Next-Generation Design Optimisation for Enterprise applied to Internal Combustion Engines

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About ENGYS

› Global providers of professional quality CFD Products
  – Based on Open Source Software (OPENFOAM)
  – Driven by innovation

› Founded in the UK (2009)
  – FOAM/OPENFOAM developers since 1999

› 6 offices worldwide
  – UK, Germany, Italy, USA, Australia, RSA

› Well established resellers network
  – Japan, Benelux, Korea, China, USA
 › General purpose CFD software suite
 › Enterprise product → professional quality + open-source
 › In production since 2010
 › HELYX-Adjoint → add-on solver module
› General purpose CFD software suite
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› HELYX-Adjoint → add-on solver module
OUTLINE

1. What is HELYX-Adjoint?
2. Topology Optimisation
3. Shape Optimisation
4. Conclusions
HELYX-Adjoint | Background

› Originally commissioned by C. Othmer, VW Research
› Mission ➔ Build a practical adjoint optimisation tool that anyone can use
› Focus remains on utility
› Accuracy is important, but not the only concern
› Performance, ease-of-use, robustness – all equally significant
› Built on HELYX-Core
› Continuous adjoint
  – Support for industrial problems (> 200M cells)
HELYX-Adjoint | Continuous vs. Discrete

Continuous Adjoint

- Difficult / time consuming derivation from governing equations
- Intuitive numerics, can reuse primal methods
- Gradient accuracy depends on details of implementation
- Highly efficient in terms of run time and RAM usage

Discrete Adjoint

- Manual and/or automatic differentiation of code
- Black-box numerics, optimisation can be challenging
- Produces exact sensitivities (consistent)
- High RAM requirements (taping and/or check-pointing)
HELYX-Adjoint | Continuous Formulation

› CFD computation: v, p → primal fields

\[
(v \cdot \nabla) v = -\nabla p + \nabla \cdot (\nu \nabla v) - \alpha v \\
\nabla \cdot v = 0
\]

› Adjoint CFD computation: u, q → “dual” fields

\[
- (\nabla u) v - (v \cdot \nabla) u = -\nabla q + \nabla \cdot (\nu \nabla u) - \alpha u \\
\nabla \cdot u = 0
\]

› Computation of sensitivities:

- Surface sensitivities → \( \frac{\partial J}{\partial \beta} \sim \frac{\partial v}{\partial n} \cdot \frac{\partial u}{\partial n} \)

- Volume sensitivities → \( \frac{\partial J}{\partial \alpha} \sim v \cdot u \)
HELYX-Adjoint | Sensitivities

Surface Sensitivities \( \partial J / \partial \beta \)
- red \( \rightarrow \) push surface in
- blue \( \rightarrow \) push surface out

\( \frac{\partial J}{\partial \beta} \rightarrow \) mass flow

\( \frac{\partial J}{\partial \beta} \rightarrow \) drag

Volume Sensitivities \( \partial J / \partial \alpha \)
- red \( \rightarrow \) free volume cells
- blue \( \rightarrow \) penalise volume cells

\( \frac{\partial J}{\partial \alpha} \rightarrow \) pressure drop

\( \frac{\partial J}{\partial \alpha} \rightarrow \) flow uniformity
HELYX-Adjoint | Key Features

› Multi-objective (> 20 different cost functions)
› Objective and constraints
  - Manufacturability constraints
› Adjoint turbulence & wall-function
› 2nd order accurate
› Easy to use GUI
OUTLINE

2. Topology Optimisation

› What is Topology Optimisation?
› Success Stories
  – Oil Channel
  – Engine Intake Port
  – Internal Flows
Specify design space and inlet/outlet interfaces

Define optimisation objectives

Calculate volume sensitivities \( \frac{\partial J}{\partial \alpha} \)
- Volume cells penalised according to objective function
- Track “optimum” interface using level-set with immersed boundary

