Hybrid LES/CAA Method for Aeroacoustic Applications

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Coming Up

Introduction

Hybrid Approach
  - Fluid Mechanics
  - Aeroacoustics

Results
  - Airframe Noise
  - Jet Noise

Conclusions
Introduction

1960s    engine noise the dominant aircraft noise source
1970s    high bypass turbofan ⇒ 10 db reduction
today    airframe noise equally important or even dominant
         over engine noise

Commercial Impact
aerial industry (Europe): 380000 (direct), 650000 (indirect)
aircraft industry (US): 680000 (direct)  
prediction growth: 13000 new aircraft up to 2013, i.e., $ 800·109

European Transport Policy for 2010
... Unless ambitious new noise standards are rapidly introduced  
    internationally to prevent further degradation of the plight of  
    local residents, there is a risk that airports could be deprived  
    of any possibility of growth.
Noise Sources During Landing

- Slat Horn
- Slat
- Wing Tip
- Flap Side Edge
- Landing Gear
- Cavities
main airframe noise sources on a high lift wing configuration
DNS Resolution Requirements

L: characteristic geometric length scale
l: integral length scale
\( \eta \): Kolmogorov length scale
\( \lambda \): sound wave length

3D simulation (isotropic turbulence): \( N \sim (L/\eta)^3 \)

\[
\begin{align*}
L & \sim l \\
l/\eta & : o(Re_t^{3/4}) \\
N & \sim Re_t^{9/4}
\end{align*}
\]

\( L \sim \lambda; \ \lambda \sim l/M_t \)

\( \Rightarrow \) resolution: turbulent near field plus acoustic far field

\[
N \sim M_t^{-3}Re_t^{9/4}
\]
Fluid Mechanical and Acoustical Scales

\[ St = \frac{\omega L}{u} : o(L/\lambda_\omega) \quad \text{nondimensional vorticity length} \]

\[ He = \frac{\omega L}{c} = Ma \cdot St : o(L/\lambda) \quad \text{nondimensional acoustic length} \]

\[ \lambda: \frac{L}{He} \sim Ma^{-1} \frac{L}{St} : Ma^{-1} \lambda_\omega \]

\( \Rightarrow \) acoustics and fluid mechanics possess different requirements

- grid resolution
- domain size
- time step
Schematic to Compute Turbulence Related Noise

Flow Problem

Direct Approach
- DNS
- LES

Hybrid Approach
- CFD
  1. step
  res. of fluid scales input for source terms
- Sound Propagation
  2. step
  acoustical scales

Acoustics

resolution of all scales
Computation of Far Field Noise

Extrapolation of acoustic data into the far field from the inhomogeneous acoustic domain surface $S_a$ applying e.g. FW-H
APE form

keep the LHS of APE-1 and insert remaining terms in the RHS objective: easy to compute source terms in compressible flows governing equations

\[
\begin{align*}
\frac{\partial \rho'}{\partial t} + \nabla \cdot (\bar{\rho} u' + \rho' \bar{u} + \rho' u' - \bar{\rho} u') &= 0 \\
\frac{\partial u'}{\partial t} + (\bar{u} \cdot \nabla) u' + (u' \cdot \nabla) \bar{u} + \nabla \left( \frac{p'}{\bar{\rho}} \right) &= f_{nonlinear} + f
\end{align*}
\]

with \( f_{nonlinear} = -\left( (u' \cdot \nabla) u' - \frac{\nabla \cdot \tau}{\rho} \right) \) and \( f = T' \nabla s - s' \nabla \bar{T} \),

using \((\bar{u} \cdot \nabla) u' + (u' \cdot \nabla) \bar{u} = \nabla (\bar{u} \cdot u') + \omega \times \bar{u} + \bar{\omega} \times u'\)

yields the APE-4 system

\[
\begin{align*}
\frac{\partial p'}{\partial t} + c^2 \nabla \cdot \left( \bar{\rho} u' + \bar{u} \frac{p'}{c^2} \right) &= c^2 q_c \\
\frac{\partial u'}{\partial t} + \nabla (\bar{u} \cdot u') + \nabla \left( \frac{p'}{\bar{\rho}} \right) &= q_m
\end{align*}
\]

with \( q_c = -\nabla \cdot (\rho' u')' + \frac{\bar{\rho} \bar{D}s'}{c_p \bar{D}t} \)

\( q_m = - (\omega \times u)' + T' \nabla s - s' \nabla \bar{T} - \left( \nabla (u')^2 \right)' + \left( \nabla \cdot \frac{\tau}{\rho} \right)' \)
Governig Equations

