Shape optimisation using breakthrough technologies

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Introduction

Shape optimisation technologies

(Automated Invention?)
Objective:

– Introduce two New and Elegant CFD shape optimisation methods.

– Do my best to describe how they work.

– Explain how these can reliably reduce your simulation time to find a shape optimised design.
Optimization

• The process of adjusting control variables to find the levels that achieve the best possible outcome.

• The challenge is to achieve optimisation efficiently
  – CFD runs can be long and expensive, even IO can be significant.
  – So we will consider systematic methods to find an optimum response with a few trials

• Consider the different choice of technology, approach and algorithm?
Fast and Reliable Design

• The tools that will be presented are all available in the current release.

• The Mesh Morph Optimiser is our first full release of this technology type.

• The adjoint concept has been 10 years in the making and is a unique offering in commercial CFD. At this point the functionality is still Beta.
Agenda

1. Introduction
2. Morphing
3. Linear shape optimisation methods
4. Derivative based optimisation method
5. Summary
Morphing
Mesh Morphing

• Applies a geometric design change directly in the solver?

• Uses a Bernstein polynomial-based morphing scheme
  – Freeform mesh deformation defined on a matrix of control points leads to a smooth deformation

• User prescribes the scale and direction of deformations to control points distributed evenly through the rectilinear region.
• Usage is based on the system of control points that can be moved freely in space
Morpher

- Deformation based on movement of one control point
• Deformation can be performed many times
- Deformation volume can have different numbers of control points (example now uses five by two points)
Examples I – F1

- Generic F1 car (Hexcore) – nose extension before

- Two control points moved in -x
Examples I – F1

• Generic F1 car (Hexcore) – nose extension after

• Two control points moved in -x
Mesh Morphing Workflow

• Stand Alone use of Morphing
  1. Setup the CFD Problem
  2. Perform the run
  3. Identify improvements in the geometry
  4. Use Morpher to modify the mesh in FLUENT itself
  5. Run the solution on the modified geometry using the previous result as an initial condition
  6. For small variations in geometry the new solution can be achieved very quickly

Note: With a little work the morph can be scripted or linked to Workbench parameter using scheme variables
Mesh Morpher Optimisation (MMO)
Mesh Morpher Optimiser (MMO)

• Workflow - Morpher coupled with optimiser

1. Setup the CFD problem
2. Invoke Mesh Morpher Tool
3. Define Objective Function
4. Define deformation region and assign deformation of control points through “Optimiser”
5. Perform solution to get the optimised design
Objective Function

• Objective Function is a single scalar value that the chosen optimizer method will drive towards a minimum.

• Typical Objective Functions
  – Lift & drag
  – Mass flow-rate for inlets, outlets or internal plane
  – Surface average pressures for walls/inlets/outlets
  – Min-max absolute pressure/temperature etc.

• Objective Function is unrestricted and can be defined using,
  – User defined functions
  – Scheme Function
Example - Morpher with Shape Optimizer

Application: L-shaped duct

Objective Function: Uniform flow at the outlet
Example - Morpher with Shape Optimizer

Application: Manifold

Objective Function: Equal flow rate through all the 18 nozzles
Example – Simple Sedan

- Defining the deformation
- And shape variables
1. Select individual control points and prescribe the relative ranges of motion.

2. More than one direction and scale of motion can be assigned using parameters

3. Choose an optimizer that will work to find the size of deformation to apply to each parameter
What does Optimisation involve

• Lets consider the Simplex algorithm
  – We need an objective
  – Variables to be considered (geometric parameters)
    • A k+1 geometric figure in a k-dimensional space is called a simplex.
    • k+1 is the number of trials to find the variables direction of improvement.
Simplex how it works

1. Rank Best, Worst and Next Best
2. Find mid point B to NB and reflect W
3. Evaluate Reflected Point
4. If Worse contract inside trial area
5. Adjust NB to W and rank new trial
6. Repeat until objective achieved
Simplex how it works

1. Rank Best, Worst and Next Best
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Example - Morpher with Shape Optimizer

Application: Incompressible turbulent flow over a car

Objective Function: Minimise Drag
Generic HVAC Duct

- HVAC duct section of an aircraft with one main outlet and two side outlets
- Objective:
  - Minimize pressure drop in the duct by optimizing the shape of branch-2

![Diagram of HVAC duct section with one main outlet and two side outlets.](image)

- Main outlet
  - Pressure = 0 Pa
- Branch outlets
  - Pressure = 0 Pa
- Inlet
  - Velocity = 10 m/s

![Mesh comparison showing baseline and modified duct configurations.](image)
Adjoint method
What does an adjoint solver do?

- An adjoint solver provides specific information about a fluid system that is very difficult to gather otherwise.

- An adjoint solver can be used to compute the derivative of an engineering quantity with respect to all of the inputs for the system.

