Scale-Resolving Simulations for Aeroacoustic Sources

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Bilbao, 7 October 2014
Overview

- Aeroacoustics: Lighthill‘s analogy
- Computational AeroAcoustics CAA
- PIANO extension for viscous simulations
- 2D Cylinder in uniform flow
Some background information about aeroacoustics

- Lighthill’s acoustic analogy (1952):

\[ \frac{\partial^2 \rho'}{\partial t^2} - a^2_{\infty} \nabla^2 \rho' = \nabla \cdot \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + f(s', \tau) \]

wave equation: \[ \frac{\partial^2 \rho'}{\partial t^2} = a^2_{\infty} \nabla^2 \rho' \]

- Möhring’s equation:

\[ \frac{D}{Dt} \left[ \frac{1}{\alpha^2} \frac{DB}{Dt} \right] - \frac{1}{\rho} \nabla \cdot (\rho \nabla B) = \frac{1}{\rho} \nabla \cdot (\rho \omega \times \mathbf{v}) + f(s) \]

→ without vortex dynamics no sound!

TU/e  DLR
Research group „Scale-Resolving Simulations of Aeroacoustic Sources“:

- started at 01.02.2014
- with two employees
- see website for latest info: www.tu-braunschweig.de/ism/forschung/ag-aq

**Research goal:** Fundamental knowledge on aeroacoustic source mechanisms through scale-resolving simulations, with focus on external flow problems

**Method:** Computational Aeroacoustics code PIANO (DLR Braunschweig)

- Hybrid approach: background flow + acoustic propagation (perturbation)
- Governing equations: LEE, APE, or non-linear Euler equations
- Block structured, high-order
- Spatial differentiation: dispersion relation preserving (DRP) scheme of Tam&Webb
- Temporal integration: 4th-order low-dispersion Runge-Kutta (LDDRK) algorithm (Hu)

→ Extended with viscous terms: DNS capable simulation tool
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Some background information about CAA

Aeroacoustics: flow induced noise

Computational AeroAcoustics (CAA): numerical simulation of noise generation and its propagation through a non-uniform medium
**Some background information about CAA: equations**

CAA equations:
- small aeroacoustic fluctuations compared to turbulent fluctuations

Linearised Euler equations (LEEs):
- dropping the viscous terms in NS
- decomposition into steady part and fluctuating part, e.g. \( \rho(x, t) = \bar{\rho}(x) + \rho'(x, t) \)

Continuity equation becomes:

\[
\frac{\partial \rho'}{\partial t} + \bar{u} \cdot \nabla \rho' + u' \cdot \nabla \bar{\rho} + \bar{\rho} \cdot \nabla u' + \rho' \cdot \nabla \bar{u} = 0
\]
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Viscous PIANO

Computational Aeroacoustics code PIANO (DLR Braunschweig):
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Viscous effects?
Important for sound propagation if a significant coupling between acoustic waves and vortical motion leads to a considerable transformation of acoustic energy into vortical motion (e.g. for noise reduction mechanisms at sharp edges, liner holes, or in porous media of passive noise reduction treatment)

OR:
Feasibility of Navier-Stokes simulation of noise generation with inclusion of viscous terms into the non-linear Euler equations
Governing equations

Compressible NS-equations in primitive formulation:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) & = 0, \\
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} + \frac{\nabla p}{\rho} & = \frac{\nabla \cdot \mathbf{\tau}}{\rho}, \\
\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p + \gamma p \nabla \cdot \mathbf{v} & = (\gamma - 1)(\mathbf{\tau} \cdot \nabla) \cdot \mathbf{v} - (\gamma - 1) \nabla \cdot \mathbf{q}.
\end{align*}
\]

Substitution of decomposition in to base flow and fluctuating part:

\[
\rho = \rho^0 + \rho', \quad \mathbf{v} = \mathbf{v}^0 + \mathbf{v}', \quad p = p^0 + p', \quad \mathbf{\tau} = \mathbf{\tau}^0 + \mathbf{\tau}', \quad \mathbf{q} = \mathbf{q}^0 + \mathbf{q}'.
\]