Navier-Stokes Equations

Time dependent, 3D flow, compressible fluid, general coordinates

\[ J \frac{\partial Q}{\partial t} + \frac{\partial H_\alpha}{\partial \xi_\alpha} = 0 \]

\[ H_\alpha = F_\alpha^I - F_\alpha^V = J \left( \begin{array}{c} \rho U_\alpha \\ \rho u_\beta U_\alpha + p \frac{\partial \xi_\alpha}{\partial x_\beta} \\ U_\alpha (\rho E + p) \end{array} \right) + \frac{J}{Re} \left( \begin{array}{c} 0 \\ \sigma_{\beta \varphi} \frac{\partial \xi_\alpha}{\partial x_\varphi} \\ (u_\beta \sigma_{\beta \varphi} + q_\varphi) \frac{\partial \xi_\alpha}{\partial x_\varphi} \end{array} \right) \]

\[ Q = [\rho, \rho u_\beta, \rho E]^T \quad \sigma_{\alpha \beta} = -2 \mu (S_{\alpha \beta} - \frac{1}{3} S_{\varphi \varphi} \delta_{\alpha \beta}) \]

\[ S_{\alpha \beta} = \frac{1}{2} \left( \frac{\partial u_\alpha}{\partial \xi_\varphi} \frac{\partial \xi_\varphi}{\partial x_\alpha} + \frac{\partial u_\beta}{\partial \xi_\varphi} \frac{\partial \xi_\varphi}{\partial x_\beta} \right) \quad q_\alpha = -\frac{k}{Pr(\gamma - 1)} \frac{\partial T}{\partial x_\alpha} \]
Time Integration, Discretization

**Integration:** 5-step Runge-Kutta Method

**Discretization:**
- Viscous terms: central differences
- Inviscid terms: AUSM

\[ F^I_\alpha = F^c_\alpha + F^p_\alpha = \frac{U_\alpha}{c} \begin{pmatrix} \frac{\rho c}{c(E + p/\rho)} \\ \frac{\rho c u_\beta}{c(\xi)} \end{pmatrix} + \begin{pmatrix} 0 \\ p\xi_\alpha/\partial x_\beta \end{pmatrix} \]

\[ F^c_\alpha = \frac{1}{2} \left[ \frac{Ma^+_{\alpha} + Ma^-_{\alpha}}{2} (f^{c+}_{\alpha} + f^{c-}_{\alpha}) + \frac{|Ma^+_{\alpha} + Ma^-_{\alpha}|}{2} (f^{c+}_{\alpha} - f^{c-}_{\alpha}) \right]_{i+\frac{1}{2}, j, k} \]

\[ p^\pm = p^\pm \left( \frac{1}{2} \pm \chi Ma^\pm_{\alpha} \right) \]
Mesh

mesh for a slat-main-airfoil-flap configuration

grid points:
• streamwise: 2000
• normal: 350
• spanwise: 65
Flow Field

\[ \lambda_2 \text{ contours} \ (Ma=0.17, \ Re_{cc}=1.6E6, \ \alpha=4^\circ) \]
LES of a 3-element high-lift system

- flow data: \( \text{Ma}=0.17 \), \( \text{Re}_{cc}=1.6\times10^6 \), \( \alpha=4^\circ \), 
  \( \alpha_{\text{slat}}=22^\circ \), \( \alpha_{\text{flap}}=38^\circ \)

- grid points in one x-y plane: 700,000
- total number of gridpoints: 45,000,000
  (divided in 32 blocks)

- max. cpu performance: 6.967 GFlops
- vectorization rate: 97 %
- used memory storage: 55 GByte

Acoustic analysis of the results

- resolved frequency range: 0.4 kHz to 7 kHz
  → data of 525 time levels is needed
  → total storage required: 950 GByte
Y-Component and Trailing Edge Sound

Y-component

Pressure distribution
Heated Coaxial Jet

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<th>Parameter</th>
<th>Value</th>
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<td>area ratio</td>
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<tr>
<td>density ratio</td>
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</tr>
</tbody>
</table>
Heated Coaxial Jet

averaged flow field

- rapid heat exchange after break-up of laminar core
- density gradients vanish after short initial region
Heated Coaxial Jet

\( \lambda_2 \) contours as a function of time
Lamb Vector, Coaxial Jet

Acoustic Simulation (3D):

- Lamb vector:
  \[ \hat{\mathbf{L}}' = (L'_x, L'_y, L'_z) = (\omega \times \mathbf{u})' \]
Heat and Entropy Sources

Acoustic Simulation (3D):

- Heat release and entropy fluctuations:

\[ (T' \nabla \bar{S} - S' \nabla \bar{T})_x \]

\[ (T' \nabla \bar{S} - S' \nabla \bar{T})_y \]

\[ (T' \nabla \bar{S} - S' \nabla \bar{T})_z \]
Acoustics of the Coaxial Jet

inner: Lamb vector distr.
outer: pert. pressure contours
Conclusions

• why hybrid methods was discussed
• acoustic perturbation equations (APE) were introduced
• unlike LEE APE is stable for arbitrary mean flow
• APE analysis evidences dominant noise sources
• hybrid approach (LEE/APE) an efficient means to tackle CAA challenges