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CONTINUOUS ADJOINT–BASED AEROACOUSTIC SHAPE OPTIMIZATION OF AN AERO–ENGINE INTAKE

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EUROGEN 2021

28-30 June 2021, Athens, Greece
14th International Conference on Evolutionary and Deterministic Methods for Design, Optimization and Control

Outline

- The Hybrid Noise Prediction Tool
- Continuous Adjoint Formulation
- Verification, Comparison to an Analytical Solution
- The Aero-Engine case
- Conclusion

The Hybrid Noise Prediction Tool

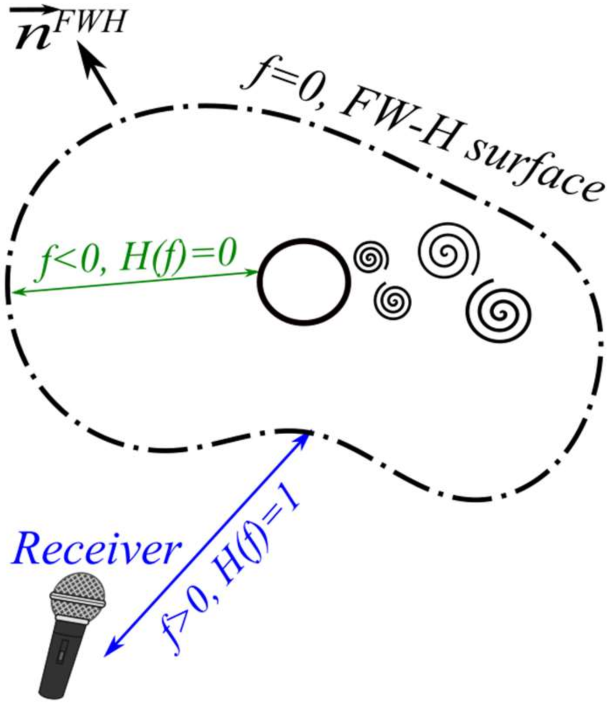
- **Flow solution using in-house GPU-enabled software, PUMA.**
  - **RANS in a relative frame of reference (MRF).**
- **Acoustic propagation based on the Ffowcs Williams and Hawkings (FW-H) Analogy.**
  - **The FW-H integral in the frequency domain:**

$$H(f)\hat{p}'(\vec{x}_r,\omega) = -\int_{f=0} \mathrm{i}\omega\hat{\mathcal{Q}}(\vec{x}_s,\omega)\hat{G}(\vec{x}_r,\vec{x}_s,\omega)ds - \int_{f=0} \hat{\mathcal{F}}_i(\vec{x}_s,\omega)\frac{\partial\hat{G}(\vec{x}_r,\vec{x}_s,\omega)}{\partial x_{s_i}}ds$$

$$\mathcal{Q}(\vec{x},t) = (\rho u_i - \rho_\infty u_{\infty i})\, n_i^{\mathrm{FWH}}$$

$$\mathcal{F}_i(\vec{x},t) = \left[\rho\,(u_i - 2u_{\infty i})\,u_j + \rho_\infty u_{\infty i}u_{\infty j} + p\delta_{ij} - \tau_{ij}\right] n_j^{\mathrm{FWH}}$$

$$\hat{G}(\vec{x}_r,\vec{x}_s,\omega) = -\frac{\exp(-\mathrm{i}kr^+)}{4\pi r^*} \qquad r^+ = \frac{1}{\beta^2}(r^* - \vec{M}\cdot\vec{r}), \quad r^* = \sqrt{(\vec{M}\cdot\vec{r})^2 + |\vec{r}|^2\beta^2}, \quad \vec{r} = \vec{x}_r - \vec{x}_s, \quad \vec{M} = \frac{\vec{u}_\infty}{c_\infty}$$



Continuous Adjoint Formulation

The objective function is the total energy contained in the spectrum of the sound pressure:

$$J = \frac{1}{N_r}\sum_{a=1}^{N_r}\int_{\omega}|\hat{p}'(\vec{x}_{r_a},\omega)|\mathrm{d}\omega \qquad |\hat{p}'| = \sqrt{\hat{p}'^2_{\mathrm{Re}} + \hat{p}'^2_{\mathrm{Im}}}$$

