Multi Objectives Optimization of an Automotive Fan Blade using an Advanced Parameterization Method

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ERCOFTAC - Design Optimisation Methods & Applications
Las Palmas de Gran Canaria, Spain
5-7 April 2006
Presentation outlines

- The parametric approach
  Parameterization method
  Optimization principles

- Industrial test-case
  Flow modeling
  Parameterization

- Results

- Conclusions
CFD issues

- 3D RANS codes can predict flow with good accuracy
- CFD more and more used to predict flow (design, optimization,...)

**BUT**

- RANS code take CPU time (5h or more)
- A large number of flow and geometric parameters:
  - pitch, chord, stagger angle, thickness, flow rate, rotational speed
  - 10 values by parameter $\Rightarrow 10^5$ Navier Stokes simulations for 5 parameters

**SOLUTIONS ?**

- Simplification of flow simulation $\Rightarrow$ real optimization ?
- Expertise $\Rightarrow$ need to make some choices
Classical Design cycling

5 hours by loop

1 day (ing.)

loop a geometry driven
loop b flow driven

sequential iterations means weak cycling

User profile: CFD expert
A new way for CFD

• Classical solvers (Fluent, elsA, Turb’Flow, …):

\[ F(q) = 0 \]

With \( F \) local conservative flux vector, \( q \) (local velocity, energy, dissipation…)

• Parametrized solvers (Turb’Design, Turb’Opty):

\[ F(q,p) = 0 \]

\( p \) the parameters (geometric, flow conditions)

\[ \frac{\partial q}{\partial p} \] the derivatives of local velocity, pressure… function of parameters

⇒ The derivatives are calculated in the all 3D domain
⇒ A database solution is built and stored

• Using the database, for example with Taylor series

\[ q(p_1 + \Delta p_1, p_2 + \Delta p_2) = q(p_1, p_2) + \Delta p_1 \frac{\partial q}{\partial p_1} + \Delta p_2 \frac{\partial q}{\partial p_2} + \Delta p_1 \Delta p_2 \frac{\partial^2 q}{\partial p_1 \partial p_2} + \ldots \]
Turb’Opty principle

- Define the Taylor series expansion to high order derivatives with
  \( q \) the vector of conservative variables (\( \rho, \rho u, \ldots \))
  \( p \) the vector of parameters (outlet static pressure, chord, \ldots)

\[
q(p+\Delta p) = q(p) + \Delta p \frac{\partial q}{\partial p} + \frac{1}{2!} \Delta p^2 \frac{\partial^2 q}{\partial p^2} + \ldots + \frac{1}{n!} \Delta p^n \frac{\partial^n q}{\partial p^n} + T_n
\]

- \( \text{Turb’Opty}^{TM} \) objectif : to calculate unknowns \( q^{(1)}, q^{(2)}, \ldots, q^{(n)} \)

- \( \text{Turb’Opty}^{TM} \) needs :
  - external information : reference solution : \( q_{\text{ref}}(p_{\text{ref}}) \)
  - internal information : equilibrium functions \( F(q,p) = 0 \)
Turb’Opty technology

- external information for Turb’Opty™: reference solution: \( g_{\text{ref}}(p_{\text{ref}}) \)

\[
\text{Files from TASCflow, Turb’Flow, elsA, …}
\]

\[
q_{\text{ref}}.
\]

- internal information: Turb’Flow™ discretized N-S Equations \( F(q,p) = 0 \)

\[
\frac{\partial F}{\partial q} \frac{\partial q}{\partial p} = -\frac{\partial F}{\partial p}
\]
Turb’Opty differenciation

\[ \frac{G \partial q}{\partial p} = R \]

L.S. (l) \quad G : jacobian matrix; \quad \frac{\partial F}{\partial p}

\[ \frac{G \partial^2 q}{\partial p^2} = R^{(1)} - G^{(1)} \frac{\partial q}{\partial p} \]

\[ \vdots \]

\[ \frac{G \partial^n q}{\partial p^n} = R^{(n-1)} - \sum_{i=1}^{n-1} C_{n-1}^i G^{(i)} \frac{\partial^{n-i} q}{\partial p^n} \]

**Extrapolation by interrogation** of the stored **database**:

\[ q(p + \Delta p) = q(p) + \Delta p \frac{\partial q}{\partial p} + \frac{1}{2!} \Delta p^2 \frac{\partial^2 q}{\partial p^2} + \ldots + \frac{1}{n!} \Delta p^n \frac{\partial^n q}{\partial p^n} + T_n \]
G from Turb’Flow solver

- Unsteady, compressible RANS equations, incompressible preconditioning

- Multi-domain structured quadrangular meshes.

- Roe, Liou,… flux splitting on a MUSCL finite volume formulation.

