Aeroacoustic optimisation by means of adjoint sensitivity maps

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AGENDA

- Continuous adjoint method for external aerodynamics
- Physical mechanisms of sound propagation to the interior
- OpenFOAM-based process for interior noise prediction
- Computing the adjoint aeroacoustic sensitivity maps
- Conclusions & future steps

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THE CONTINUOUS ADJOINT METHOD
FORMULATION FOR NS-EQUATIONS

- Optimization problem:
  minimize the objective function: \( J = J(\hat{v}, p, b) \)
  subject to: \( \tilde{R}(\hat{v}, p, b) = \hat{0} \)

- Augmented objective function:
  \( L = J + \int_\Omega q R^p d\Omega + \int_\Omega \hat{u} \cdot \tilde{R}^v d\Omega \)
  \( \delta_{\hat{v}, p} = 0 \)

- Variation:
  \( \delta L = \delta_{\hat{v}, p} \left( J + \int_\Omega q R^p d\Omega + \int_\Omega \hat{u} \cdot \tilde{R}^v d\Omega \right) + \delta_b \left( J + \int_\Omega q R^p d\Omega + \int_\Omega \hat{u} \cdot \tilde{R}^v d\Omega \right) \)

Flow (primal) Equations
\[
\begin{align*}
\tilde{R}(\hat{v}, p, b) &= \left\{ \begin{array}{l}
R^q = \nabla \cdot \hat{u} = 0 \\
R^u = -\frac{\partial \hat{u}}{\partial t} + (\hat{v} \cdot \nabla)\hat{u} - \nabla \hat{u} \cdot \hat{v} - \nabla \cdot \tau^a + \nabla q = \hat{0}
\end{array} \right.
\end{align*}
\]

Adjoint Equations
\[
\tilde{R}(\hat{u}, q) = \left\{ \begin{array}{l}
R^q = \nabla \cdot \hat{u} = 0 \\
R^u = -\frac{\partial \hat{u}}{\partial t} + (\hat{v} \cdot \nabla)\hat{u} - \nabla \hat{u} \cdot \hat{v} - \nabla \cdot \tau^a + \nabla q = \hat{0}
\end{array} \right.
\]

Sensitivity Derivatives:
\[
\frac{\delta L}{\delta b} = \int_S \left[ -\nu \frac{\partial \hat{u}}{\partial n} \cdot \frac{\partial \hat{v}}{\partial n} + \ldots \right] dS
\]
THE CONTINUOUS ADJOINT METHOD

Flow (primal) Equations

\[ \vec{R}(\vec{v}, p, b) = \]
\[ \left\{ \begin{array}{l}
R^p = \nabla \cdot \vec{v} = 0 \\
R^v = \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} - \nabla \cdot \mathbf{\tau} + \nabla p = \vec{0}
\end{array} \right. \]

Adjoint Equations

\[ \vec{R}(\vec{u}, q) = \left\{ \begin{array}{l}
R^q = \nabla \cdot \vec{u} = 0 \\
R^u = -\frac{\partial \vec{u}}{\partial t} + -(\vec{v} \cdot \nabla)\vec{u} - \nabla \vec{u} \cdot \vec{v} - \nabla \cdot \mathbf{\tau}^a + \nabla q = \vec{0}
\end{array} \right. \]

Sensitivity Derivatives:

\[ \frac{\delta L}{\delta b} = \int_s -\nu \frac{\partial \vec{u}}{\partial n} \cdot \frac{\partial \vec{v}}{\partial n} + [... \]dS
PHYSICAL MECHANISMS OF SOUND PROPAGATION TO THE INTERIOR

1. Noise creation
2. Sound propagation to window
3. Structural vibration
4. Noise radiation in the interior
PROCESS FOR INTERIOR NOISE PREDICTION

1. Noise creation (time resolved CFD)
   - OpenFOAM 2.1.1
   - IDDES Spalart Allmaras
   - SnappyHexMesh for meshing

2. Noise radiation (Kirchhoff-Integral)
   - OpenFOAM 2.1.1
   - Fully parallelised

3. Structure vibration (Bending waves)
   - OpenFOAM 1.6-ext
   - Using finiteArea solver

4. Sound propagation (Wave equation)
   - OpenFOAM 1.6-ext
   - Castellated mesh in vehicle interior

\[ R^p = \nabla \cdot \vec{v} = 0 \]
\[ \vec{R}^\nu = \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} - \nabla \cdot \tau + \nabla p = 0 \]