Design variables b_i **are updated with a steepest descent algorithm** $b_i^{\mathrm{new}} = b_i^{\mathrm{old}} - \eta\frac{\delta J}{\delta b_i}$

Lagrangian: $J_{aug} = J + \int_{T_s}\int_{\Omega}\Psi_n R_n \mathrm{d}\Omega\mathrm{d}t$ $\xrightarrow{\text{Differentiation w.r.t. } b_i}$ $\frac{\delta J_{Aug}}{\delta b_i} = \frac{\delta J}{\delta b_i} + \int_{T_s}\int_{\Omega}\Psi_n\frac{\delta R_n}{\delta b_i}\mathrm{d}\Omega\mathrm{d}t$

$$\frac{\delta J}{\delta b_i} = \int_{T_s}\int_{\Omega} FAE_n\frac{\delta U_n}{\delta b_i}\mathrm{d}\Omega\mathrm{d}t + \int_{T_s}\int_{S_w} ABC_n\frac{\delta U_n}{\delta b_i}\mathrm{d}S\mathrm{d}t + \int_{T_s}\int_{\Omega} SD^{\Omega}_{ml}\frac{\partial}{\partial x_m}\left(\frac{\delta x_l}{\delta b_i}\right)\mathrm{d}\Omega\mathrm{d}t + \int_{T_s}\int_{\Omega} SD^{S}\frac{\delta x_l}{\delta b_i}\mathrm{d}S\mathrm{d}t$$

Field Adjoint Equations

Adjoint Boundary Conditions

Sensitivity Derivative

Sensitivity Derivative

Field Adjoint Equations & Sensitivity Derivatives

FAE: $$-\frac{\partial \Psi_m}{\partial t} - \frac{\partial f_{nk}^{inv}}{\partial U_m}\frac{\partial \Psi_n}{\partial x_k} - \left(\frac{\partial \tau_{qk}^{adj}}{\partial x_k} - \frac{\partial \Psi_5}{\partial x_k}\tau_{kq}\right)\frac{\partial u_q}{\partial U_m} - \frac{\partial q_k^{adj}}{\partial x_k}\frac{\partial T}{\partial U_m} - \frac{\partial J}{\partial U_m}\delta(f) = 0$$

ABC: $\Psi_{m+1} n_m = 0$ **and** $q_k^{adj} n_k = 0$ **on solid surfaces.**

Sensitivity derivatives:

$$\frac{\delta J}{\delta b_e} = -\int_{T_s}\int_{\Omega}\left[\Psi_n\left(\frac{\partial f_{nk}^{inv}}{\partial x_i} - \frac{\partial f_{nk}^{vis}}{\partial x_i}\right) + \tau_{mk}^{adj}\frac{\partial u_m}{\partial x_i} + q_k^{adj}\frac{\partial T}{\partial x_i}\right]\frac{\partial}{\partial x_k}\left(\frac{\delta x_i}{\delta b_e}\right)d\Omega dt$$
$$+ \int_{T_s}\int_{S}\left(p\Psi_{k+1} - \Psi_n f_{nk}^{inv} + \Psi_5 q_k + \Psi_5 u_m \tau_{mk}\right)\frac{\delta n_k}{\delta b_e} dS dt$$

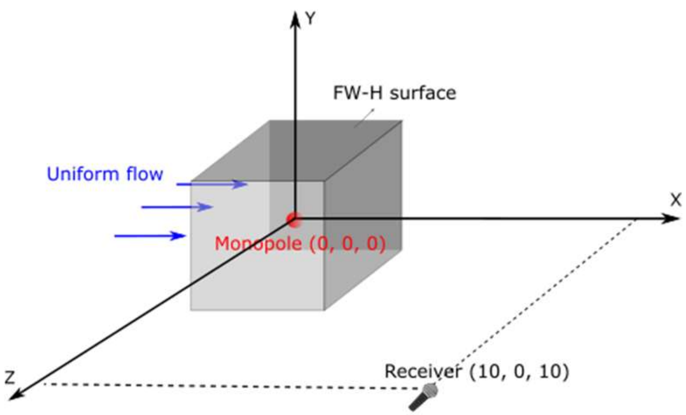
$$\tau_{mk}^{adj} = (\mu + \mu_t)\left[\frac{\partial \Psi_{m+1}}{\partial x_k} + \frac{\partial \Psi_{k+1}}{\partial x_m} + \frac{\partial \Psi_5}{\partial x_m}u_k + \frac{\partial \Psi_5}{\partial x_k}u_m - \frac{2}{3}\delta_{mk}\left(\frac{\partial \Psi_{l+1}}{\partial x_l} + \frac{\partial \Psi_5}{\partial x_l}u_l\right)\right]$$
$$q_k^{adj} = C_p\left(\frac{\mu}{\mathrm{Pr}} + \frac{\mu_t}{\mathrm{Pr_t}}\right)\frac{\partial \Psi_5}{\partial x_k}$$