Output “smooth” surface optimised shape

“One-shot” approach
Topology Optimisation | Success Story

Oil Channel

› Decrease system power losses
› Improved level-set immersed boundary representation
› Mitigate recirculation induced local optima

Courtesy of Dr. Takeshi Yamaguchi (AISIN AW)
Oil Channel

- Optimisation complete in <1hr
- Zero level-set extracted and new design re-meshed
- ~30% reduction in power losses verified
- HELYX-Adjoint makes optimal design routine
Topology Optimisation | Success Story

Engine Intake Port

› Design port flow
› Targets to achieve:
  – Maximise Mass Flow Rate
  – Maximise Swirl Index $\omega$
› Compressible flow
› $k$-$\omega$ SST turbulence model

Packaging space (brown colour)
Fixed space (red colour)
Topology Optimisation | Success Story

Engine Intake Port

› Input data for the project:
  – Number of valves = 2
  – Valve lift = 9mm

› Targets to achieve:
  – Maximise Mass Flow Rate
  – Maximise Swirl Index $\omega$

\[
\omega = \frac{\sum V_y \rho dV \cdot (zV_x - xV_z)}{\sum \rho dV}
\]

Inlet
$P_1 = 101325 \text{ Pa}$

Swirl monitoring cylinder
Centered @ $Y = 1.5 \times$ bore
Height = 10mm

Outlet
$P_2 = \text{const}$
Topology Optimisation | Success Story

Engine Intake Port

› helyxHexMesh utility
› Mesh size: 3.6M cells
› Near-wall layers: 3
› Target cell size (port arms and valves): 0.4mm
Topography Optimisation | Success Story

Engine Intake Port

› Design A is the optimal solution for swirl objective
› Design C is the optimal solution for mass flow rate objective
› Design B is a trade-off in terms of both the design objectives and was selected by the as a compromise solution
Topology Optimisation | Success Story

Engine Intake Port

Velocity Streamlines

Velocity contour at swirl monitoring plane
Topology Optimisation | Other Examples

Internal Flows

Taken from “The Adjoint Method Hits the Road” by C. Othmer [2014]
3. Shape Optimisation

OUTLINE

› What is Shape Optimisation?
› Morphing
› Success Stories
  – Exhaust Port
  – Manifold Optimisation
Shape Optimisation

› Based on steady RANS or time averaged primal (LES/DES)

› Morph design using HEYLEX morphing solutions:
  – Node-based deformation
  – Volumetric NURBS deformation

› Morphing using 3rd-party tools:
  – ANSA, Sculptor, CAMILO, etc.

\[
\frac{\partial J}{\partial \beta} \rightarrow \text{mass flow}
\]

\[
\frac{\partial J}{\partial \beta} \rightarrow \text{drag}
\]
Shape Optimisation | Morphing

Node-based Deformation

› Implicit smoothing
› Mesh optimisation for improved deformation

Optimisation History

Baseline

Optimised: -2% Cd
Shape Optimisation | Morphing

Node-based Deformation

› Smooth for vector \( \vec{d} = \vec{G} \cdot \vec{n} \)

› Smooth the magnitude of the displacement

\[
\vec{d} - \varepsilon \nabla^2 \vec{d} = \vec{d}_{\text{init}}
\]

\( \vec{d}_{\text{init}} \): Initial Field, \( \vec{d} \): Smooth Field, \( \varepsilon \): smoothing intensity

Smoothing radius of 3cm.

