A quasi-potential flow formulation for predicting acoustic shielding by a lifting body with finite element methods

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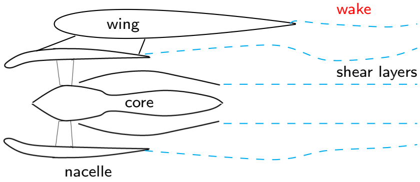
Aircraft external noise radiation

Motivation:

- Acoustic radiation in large-scale unbounded domains still computationally challenging
- Shear layer refraction is important for estimating aircraft acoustic installation effects
- Wave refraction by shear layers and wake is not included in full potential formulations



Outline

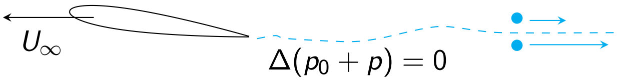
- Free shear layer for a potential formulation
- Lift generation in quasi-potential flows
- Wave refraction by quasi-potential flows
- Test case: wave scattering by a NACA0012
- Concluding remarks

Modeling free shear layers on potential flows

- Flow non-potential around bodies and on shear layers
- Shear layer with no thickness

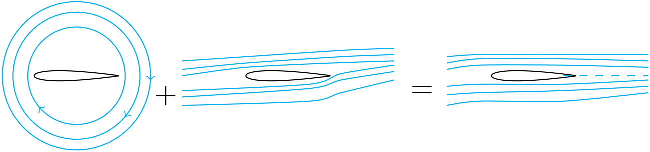
Physical model

- Continuity of pressure across the shear layer
- Continuity of particle velocity normal to the shear layer
- Discontinuity of particle velocity tangent to the shear layer



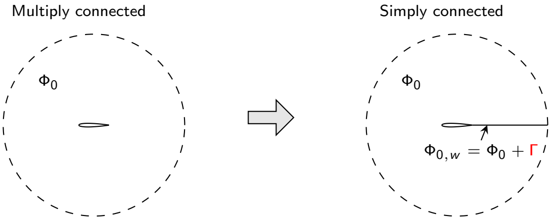
Lift generation on quasi-potential flows

- Circulatory solution is non-potential
- Superposition of circulatory and potential solution



Generation of the circulatory solution:

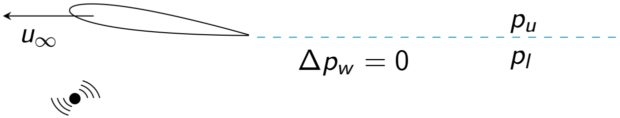
- Circulation Γ as discontinuity solution at the shear layer



Simplified shear layer model for wave refraction

- Shear layer model: linear with fix extent
- Continuity of normal particle displacement satisfied by assuming an incompressible mean flow
- Continuity of acoustic pressure across the shear layer explicitly imposed

$$\Delta p_w = p_u - p_l = 0 \tag{1}$$



Numerical solution

1) Steady incompressible potential mean flow

Finite Element Method (FEM):

$$\nabla^2 \Phi_0 = 0$$

$\leftarrow$ Shear layer: $\Phi_{0,w} = \Phi_0 + \Gamma$

2) Wave propagation

FEM:

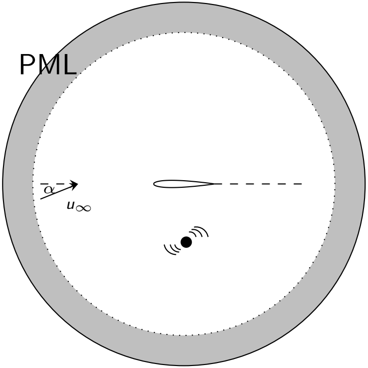
$$\frac{\partial}{\partial t}\left(\frac{D_0\phi}{Dt}\right) - \nabla \cdot \left(c_\infty^2 \nabla\phi - \frac{D_0\phi}{Dt}\mathbf{u}_0\right) = 0$$

$\leftarrow$ Shear layer: $\Delta p_w = 0$

with $p = -\rho_\infty \frac{D_0\phi}{Dt}$ and $\frac{D_0\phi}{Dt} = \frac{\partial\phi}{\partial t} + \mathbf{u}_0 \cdot \nabla\phi$

Wave propagation solved in the frequency domain (steady state).

Test case: scattering by a NACA 0012



PML: Perfectly Matched Layer

α : angle of attack

u_∞ : uniform flow velocity

- Mean flow: shear layer extent tuned to satisfy the Kutta condition
- Wave propagation: Kutta condition forced at the trailing edge

Predominance of source amplification due to uniform flow effects

Effect of the mean flow Mach number

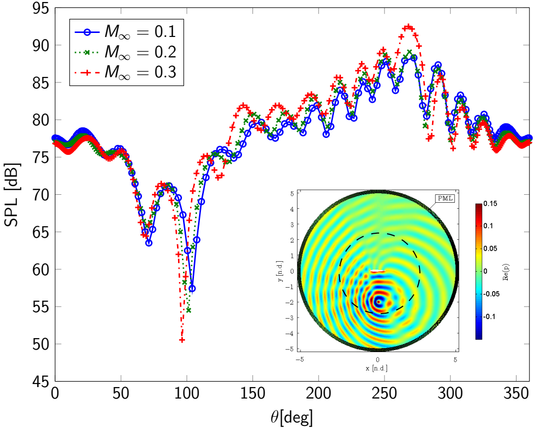


Figure: Sound pressure level. $He = kL = 9.24$, $R_{fp} = 2.5L$, $\alpha = 4^\circ$. Scattering by a NACA 0012 from a monopole source with a non-uniform mean flow.