Verification w.r.t. Analytical Solution

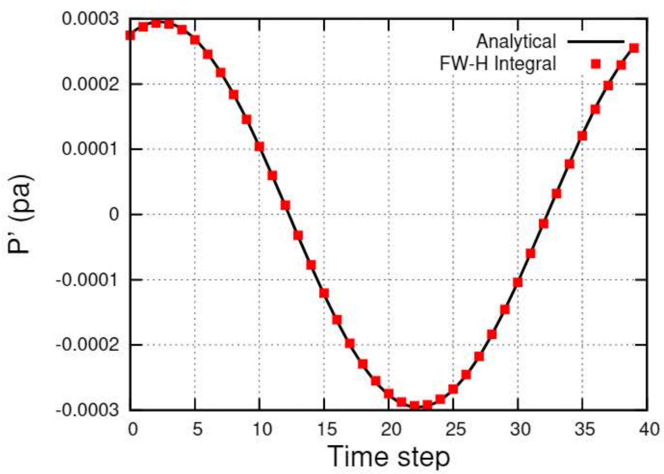
Perturbation field from a monopole sound source in flow $p' = -\rho_0(\frac{\partial\phi}{\partial t} + v_{\infty 1}\frac{\partial\phi}{\partial x}),\ v' = \nabla\phi$ **and** $\rho' = p'/c_0{}^2$

Velocity potential of monopole in flow for 3D $\phi(\vec{x}_r, \vec{x}_s, \omega) = A\exp(\mathrm{i}\omega t)\frac{\exp(-\mathrm{i}kr^+)}{4\pi r^*}$

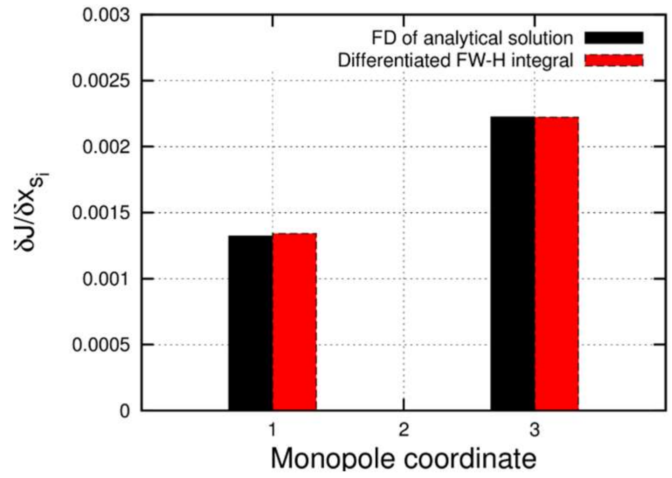
Verification of the FW-H implementation and differentiation