- Turbulence effects described by LES or the 2-equations k-ω model of Wilcox, Kok,…

- Time integration implemented by explicit or implicit scheme, multi grid.
Design cycling

The parametric approach
Industrial test-case
Results
Conclusions

Parameterization method
Optimization principles

Design, Optimization,
Other physics

1-3 days (ing.)
1.5 hours by derivate
5 hours by loop

User profile: CFD expert
User profile: designer

-loop a geometry-driven
-loop b flow driven

sequential iterations means weak cycling
no iteration just automation
Optimization principle

- Function to minimise

\[ \mathcal{F}_{\text{obj}} \]

- Gradient Method

- Adjoint State

- High order derivation

Reference Minimum 1 Minimum 2 Parameter
Turb’flow blind test

\[ \Delta P_s : \]
- Experiment = 235 pa
- Turb’Flow = 240 pa

3D Mesh : 1.9 M points
Flow maps with Turb’Opty

The parameterization

Results

Conclusions
Building the database

ΔPs:
Experiment = 235 pa
Turb’Flow = 240 pa

Blade to blade cutting plane to build the database

3D Mesh: 1,9 M points
Fluid characteristics

- Viscous perfect gas
  - perfect gas constant ($r$) | 287 J kg$^{-1}$ K$^{-1}$
  - heat capacity ratio ($\gamma$) | 1.4
  - dynamic viscosity ($\mu$) | $1.81 \times 10^{-5}$ kg m$^{-1}$ s$^{-1}$
  - thermal conductivity ($\lambda$) | 2.61 kg m s$^{-3}$ K$^{-1}$

- Wilcox k – $\omega$ turbulence model

- No-slip condition (adiabatic)
Flow configuration

- **inlet boundary conditions**
  
  \[
  \begin{align*}
  \rho_{\text{in}} & = 1.17 \text{ kg m}^{-3} \\
  U_{x \text{ in}} & = 34 \text{ m s}^{-1} \\
  V_{y \text{ in}} & = -7.5 \text{ m s}^{-1} \\
  \omega_{\text{in}} & = 3000 \text{ tr mn}^{-1}
  \end{align*}
  \]

- **outlet boundary conditions**
  
  \[P_{s \text{out}} = 10^5 \text{ Pa}\]
The parametric approach

Industrial test-case

Results

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14 geometric parameters

chord

Stagger angle

camber

camber location
Robust Design

Sensibility study for Robust Design

Mono parametric exploration

Loss factor

Parameter

stagger
chord
A
B
d
xd
rbaa
rbab
Ta
e
xe
Rc
rbf
Tf

reference value
minimum value
maximum value
The parametric approach

Industrial test-case

Results

Conclusions

Flow configuration

The parameterization

The optimization

The second order influence

The parameterization

The optimization

- Reference value
- Turb'Opty extrapolation - order 1
- Turb'Opty extrapolation - order 2

Reference value
- minimum value
- maximum value

Parameter

stagger
chord
A
B
d
xd
rbaa
rbab
Ta
c
xe
Rc
rbf
Tf

Loss factor

0.15
0.145
0.14
0.135
0.13

90%
100%
110%

parameter value (%)
1\textsuperscript{st} Optimization result

Loss Coefficient:

\[ \tilde{\omega} = \frac{P_t^{\text{in}} - P_t^{\text{out}}}{P_t^{\text{in}} - P_s^{\text{in}}} \]

Cascade Power:

\[ \Delta P_s \]

- 12.6%

+ 7.0%

269 pa

Profil modifications 0.141
Map flow analysis

Cascade Power:

\[ F = \dot{m} \Delta W_\theta = \dot{m}(V_{\text{out}} - V_{\text{in}}) \]

Loss Coefficient:

\[ \tilde{\omega} = \frac{P_{\text{in}} - P_{\text{out}}}{P_{\text{t}} - P_{\text{s}}} \]
The parametric approach
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PARETO Front

1 data base = 40 hours

5 coupled design parameters, 2 objectives

GA parameters
- $N_{pop} = 500$
- $N_{gen} = 100$
- $N_{arch} = 20$

GA performances
- $N_{sol} = 241$
- CPU time = 1850 s.
PARETO Front

50 000 evaluations = 3/4 hour

5 coupled design parameters, 3 objectives
Adjustment 2D/3D

The parameterization

The optimization

The parametric approach

Industrial test-case

Results

Conclusions
Two steps optimization (1/3)

4 objectives
## Two steps optimization (2/3)

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>1st optimization</th>
<th>2nd optimization (Turb'Opty)</th>
<th>2nd optimization (Turb'Flow)</th>
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<tbody>
<tr>
<td>Efficiency</td>
<td>0.671</td>
<td>0.713</td>
<td>0.750</td>
<td>0.750</td>
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<tr>
<td>Pressure rise</td>
<td>290</td>
<td>319.5</td>
<td>312</td>
<td>297</td>
</tr>
<tr>
<td>Loss factor</td>
<td>0.1002</td>
<td>0.0677</td>
<td>0.0472</td>
<td>0.0506</td>
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<tr>
<td>Torque</td>
<td>0.540</td>
<td>0.559</td>
<td>0.519</td>
<td>0.495</td>
</tr>
</tbody>
</table>
Operation range

Pressure rise

Loss factor
Experimental result (ECL)

The parametric approach
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Blade Force

Incidence

Turb’Opty Blade
Reference Blade

CD
CD optim
Summary

- A multi-objectives optimization using a parametrization technique has been realized.

- This cutting edge approach offers:
  - a high flexibility: simplicity, use for robust design and parametric studies, no problem of convergence of the CFD solver, only one grid.
  - a significant reduction of time: coupling with other physics, use of optimization algorithms that need lots of evaluations.

- Future works for complex physics (bifurcation, shocks, …)