Numerical Simulation of Acoustic Effects of Engine Installation for New Concepts of Aircrafts

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ONERA

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Context

- Future aircraft projects
- Engine noise shielding by airframe
- Numerical simulation
Tools for numerical simulation of acoustic shielding effects

**Noise source modeling**
- Engine noise sources (fan, jet) are very complex
- Interesting results can be obtained by using **simplified source**: distribution of monopoles

**Noise prediction**

**Acoustic propagation simulation**
May include effects of:
- **Scattering** on complex solid bodies
- **Refraction** through non-uniform mean flows
## In-house solvers developed at ONERA

<table>
<thead>
<tr>
<th></th>
<th><strong>BEMUSE</strong></th>
<th><strong>sAbrinA</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solved equation(s)</td>
<td>Helmholtz</td>
<td>Euler (in pertubation form)</td>
</tr>
<tr>
<td>Numerical method</td>
<td>Boundary Element Method</td>
<td>Finite difference, high order</td>
</tr>
<tr>
<td></td>
<td>Variational formulation</td>
<td>spatial schemes and filter</td>
</tr>
<tr>
<td>Grid</td>
<td>Body surface</td>
<td>Fluid</td>
</tr>
<tr>
<td></td>
<td>Unstructured</td>
<td>Structured</td>
</tr>
<tr>
<td>Scattering effect on rigid</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>bodies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refraction effects through</td>
<td>No flow (uniform flow under</td>
<td>Yes</td>
</tr>
<tr>
<td>non uniform flow</td>
<td>progress)</td>
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</table>

*ONERA*
In-house solvers developed at ONERA

Part I : BEMUSE code
**BEMUSE solver: Context of design**

**European Project ROSAS (Research On Silent Aircraft concepts)**

**ONERA’s objectives in task 3.3.3 (« Numerical work »):**
* Fuselage, wing and empennage shielding effects assessment*
* Acoustic scattering from distribution of point sources*
* Geometry: ROSAS aircraft, scale 1:1 Model with up to 100,000 Degrees Of Freedom (DOF)*
* Frequency: up to fan blade passing frequency (BPF)*
* Running on parallel PC Cluster (powerful / cheap)*

**Code design:**
* Parallel BEM (Boundary Element Method) code*
* Built from existing BEM modules (electromagnetism)*
* Computer: ONERA’s PC Cluster: 32 biprocessor PCs*
Boundary Element Method

Helmholtz equation \( \Delta p(x) + k^2 p(x) = 0 \) \( \left( k = \frac{\omega}{c} \right) \)

Rigid boundary condition on \( \Sigma \) \( \frac{\partial p}{\partial n} = 0, \quad x \in \Sigma \)

Sommerfeld radiation condition on \( \Lambda \)

Integral solution using a free-space Green function

\[
\int_{\Sigma} \left[ p(y) \frac{\partial G(x, y)}{\partial n} - \frac{\partial p}{\partial n} (y) G(x, y) \right] dy = \begin{cases} p(x) & x \in \Omega_e \\ \frac{1}{2} p(x) & x \in \Sigma \\ 0 & x \in \Omega_i \end{cases} \quad G(x, y) = \frac{e^{-ik\|x-y\|}}{4\pi\|x-y\|}
\]

Discretization using a shape function \([N]\) to interpolate \( p \) and its derivative on \( n \) DOF on \( \Sigma \)

\[
\frac{1}{2} p(x) = \sum_{i=1}^{n} \int_{\Sigma} \frac{\partial G(x, y)}{\partial n} [N] dy \{ p(x_i) \} - \sum_{i=1}^{n} \int_{\Sigma} G(x, y) [N] dy \left\{ \frac{\partial p}{\partial n} (x_i) \right\}
\]

Set of \( n \) linear equations : \( [H][p] = -[G] \left\{ \frac{\partial p}{\partial n} \right\} \) \([H]\) and \([G]\) are \( n \times n \) symmetric plain matrices
**BEMUSE validation**
Acoustic scattering on a rigid sphere : $r = 1$
Incident spherical wave : frequency $= 600$ Hz
Normalized frequency $kr = 11$