Pressure fluctuation at receiver location



Derivatives w.r.t. monopole coordinates



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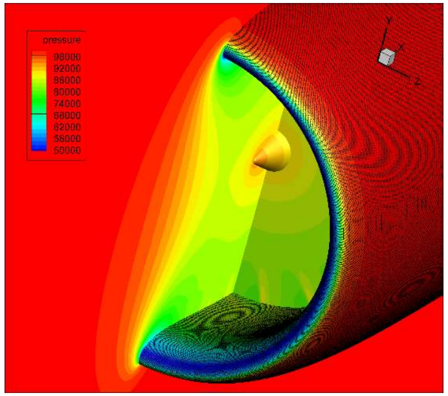
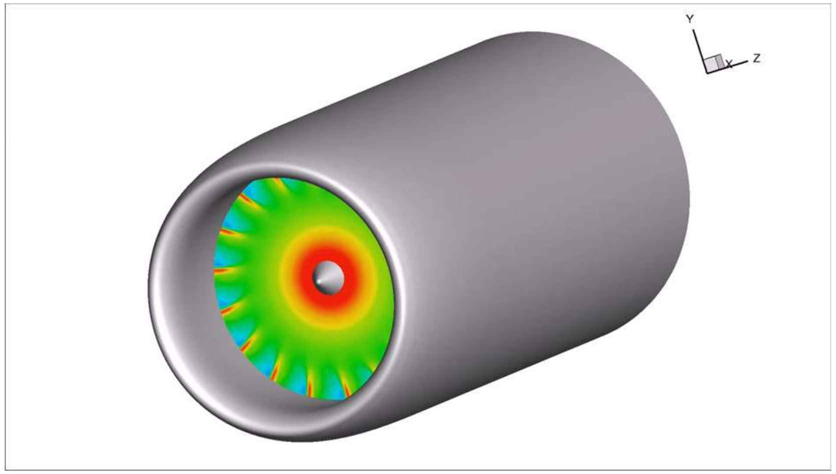
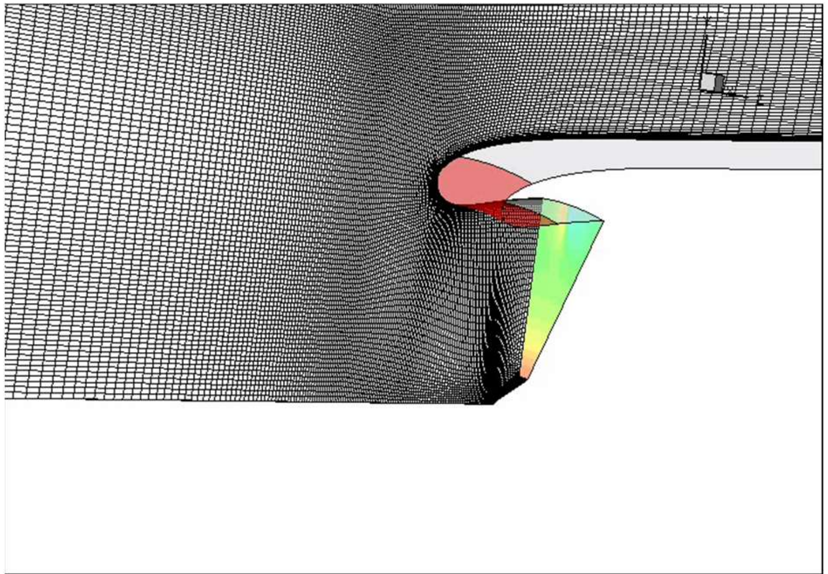
The Aero-Engine Intake



- Generic intake geometry (scaled to match the Vital fan) by RR.
- Pressure distribution on the fan inlet provided
  by ISVR of the University of Southampton.
- S-A Turbulence model
- Single blade passage Mesh ~ 3.7M nodes on 100 meridional planes
- ~16 K nodes on FWH surface
- Flow and adjoint solved in a rotating frame of reference (steady).