(for a detailed derivation: see Ewert et al. VKI-lecture series 2012)
Finally, viscous NLPE with steady baseflow:

\[
\frac{\partial \rho'}{\partial t} + \mathbf{v} \cdot \nabla \rho' + \mathbf{v}' \cdot \nabla \rho^0 + \rho \nabla \cdot \mathbf{v}' + \rho' \nabla \cdot \mathbf{v}^0 = r_1^0 ,
\]

\[
\frac{\partial \mathbf{v}'}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v}' + (\mathbf{v}' \cdot \nabla) \mathbf{v}^0 + \frac{\rho'}{\rho} (\mathbf{v}^0 \cdot \nabla) \mathbf{v}^0 + \frac{\nabla p'}{\rho} = \nabla \cdot \mathbf{\tau}' + \frac{\rho^0}{\rho} r_2^0 ,
\]

\[
\frac{\partial \rho'}{\partial t} + \mathbf{v} \cdot \nabla \rho' + \mathbf{v}' \cdot \nabla \rho^0 + \gamma p \nabla \cdot \mathbf{v}' + \gamma p' \nabla \cdot \mathbf{v}^0 =
\]

\[
(\gamma - 1) [(\mathbf{\tau}' \cdot \nabla) \cdot \mathbf{v} + (\mathbf{\tau}^0 \cdot \nabla) \cdot \mathbf{v}' - \nabla \cdot \mathbf{q}'] + r_3^0 .
\]

with residual turbulent viscous and heat fluxes:

\[
r_1^0 = 0 ,
\]

\[
r_2^0 = - \frac{\nabla \cdot \mathbf{\tau}^0}{\rho^0} ,
\]

\[
r_3^0 = - (\gamma - 1) [(\mathbf{\tau}^0 \cdot \nabla) \cdot \mathbf{v}^0 - \nabla \cdot \mathbf{q}^0] .
\]
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Overset simulation: cylinder in uniform flow

Reminder Overset approach: background flow (RANS) + perturbation scale-resolving simulation

Same testcase as in Inoue & Hatakeyama (JFM 2002)
Circular Cylinder in Uniform Flow

Background flow obtained from steady RANS with the DLR TAU code → only half simulated to prevent unsteady vortex shedding
O-grid (diameter = 300D), 90k points.

Streamlines at Re = 150, M = 0.3

source: Moghadam (2012)
Circular Cylinder in Uniform Flow

Overset simulation grid:

Only small part of domain shown (one out of three points)
Circular Cylinder in Uniform Flow

\[ M = 0.3 \text{ and } Re = 150: \]

Iso-contours pressure fluctuations:

\[ vorticity: \]

\[ t = t_1: \]

\[ t = t_1 + 0.5T: \]
Circular Cylinder in Uniform Flow

M = 0.3 and Re = 150:

$f = 18.67 \text{ Hz} \Rightarrow St = 0.183$

Fey et al. (1998): $St = 0.2684 - 1.0356Re^{-0.5} \Rightarrow St = 0.184$
Circular Cylinder in Uniform Flow

Propagation of pressure waves (M=0.2):

 Iso-contours pressure fluct. (M=0.3):
Circular Cylinder in Uniform Flow

Propagation of pressure waves (M=0.2):

Tendency of pressure peaks decay proportional to $r^{-0.5}$, in agreement to theoretical expectations.
Circular Cylinder in Uniform Flow

Figure 3 from Inoue & Hatakeyama (JFM 2002):

Comparison of Inoue & Hatakeyama and present study (both $M=0.3, \text{Re} = 150$):

<table>
<thead>
<tr>
<th></th>
<th>$\overline{c_l}$ [-]</th>
<th>$\Delta c_l$ [-]</th>
<th>$\overline{c_d}$ [-]</th>
<th>$\Delta c_d$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inoue and Hatakeyama [7]</td>
<td>0.0</td>
<td>0.52</td>
<td>1.38$^a$</td>
<td>2.6 $\cdot 10^{-2}$</td>
</tr>
<tr>
<td>present study</td>
<td>$8.5 \cdot 10^{-4}$</td>
<td>0.53</td>
<td>1.35</td>
<td>2.8 $\cdot 10^{-2}$</td>
</tr>
</tbody>
</table>

$^a$ Estimated from Fig. 3 in Ref. [7]
Circular Cylinder in Uniform Flow

Animation of pressure fluctuation for $M = 0.3$, $Re = 150$ :
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