**BEM computations**
1) BEMUSE code on PC (1 node)
2) SYSNOISE code on UNIX workstation

Unstructured grid:
2562 DOF

**Analytical solution**

$$ (r, \theta, \varphi) = \sum_{l=0}^{+\infty} \sum_{m=-l}^{+l} v_l^m h_l^{(1)}(kr) \frac{1}{k} \frac{\partial}{\partial r} h_l^{(1)}(kr) Y_l^m(\theta, \varphi) $$
Grid construction

- ROSAS aircraft UWN, OWN, RFN
- Up to 110,000 DOF
- Simplified but realistic shape
  - Analytical sections
  - Direct junction wing/fuselage

Reference configuration:
Under Wing Nacelle (UWN)
Results

Pressure distribution at aircraft surface
* Incident, scattered, total fields

Directivity diagrams
* Circles in XY, XZ and YZ planes
* Centered at fuselage center X = 25 m
* Mid-field: R = 50 m (one fuselage length)
Results: Pressure distribution at aircraft surface

Incident field  Scattered field  Total field
Results: Directivity diagrams in the ZX plane ($r =$ one fuselage length)

Not corrected from the distance source-observer

Corrected from the distance source-observer
**Results: Tentative of comparison with CEPRA 19 experiments (ROSAS campaign)**

<table>
<thead>
<tr>
<th></th>
<th>BEM computation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aircraft</strong></td>
<td>ROSAS Aircraft</td>
<td>Airbus aircraft</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>1:1</td>
<td>1:11 (1:16 w.r.t. ROSAS A/C)</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>Monopole (at the engine inlet)</td>
<td>TPS (certainly not spherical)</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>150 Hz (→ 2.4 kHz at 1:16)</td>
<td>6 kHz</td>
</tr>
<tr>
<td><strong>Observer</strong></td>
<td>R = 50 m (one fuselage length)</td>
<td>R = 6 m (two fuselage lengths)</td>
</tr>
</tbody>
</table>

**BEMUSE (ZX plane)**

**10° - band integrated directivity**

**5950 Hz - 0 m/s**
Application of BEMUSE to installation effects studies: Next steps

- Computations on larger grids (110,000 DOF) and at higher frequencies (under progress)

- Grids: - half-grids (aircraft symmetry), under progress
  - more realistic grids (from aircraft CAD files)

- Improve the fan source model, derive a jet noise source model

- Implement and test a convected wave equation (propagation in uniform flow)

- Go to higher frequencies: Develop Fast Multipole Method (FMM) (under progress)
In-house solvers developed at ONERA

Part II : sAbrinA code
sAbrinA
(Solver for Aeroacoustics BRoadband INteractions from Aerodynamics): a 3D multi purposes CFD / CAA code

FLU3M
Industrial CFD software, structured, finite volume, multidomain

E3P
Acoustic propagation via Euler perturbation equations, finite difference, high order schemes, monodomain

PEGASE
Unsteady CFD: LES/DNS, NLDE

- Navier-Stokes or non linear Euler equations, in their conservative form
- Complete or Splitted (mean flow / perturbations) variables
- (Explicit, centered) 2nd order Finite Volumes or 6th order Finite Differences space schemes
- (Explicit) 3rd order or (Implicit) 2nd order time marching scheme
- (Explicit) 10th order filter schemes
- Curvilinear, multi-domains meshes
- Specific (rigid wall, symmetry, periodicity, exit) boundary conditions
CCA tasks: formulation

Conservative Euler equations

\[ \partial_t \mathbf{u} + \nabla \cdot \mathbf{F} = \mathbf{S} \]