Hydrodynamic pressure \( p \) on the mirror

\[ p' = \int_{mirror} \left[ \frac{1}{r^3} (\vec{r} \cdot \hat{n}) p + \frac{1}{cr^2} (\vec{r} \cdot \hat{n}) \frac{\partial p}{\partial t} \right] dS \]

\[ R^w = \frac{\partial^2 w}{\partial t^2} + \eta_1 \frac{D}{m'} \nabla^4 w + \eta_2 \frac{\partial w}{\partial t} + \eta_3 \sqrt{\frac{D}{m'} \frac{\partial}{\partial t}} \nabla^2 w - \frac{p'}{m'} = 0 \]

BC on the window:
\[ \frac{\partial p^a}{\partial n} - \rho \frac{\partial^2 w}{\partial t^2} = 0 \]
WIND NOISE PREDICTION

1. Turbulent Flow
2. Sound Radiation
3. Structural Vibration
4. Cabin Noise

Frequency, Hz

SPL, dB

experiment
simulation

with 1mm mesh valid up to 5 kHz

Time = 0.060000

Frequency, Hz

SPL, dB

experiment
simulation

with 1mm mesh valid up to 5 kHz
ADJOINT PROCESS FOR SENSITIVITIES COMPUTATION

1. Noise creation (time resolved CFD)
2. Noise radiation (Kirchhoff-Integral)
3. Structure vibration (Bending waves)
4. Sound propagation (Wave equation)

Primal simulation

Each time step has an effect on the following time steps

Adjoint simulation

What is the sensitivity of each time step?

The information of this sensitivity has to travel backwards in time
ADJOINT PROCESS FOR SENSITIVITIES COMPUTATION

\[ R^q = \nabla \cdot \vec{u} = 0 \]
\[ \tilde{R}^u = -\frac{\partial \vec{u}}{\partial t} + (\vec{v} \cdot \nabla) \vec{u} - \nabla \vec{u} \cdot \vec{v} - \nabla \cdot \vec{r}^a + \nabla q = 0 \]

BC on the mirror:
\[ \vec{u} \hat{n} = -q' \]

\[ q' = \int_{\text{window}} f(z(\vec{x}, t), \vec{x}) dS \]

\[ R^z = \frac{\partial^2 z}{\partial t^2} + \frac{D}{m'} \nabla^4 z - \eta_2 \frac{\partial z}{\partial t} - \eta_3 \sqrt{\frac{D}{m'} \frac{\partial}{\partial t}} \nabla^2 z - c^2 \rho \frac{\partial^2 q}{\partial t^2} = 0 \]

\[ R^{q^a} = \frac{\partial^2 q}{\partial t^2} + \nabla^2 q^a + \frac{\delta J}{\delta q^a} = 0 \]

4. Adjoint Navier-Stokes (\( \vec{u}, q \))
- OpenFOAM 2.1.1
- Adjoint solver provided by ENGYS + in-house modifications
- Checkpointing technique to save primal fields

3. Adjoint Kirchhoff-Integral (\( q' \))
- OpenFOAM 2.1.1
- Fully parallelised

2. Adjoint Bending waves (\( z \))
- OpenFOAM 1.6-ext
- Using finiteArea solver

1. Adjoint Wave equation (\( q^a \))
- OpenFOAM 1.6-ext

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ADJOINT PROCESS FOR SENSITIVITIES COMPUTATION

1. Noise creation (time resolved CFD)
2. Noise radiation (Kirchhoff-Integral)
3. Structure vibration (Bending waves)
4. Sound propagation (Wave equation)

Adjoint aeroacoustic sensitivities on the vehicle mirror

1. Adjoint Wave equation ($q^a$)
2. Adjoint Bending waves ($z$)
3. Adjoint Kirchhoff-Integral ($q'$)
4. Adjoint Navier-Stokes ($\vec{u}, q$)
ADJOINT AEROACOUSTIC SENSITIVITIES

Simulation of the adjoint aeroacoustic chain

Red: push in to reduce interior noise
Blue: pull out to reduce interior noise
ADJOINT AEROACOUSTIC SENSITIVITIES

Local Morphing ➔ ≈ 8% reduction

Red: push in to reduce interior noise
Blue: pull out to reduce interior noise
CONCLUSIONS & FUTURE STEPS

• Continuous adjoint method for interior noise prediction developed and implemented in OpenFOAM – including all steps of noise propagation from the flow to the interior

• One-step optimisation performed as proof of concept

• Solutions for the bottlenecks of data handling and computational cost are under consideration

• A complete optimization process will be performed in the future

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http://ioda.sems.qmul.ac.uk

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