operational uncertainties).
  – Method of Moment
  – Monte Carlo family
  – Polynomial Chaos family
  – ...

  – 4 first statistical moments (mean value, standard deviation, skewness, kurtosis)
  – PDF
  – CDF
  – Cl, Cm, CD
  – Wing spanwise Cl distribution
  – Cp

Method of Moment: first order

\[
\begin{align*}
X_{\text{INPUT}} & \sim \text{beta law} & \Rightarrow & & X_{\text{OUTPUT}} & \sim \text{beta law} \\
\text{mean value:} & & \mu_{\text{OUTPUT}} & = F(\mu_{\text{INPUT}}) \\
\text{standard deviation:} & & \sigma_{\text{OUTPUT}} & = |\nabla F| \times \sigma_{\text{INPUT}}
\end{align*}
\]
• **Quantified uncertainties** : aerodynamic & geometric parameters

### Mach
- Most likely value: 0.8
- Min: 0.795
- Max: 0.807

### Angle of attack
- Most likely value: 2
- Min: 1.97
- Max: 2.1

### Delta twist angle
- Most likely value: 0.01
- Min: -0.5
- Max: 0.2

**Beta law**

Mean value = 0.8003
Standard deviation = 0.002087
Skewness = 0.1509
Shape parameter P = 3.143
Shape parameter Q = 4.000

Mean value = 2.012
Standard deviation = 0.02312
Skewness = 0.5066
Shape parameter P = 1.900
Shape parameter Q = 4.000

Mean value = -0.04231
Standard deviation = 0.1248
Skewness = -0.4251
Shape parameter P = 4.000
Shape parameter Q = 2.118
- **Twist angle** uncertainty propagation: *Cl pressure distribution*

  **Case**: Spalart Allmaras turbulence modeling, MESH 1

  \[ Cl_{\text{wing}} = 0.349 / 2 \]
Method of Moment: 

allows to deal with lots of uncertain variables

N uncertain variables \( \rightarrow \) N linear systems

- Several uncertain variables …

Method of Moment: \textit{first order} with N independent inputs

\[ X_{\text{OUTPUT}} = F(X_{1\text{INPUT}}, \ldots, X_{N\text{INPUT}}) \]

\[ X_{\text{OUTPUT}} \sim \text{beta law} \]

\[ \rightarrow \]

\[ X_{\text{OUTPUT}} \sim \text{beta law} \]

mean value:

\[ \mu_{\text{OUTPUT}} = F(\mu_{1\text{INPUT}}, \ldots, \mu_{N\text{INPUT}}) \]

standard deviation:

\[ \sigma_{\text{OUTPUT}} = \sqrt{\sum_{i}^{N} (\nabla_{x_i} F)^2 \times (\sigma_{i\text{INPUT}})^2} \]
8 twist angle uncertainties propagation

Case: Spalart Allmaras turbulence modeling, MESH 1

Section 5

(gradient by direct method)
Outline

• Definition and Measurements of Uncertainties
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RDM

- Robust Design: find a design insensitive to small changes of uncertainties
- Reliability-Based Design: seek a design with a probability of failure less than an acceptable value
Two kinds of geometrical variables:

- Optimization variables for design conception:
  e.g. wing trailing edge camber angle
  \[
  \text{camber} = -15^\circ
  \]

- Uncertainties variables:
  e.g. wing tip twist angle
  \[
  \text{twist} = +5^\circ
  \]

Adjoint method \(\rightarrow\) complexity independent of number of variables
Deterministic optimization

Deterministic optimisation: 
\[
\min CD
\]
Variables: AoA, \textit{Camber}
Constraint: 
\[
CL = 35 \text{ cts}
\]
Uncertainty quantification

Uncertain variable = twist angle
Optimization & uncertainties

σ constraint optimisation:

$$\min \mu_{CD}$$

Variables: $\text{AoA}$, Camber

Constraints:

$$CL = 35 \text{ cts}$$
$$\sigma_{CD} \leq 15 \text{ cts}$$
σ constraint optimum:

\[ \text{camber} = -5.2^\circ \]

\[ \text{min CD} = 379.0 \text{ cts} \]

→ Gain : 11.5 cts
Optimization & uncertainties

MinMax optimisation:

\[ \min \mu_{CD} + 3\sigma_{CD} \]

Variables: \( AoA, \textbf{Camber} \)

Constraint:

\( CL = 35 \, \text{cts} \)
Optimization & uncertainties

<table>
<thead>
<tr>
<th>Camber</th>
<th>$\mu_{CD}$</th>
<th>$\sigma_{CD}$</th>
<th>$\mu_{CD} + 3\sigma_{CD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial shape</td>
<td>0,0°</td>
<td>390,50</td>
<td>16,80</td>
</tr>
<tr>
<td>Determ opt</td>
<td>-4,0°</td>
<td>378,60</td>
<td>15,50</td>
</tr>
<tr>
<td>$\sigma$ opt</td>
<td>-5,2°</td>
<td>379,00</td>
<td>15,00</td>
</tr>
<tr>
<td>MinMax opt</td>
<td>-7,0°</td>
<td>381,40</td>
<td>13,80</td>
</tr>
</tbody>
</table>

Remark: According to MoM order 1 methodology and Pearson approach, for the same price as $\sigma$ constraint optimization, we are in position to solve Reliability Optimization.

In addition to:

$X_{\text{input}}$ probability law $\rightarrow X_{\text{output}}$: same law
Mean value: $\mu_{\text{output}} = f(\mu_{\text{input}})$
Standard deviation: $\sigma_{\text{output}} = |\text{VF}| \times \sigma_{\text{input}}$

We recall that: 3rd and 4th statistical moment coefficients are unchanged.

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Price of Uncertainties

\[
\text{Price (M$) = 8000 x (Range (Nm)) - 500}
\]

- ΔRange of 2 to 3% ~ around 1M$/aircraft sailed
- ΔConsumption of 2% ~ fuel cost 0.5 to 1M$ during aircraft lifetime

Falcon F7X
5700 Nm
Conclusion

• Evaluation of uncertainties associated to each Measurement should be the result of a detailed and justified methodology

• Treatment of uncertainties enables a rigorous management of Performance Engagements and associated Risks
Q&A