Courtesy of FCA

Courtesy of Rolls Royce
Shape Optimisation | Morphing

Node-based Deformation

1. Insert Shape
2. Primal Solution
3. Adjoint Solution
4. Define Constraint Patches & Smoothing Radius
5. Sensitivity Smoothing
6. Surface Deformation
7. Converge
8. Mesh adaptation
9. In-house Morpher
10. Surface Mesh Regularization
11. Take Optimal Shape
Shape Optimisation | Morphing

vNurbs Deformation

› Points construct lattices (topological cubes)

› Two step procedure:
  – Training (Mapping the mesh to the control point structure)
  – Deforming (Displacing the control points and the mesh, based on the map created)
Shape Optimisation | Morphing

vNurbs Deformation

› Input:
  – Number of control points in U, V, W directions
  – Polynomial degree in U, V, W direction

› Boundary control points can stay fixed to ensure $C_0$ and $C_1$ continuity

› Coupling with the adjoint:
  – Sensitivities can be mapped to the control point structure just like the mesh
  – Control point sensitivities can be used with an optimizer to perform optimization

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Exhaust Port

- Exhaust port modification for increased flow rate
- Shape optimisation → modify geometry based on surface sensitivities
- Design objective:
  - Maximum flow rate

Success Story | Volkswagen Group

Taken from “The Adjoint Method Hits the Road” by C. Othmer [2014]
Success Story | Volkswagen Group

Exhaust Port

Taken from “The Adjoint Method Hits the Road” by C. Othmer [2014]

Mass flow sensitivities

[F. Kunze and R. Niederlein]
Success Story | Röchling

Manifold Optimisation

› HELYX-Adjoint employed to produce a duct configuration with maximum flow uniformity on a manifold lower end

› Three different approaches employed:
  - Surface shape optimisation
  - Volume topology optimisation
  - Topology + Shape optimisation
Success Story | Röchling

Manifold Optimisation

› Fluid:
  − Air @ 20°C
  − \( \rho = 1.204 \text{ kg/m}^3 \)
  − \( \mu = 1.812 \text{e-5 Pa} \cdot \text{s} \)

› Incompressible flow

› Inlet volumetric flow rate = 450 kg/h

› Outlet reference pressure = 101325 Pa

› Design Objective:
  − Maximisation of flow uniformity by measuring the average mass flow rate on 7 outlet cells on the manifold lower end
Shape Optimisation Workflow:

1. Evaluate the adjoint surface sensitivities on the baseline shape provided by Röchling
2. Apply a free-form lattice-based mesh deformation morphing tool available in HELOYX
3. Calculate the new adjoint surface sensitivities
4. Repeat 2-3 until an optimal shape is found
Success Story | Röchling

Manifold Optimisation

Topology Optimisation Workflow

1. Evaluate the adjoint volume sensitivities on the packaging space provided by Röchling
2. Employ a level-set engine to track optimal solid-fluid interface
3. Apply interface curvature limitation to produce a smooth duct surface with manufacturing potential
4. Get a final smooth optimised interface
Success Story | Röchling

Manifold Optimisation

› Topology + Shape Optimisation Workflow:
  1. Run the topology optimisation workflow
  2. Apply a free-form lattice-based mesh deformation morphing tool available in HELOYX on the optimised shape obtained in (1)
  3. Calculate the new adjoint surface sensitivities
  4. Repeat 2-3 until an optimal shape is found
Success Story | Röchling

Manifold Optimisation

Optimisation Results

- Mass Flow Rate [kg/h]
- cell1, cell2, cell3, cell4, cell5, cell6, cell7

Legend:
- Baseline
- Optimised – Shape
- Optimised – Topology
- Optimised – Topology and Shape
- Target
Success Story | Röchling

Manifold Optimisation

Shape optimisation optimal surface  Topology optimisation optimal surface  Topology+Shape optimisation optimal surface
Conclusions

› A unique continuous adjoint formulation for topology and shape optimisation developed by ENGYS was presented
› Fully validated and deployed in industrial settings
› Professional solution available in the HELYX-Adjoint add-on module
› Unparalleled efficiency in design optimisation for fluid systems
› Large cases (200M+) cases can be handled by HELYX® Adjoint
› Automatic surface morphing for advanced shape optimisation
› Fully open-source solution
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Questions?

THANK YOU VERY MUCH!