Summary

Key Ideas

- Fundamentals
- Adjoint equations
- Workflow
- Shape sensitivity
- Gradient algorithm & optimization
- Mesh morphing
- Mesh adaptation

Current Functionality

- Features in Fluent 14 & 14.5

Examples

- Internal flows
- Robust design
- External flows
Key Ideas
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

HOW ARE CHANGES TO KEY OUTPUTS DEPENDENT ON CHANGES TO THE INPUTS?

Inputs
- Boundary mesh
- Interior mesh
- Material properties
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  - Flow angle
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  - ...
- ...

Outputs
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  - Lift
  - Drag
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ADJOINT SOLVER
Fundamentals

- **Discrete or continuous adjoint?**
- Continuous
  - Mathematically formal.
  - Adjoint is constructed at PDE level.
  - Easier initial implementation.
  - Wall functions, boundary conditions and expansion to richer physics can all be problematic.

- **Discrete**
  - Numerically formal.
  - Adjoint is constructed at the level of the discretized equations.
  - Mechanical process to construct the adjoint – somewhat challenging.
  - Easier to test.

**CHosen Method**
Key Ideas - Workflow

Workflow

• Solve the flow equations and post-process the results as usual.
• Pick an observation that is of engineering interest.
  ➢ Lift, drag, total pressure drop?
• Set up and solve the adjoint problem for this observation
  ➢ Define solution advancement controls
  ➢ Set convergence criteria
  ➢ Initialize
  ➢ Iterate to convergence
• Post-process the adjoint solution to get
  ➢ Shape sensitivity
  ➢ Sensitivity to boundary condition settings
  ➢ Contour & vector plots
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.
- These are the places where changes to the shape can have a big impact on the quantity of interest.
- The guidance is specific to the quantity of interest, and the current flow state.
Key Ideas – Mesh Morphing

Completing the design cycle
Mesh Morphing

- Sensitivity of lift to surface shape
- Use Bernstein polynomial-based morphing scheme
- Adjoint to deformation operation
- Surface shape sensitivity becomes control point sensitivity
- Benefit of this approach is two-fold
  - Smooths the surface sensitivity field
  - Provides a smooth interior mesh deformation
- Select portions of the geometry to be modified
Key Ideas – Mesh Morphing

Constrained motion

- Some walls within the control volume may be constrained not to move.
- A minimal adjustment is made to the control-point sensitivity field so that deformation of the wall is eliminated. Cast as a least-squares problem.

Actual change 3.1
\[ \Delta P = -213.8 \]

Total improvement of 8%
Solution-based mesh adaptation

• Details not presented here
• Regions in the flow domain where the adjoint solution is large is susceptible to having a strong effect of discretization errors on the quantity of interest.
• Adapt in regions where the adjoint solution is large
What have we learned so far?

• An adjoint solver can be used to compute the derivative of a chosen observation of engineering interest with respect to all the input data for the system.
• The adjoint equations form a linear system.
• Solving an adjoint problem is not trivial – about as much effort as a flow solution.
• The adjoint solution provides guidance on the optimal adjustment that will improve a system’s performance.

• An adjoint solution can be used to estimate the effect of a change prior to actually making the change.
• Shape sensitivity data can be combined with mesh morphing to guide smooth mesh deformations.
• An adjoint solution can be used as part of a gradient-based optimization algorithm.
• An adjoint solution can be used to guide mesh adaptation.
Current Functionality
Current Functionality

The adjoint solver is released with all Fluent 14 packages.

Documentation is available
- Theory
- Usage
- Tutorial
- Case study

Training is available

Functionality is activated by Loading the adjoint solver addon module

A new menu item is added at the top level.
Current Functionality Application Drivers

Key initial application areas are:
• Low-speed external aerodynamics
  – F1 (increase downforce)
  – Production automobiles (decrease drag)
• Low-speed internal flows
  – Total pressure drop (reduce losses)

In Fluent 14.5 a mechanism for users to define a wide range of observables of interest will be provided.

  • Forces
  • Moments
  • Pressure drop
  • Swirl
  • Ratios
  • Products
  • Variances
  • Linear combinations
  • Unary operations
GUI

- Follow as close as possible same design layout as Fluent solver
  - Specify observable
  - Adjoint solution advancement controls
  - Residual monitors
  - Initialization and iteration
  - Post-processing: contours, vectors.
  - Results reporting
  - Mesh-morphing with pre-calculation of expected change in observable.

TUI

```
/adjoint>
controls    morphing/   reporting/
monitors/   observable/ run/```
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
Current Limitations

- Limitations on models
  - Porous media
  - MRF
  - ....
  - These can be added in time
- Adjoint solver stability
  - For some cases converging the adjoint solver can be difficult
    - Inherently unsteady flow – oscillations in aerodynamic loads can signal that the adjoint may have difficulties.
    - Flows with strong shear of particular character
      - Saddle point, attracting focus, attracting node
    - Stabilization mechanism is in place. Still room for improvement here.
Examples
Internal flow – Simple 2D

Full discrete adjoint for shape sensitivity

Frozen turbulence

Reduce total pressure drop, $\Delta P$, through the system

$\Delta P = -232.8$
Expect change 10.0
Actual change 9.0
$\Delta P = -223.8$
Expect change 8.9
Actual change 6.9
$\Delta P = -216.9$
Expect change 7.0
Actual change 3.1
$\Delta P = -213.8$

Total improvement of 8%
Internal flow – Simple 3D

Total pressure

Sensitivity of total pressure drop to shape
Internal flow – Simple 3D

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

Final design
Surface map of the drag sensitivity to shape changes
Choose a control volume that encloses the upper part of the rear corner of the vehicle

(Half vehicle)
Baseline drag = 125.8N
Expected change = -1.1N
Actual change = -1.0N

Sequence of exaggerated surface displacement vector fields
External Automotive Aerodynamics - Sedan
External Automotive Aerodynamics – Small car

Surface map of the drag sensitivity to shape changes

Surface map of the drag sensitivity to shape changes
F1 front wing:

Goal is more downforce

Run a standard flow calculation to get a baseline flow field

Run the adjoint solver to give guidance on how to get more downforce
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
Adjointsolution: 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
Downforce enhancement for a generic race car

Increase the downforce on the vehicle

Look for regions of high sensitivity of downforce to shape
Downforce enhancement for a generic race car

Front wing redesign to generate more downforce

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Predicted</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
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<td>425.7</td>
</tr>
<tr>
<td>Modified</td>
<td>447.4</td>
<td>451.1</td>
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</tbody>
</table>
Lift enhancement for a generic race car

Rear wing redesign to generate more downforce

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Predicted</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>---</td>
<td>425.7</td>
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<tr>
<td>Modified</td>
<td>481.3</td>
<td>492.5</td>
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</tbody>
</table>
Conclusion

Reviewed key parts of adjoint method for CFD

- The origin of the adjoint as a method
- How to interpret adjoint data
- How to use adjoint data in a gradient algorithm
- Combining mesh morphing with the adjoint
- Adjoint-based mesh adaptation

Current Functionality

- Adjoint solver is a full feature in Fluent 14.
- GUI/TUI
- Documentation available
- Training

Examples

- Internal flows
  - Ductwork
  - IC Engine
  - Robust Design

- External automotive flows
  - Drag
  - Downforce in F1