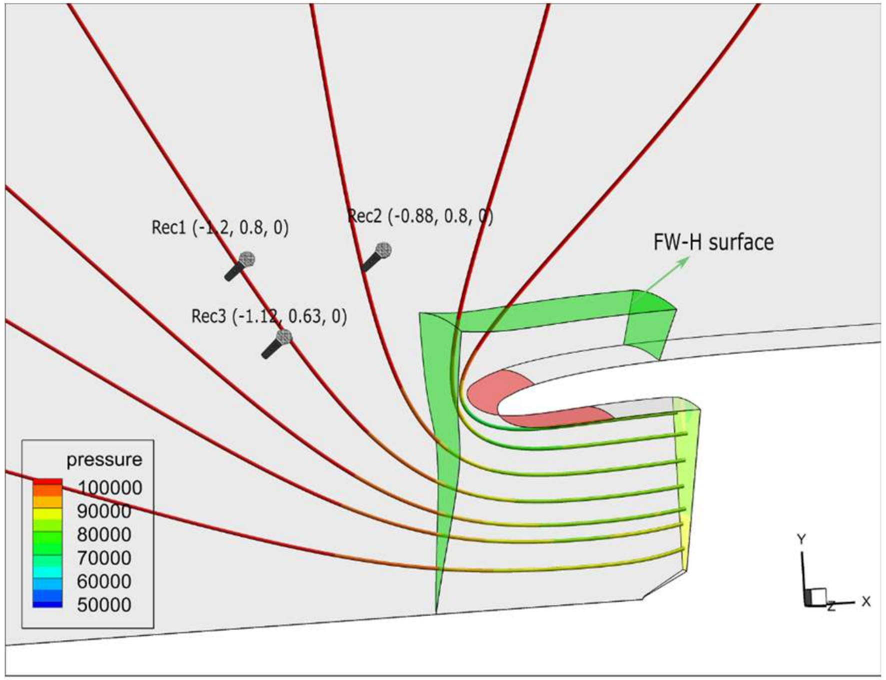


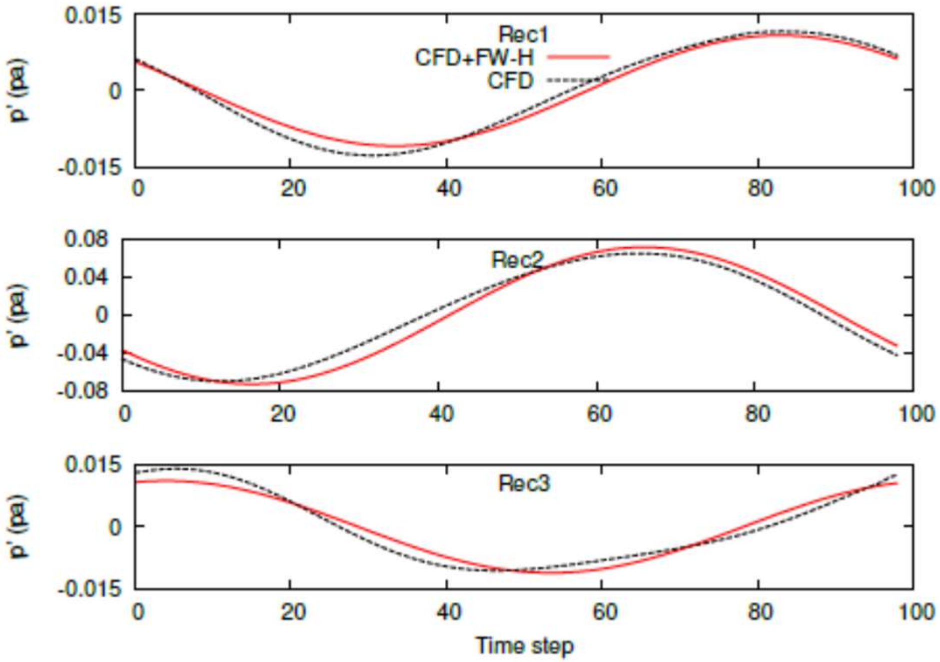


Optimization of a Turbofan Intake

Comparison between