- For example
  - Derivative of drag with respect to the shape of a vehicle.
  - Derivative of total pressure drop with respect the shape of the flow path.
Key Ideas - Fundamentals

High-level “system” view of a conventional flow solver

Inputs
- Boundary mesh
- Interior mesh
- Material properties
- Boundary condition 1
  - Flow angle
  - Inlet velocity
  - …
  - …

Outputs
- Field data
  - Contour plots
- Vector plots
- xy-plots
- Scalar values
  - Lift
  - Drag
  - Total pressure drop
**Key Ideas - Fundamentals**

**Inputs**
- Boundary mesh
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**ADJOINT SOLVER**

**HOW ARE CHANGES TO KEY OUTPUTS DEPENDENT ON CHANGES TO THE INPUTS?**
Key Ideas - Fundamentals

Flow solution $q$, and the inputs to the problem $c$.

\[ J(q; c) \quad R(q; c) = 0 \]

Change the inputs $c$ by $\delta c$

\[
\delta J = \frac{\partial J}{\partial q} \delta q + \frac{\partial J}{\partial c} \delta c \quad \frac{\partial R}{\partial q} \delta q + \frac{\partial R}{\partial c} \delta c = 0
\]

Engineer a particular linear combination of linearized NS equations – introduce multipliers $\tilde{q}$

\[
(\frac{\partial R}{\partial q})^T \tilde{q} = \frac{\partial J}{\partial q}
\]

\[
\begin{bmatrix}
(\tilde{q})^T \\
\frac{\partial R}{\partial q}
\end{bmatrix}
\delta q + \begin{bmatrix}
(\tilde{q})^T \\
\frac{\partial R}{\partial c}
\end{bmatrix} \delta c = 0
\]

After substitutions

\[
\delta J = \left( \frac{\partial J}{\partial c} - \tilde{q}^T \frac{\partial R}{\partial c} \right) \delta c
\]
Key Ideas – Adjoint Equations

- Construct and solve an adjoint problem to get a helper solution

\[
\left( \frac{\partial R}{\partial q} \right)^T \tilde{q} = \frac{\partial J}{\partial q}
\]

This innocent-looking system of equations is at the heart of the adjoint solver.

- Solve using AMG

- Involves a familiar process
  - Solution advancement controls – Courant number, under-relaxation
  - Residuals & iterations
  - Roughly the same effort as a conventional flow solution
Key Ideas – Shape Sensitivity

Shape sensitivity: Sensitivity of the observed value with respect to (boundary) grid node locations

\[ \delta(Drag) = \sum_{mesh} w^n \cdot \delta x^n \]

Visualization of shape sensitivity

- Uses vector field visualization.
- Identifies regions of high and low sensitivity.
Constrained motion

• Some walls within the control volume may be constrained not to move.

Actual change 3.1
$\Delta P = -213.8$

Total improvement of 8%
Pressure drop reduction example
Key Ideas – Mesh Adaptation

Solution-based mesh adaptation

- Regions in the flow domain where the adjoint solution is large have a strong effect of discretization errors in the quantity of interest.

- Adapt in regions where the adjoint solution is large
Current Functionality

- ANSYS-Fluent flow solver has very broad scope
- Adjoint is configured to compute solutions based on some assumptions
  - Steady, incompressible, laminar flow.
  - Steady, incompressible, turbulent flow with standard wall functions.
  - First-order discretization in space.
  - Frozen turbulence.
- The primary flow solution does NOT need to be run with these restrictions
  - Strong evidence that these assumptions do not undermine the utility of the adjoint solution data for engineering purposes.
- Fully parallelized.
- Gradient algorithm for shape modification
  - Mesh morphing using control points.
- Adjoint-based solution adaption
Internal flow – Simple 3D

Total pressure

Sensitivity of total pressure drop to shape
Total pressure drop = -23765 Pa
Predicted change    = 2858 Pa
Actual change       = 2390 Pa
180° Elbow optimization

Thanks to Hauke Reese
ANSYS Germany
180 Elbow: Optimization Loop

Base design

End design
IC Engine flow

Shape sensitivity vectors

Contours of magnitude of shape sensitivity
External Automotive Aerodynamics – Small car

Surface map of the drag sensitivity to shape changes

Surface map of the drag sensitivity to shape changes
Generic F1 Front Wing Example

- Adjoint computation takes about the same resources as the baseline flow calculation.
- Gives the sensitivity of the downforce to the shape of the wing.
  - Regions of high and low sensitivity.
Adjoint solution:

- Quantifies the effect of specific changes to shape upon downforce
- Suggests an optimal modification to the shape to enhance downforce

Baseline downforce = 905.4N
Predicted improvement = 41.6N
Actual improvement = 39.1N
Generic F1 Front Wing Example
Summary
Summary

• Two new approaches to consider
  – The morpher and optimisation provide efficient tool to make and compare geometric adjustments.
  – Consider using the adjoint to guide the morpher.
  – The Adjoint alone is also very useful to identify key sensitivities.

• These are new technologies which will continue to be enhanced.

• We encourage you to consider these techniques and will be happy to assist you.