Assuming perfect gas state law and neglecting remote massic forces:

\[
\mathbf{u} = \begin{cases}
\rho \\
\rho \mathbf{v} \\
\rho \frac{\mathbf{v}^2}{2} + \frac{1}{\gamma-1} p
\end{cases}
\]

\[
\mathbf{F} = \begin{bmatrix}
\rho \mathbf{v} \\
\rho \mathbf{v} \otimes \mathbf{v} + p \mathbf{I} \\
\left( \frac{\rho \mathbf{v}^2}{2} + \frac{\gamma}{\gamma-1} p \right) \mathbf{v}
\end{bmatrix}
\]

\[ \mathbf{S} = \text{external sources} \]

Mean flow / perturbation splitting:

\[ \mathbf{u} = \mathbf{u}_p + \mathbf{u}_0 \]

Full (non-linearized) conservative Euler equations in perturbation formulation:

\[ \partial_t \mathbf{u}_p + \nabla \cdot \left[ \mathbf{F} \left( \mathbf{u}_p + \mathbf{u}_0 \right) - \mathbf{F} \left( \mathbf{u}_0 \right) \right] = \mathbf{S} \]
Validation of sAbrinA on CAA complex test cases

Harmonic source & uniform flow

Harmonic source, Joukowsky profile

Ducted mode & uniform flow

Aeolian tone noise

Harmonic source & multiple obstacles

Harmonic source & supersonic shear layer

Trailing edge noise

Rotor/stator interaction noise

Downstream fan noise
Application:
2D acoustic scattering from a point source located in the vicinity of a high-lift wing immersed in a **non-uniform flow**

CAA computation strategy
- Build a homogeneous CAA grid
- Interpolate the mean flow from CFD to CAA grid
- Perform 2D CAA computations
  * without mean flow (validation vs. BEM)
  * with non-uniform mean flow

RANS viscous mean flow grid topology and results (0° & 4° incidence)
• Grid adapted up to 30 kHz
• Mean flow interpolation from the CFD to the CAA grid: use of TECPLOT routine
Early computations (in the context of airframe noise characterization)
Monopole located inside the slat cove
(1/2) Propagation in a quiescent medium (no flow), and validation against BEM

FD, 6\textsuperscript{th} order, RK3
\[ f = 8 \text{ kHz} \]
\[ \Delta t = 5 \times 10^{-7} \text{ s} \ (= \frac{T_{\text{source}}}{250}), \quad \text{CFL} = 0.8 \]

Source at 8 kHz

\[ \frac{1}{2} \text{Propagation in a quiescent medium (no flow), and validation against BEM} \]
Early computations (in the context of airframe noise characterization)
Monopole located inside the slat cove
(2/2) Propagation through the non-uniform (RANS) mean flow

\[ p_{RMS}(\theta) \sqrt{r} = f(\theta) \]

(WITHOUT MEAN FLOW) (WITH NON-UNIFORM MEAN FLOW) (WITH AND WITHOUT NON-UNIFORM MEAN FLOW)

(R. Guénanff, E. Manoha)
Application in the context of installation effects
Monopole located above the suction side
Propagation in the non-uniform (RANS) mean flow

Source
Chord / $\lambda = 54$

$f = 21 \text{ kHz}$

$f = 16 \text{ kHz}$

sAbrinA code

PIANO code (Roland EWERT, DLR)
ROSAS benchmark (TCD / DLR / IST)

(R. Guénanff)
Application of sAbrina to installation effects studies: Next steps

- Develop innovative techniques to facilitate complex meshes design (2D, 3D)
  - Non-conformal interface (R. Guénanff PhD thesis)
  - Curvilinear/Cartesian interface (G. Desquesnes PhD thesis)

- Study installation effects on 3D realistic aircraft geometry

- Extend the sAbrina capabilities to the treatment of other installation effect configurations
Other Installation effects study with sAbrinA

Numerical Simulation of the Downstream Fan Noise of a Coaxial Jet with a Shielding Surface

by Stéphane REDONNET, Eric MANOHA (ONERA)
and Owen KENNING (QinetiQ)

Friday 12 November, 11:25

Coming soon…