hybrid method and (U)RANS

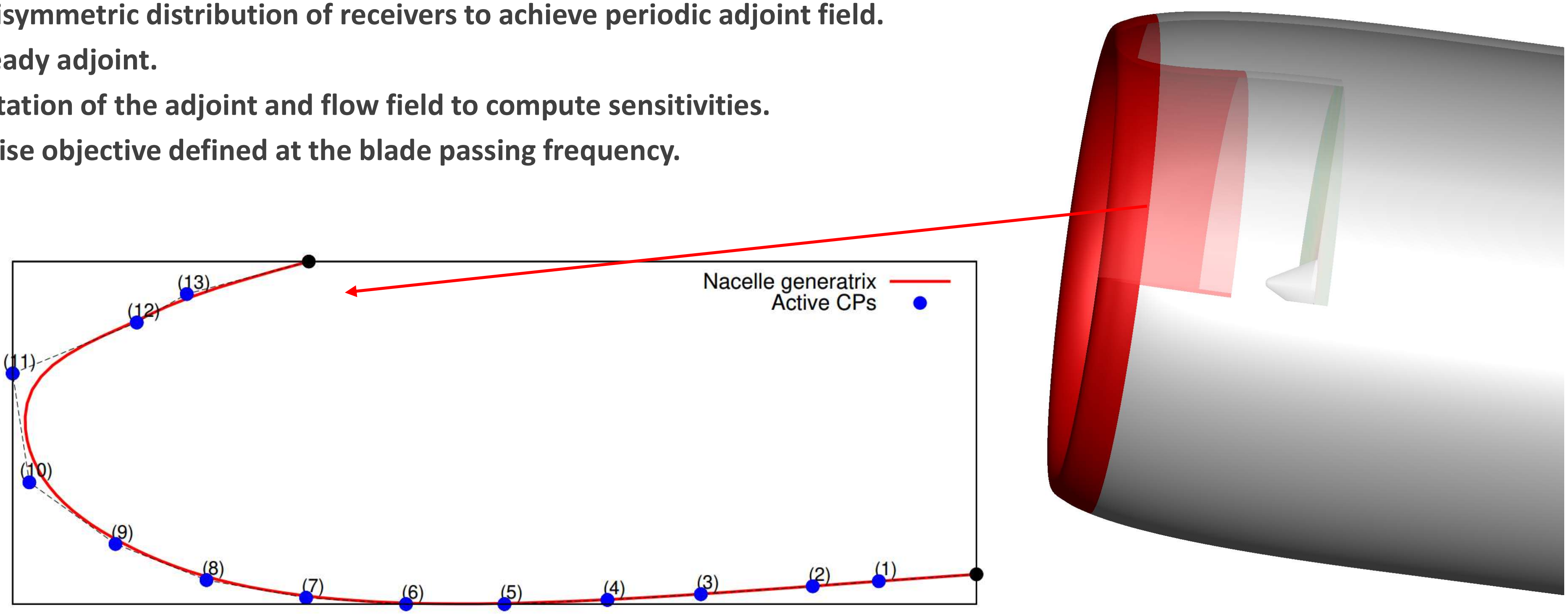
- **Unsteady data on the FW-H surface extracted by performing rotation.**