Phase shift of the shielding effect due to a change in incidence

Effect of the angle of attack

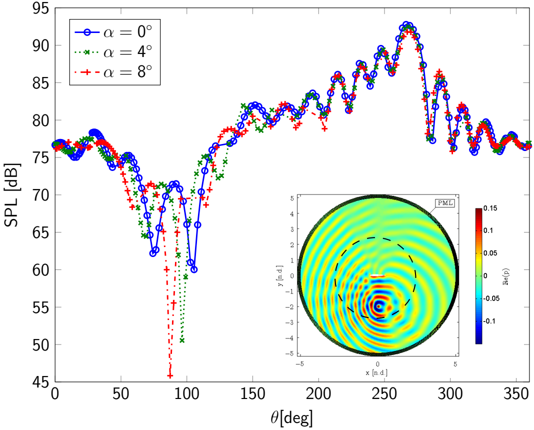


Figure: Sound pressure level. $He = kL = 9.24$, $R_{fp} = 2.5L$, $M_\infty = 0.3$. Scattering by a NACA 0012 from a monopole source with a non-uniform mean flow.

Concluding remarks

Model

- Lift generation and wave refraction by shear layers modeled with a limited increase in computational resources: quasi-potential formulation

  contribution:

  - A validated solution for mean flows was integrated with an existing shear layer model for wave refraction

Physical insight

- Wave propagation around lifting bodies:

  - noise amplification is mainly due to uniform flow convection of sound sources
  - Incidence affects mainly the extent of the shielded area

Thank you.

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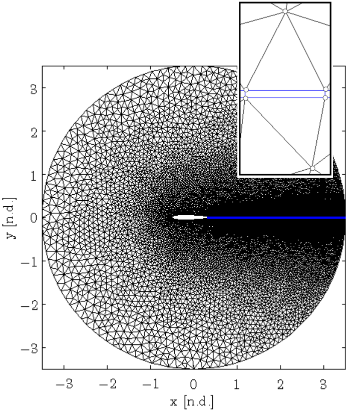
Weak formulation and FE model

Mean flow:

$$\int_{V-V_w} \nabla W \cdot \nabla \Phi_0 dV + \int_{V_w} \nabla W \cdot \nabla \Phi_{0,w} dV = \int_{\partial V} W(\nabla \Phi_0 \cdot \mathbf{n}) dS \qquad (2)$$

- $\Phi_{0,w} = \Phi_0 + \Gamma$
- Polynomial interpolation:
  $\Phi_0 = \sum_{m=1}^{M} N_m \Phi_{0_m}$
  $\Phi_{0,w} = \sum_{m=1}^{M} N_m \Phi_{0_m} + N_g \Gamma$
- Linear FEM with
  $0.4L \leq L_e \leq 5 \cdot 10^{-3} L$



Weak formulation and FE model

Wave propagation:

$$\int_V \rho_0 \nabla \Upsilon^* \cdot \nabla \tilde{\phi} dV - \int_V \frac{\rho_0}{c_0^2} (\mathbf{u}_0 \cdot \nabla \Upsilon^*)(\mathbf{u}_0 \cdot \nabla \tilde{\phi}) dV + i\omega \int_V \frac{\rho_0}{c_0^2} [\tilde{\phi}(\mathbf{u}_0 \cdot \nabla \Upsilon^*) - \Upsilon^* (\mathbf{u}_0 \cdot \nabla \tilde{\phi})] dV$$
$$- \omega^2 \int_V \frac{\rho_0}{c_0^2} \Upsilon^* \tilde{\phi} dV = \int_{\partial V} \frac{\rho_0}{c_0^2} [c_0^2 \Upsilon^* \nabla \tilde{\phi} - \mathbf{u}_0 \Upsilon^* (\mathbf{u}_0 \cdot \nabla \tilde{\phi}) - i\omega \mathbf{u}_0 \Upsilon^* \tilde{\phi}] \cdot \mathbf{n} dS + \mu \int_{V_W} \Upsilon^* \Delta p dV \quad (3)$$

- Penalty factor $\mu = 10^5$
- Polynomial interpolation:
  $\tilde{\phi} = \sum_{m=1}^{M} N_m \phi_m$
  $p = -\rho_\infty (i\omega \tilde{\phi} + \mathbf{u}_0 \nabla \tilde{\phi})$
- Linear FEM with 15 Dof/λ