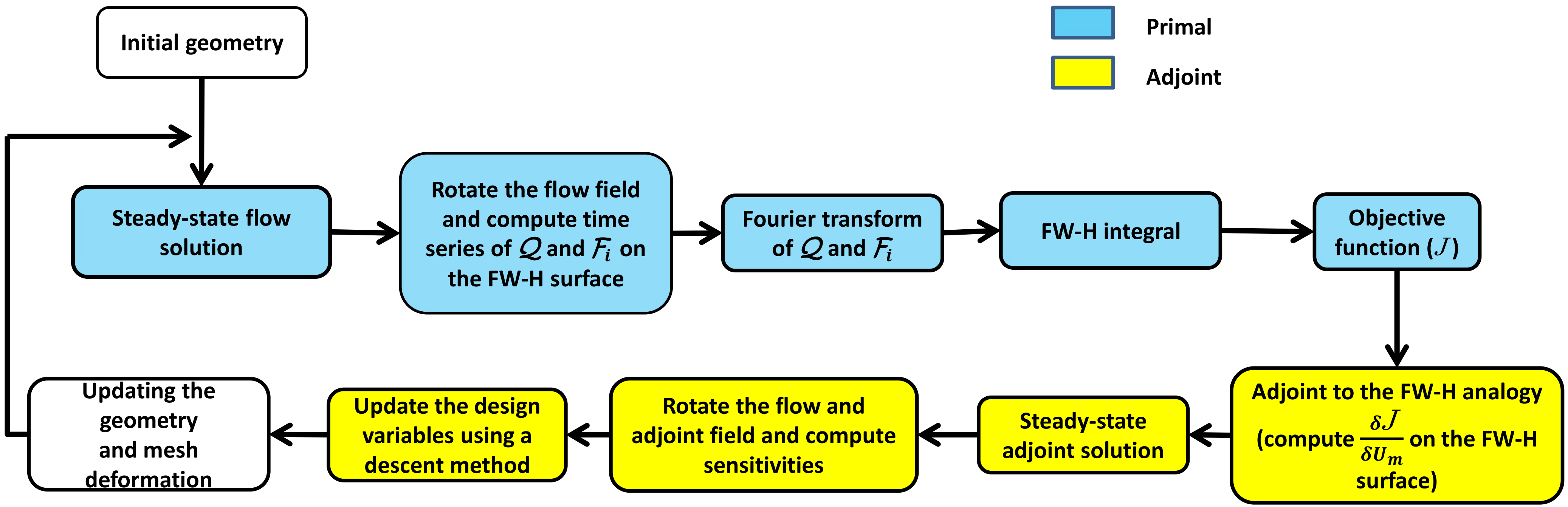


Optimization of a Turbofan Intake

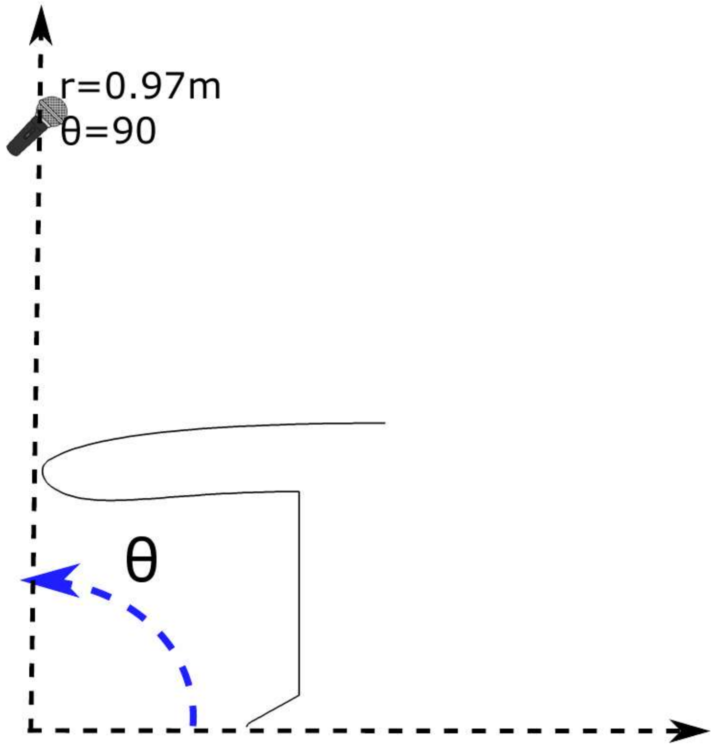
- Generatrix parameterized using 15 control points.
- 13 are allowed to vary in the axial and radial direction; 26 DVs.
- Axisymmetric distribution of receivers to achieve periodic adjoint field.
- Steady adjoint.
- Rotation of the adjoint and flow field to compute sensitivities.
- Noise objective defined at the blade passing frequency.

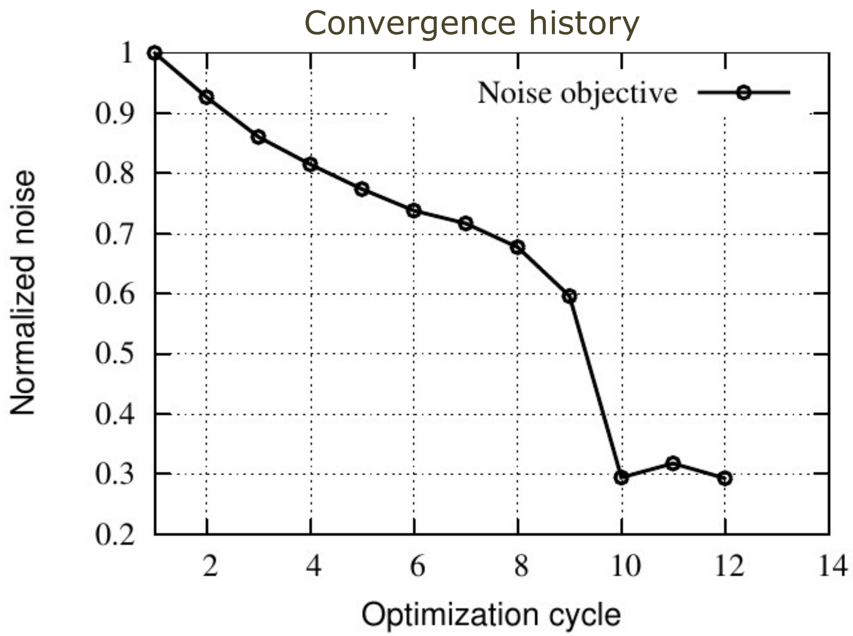


Aeroacoustic Shape Optimization Flowchart



Optimization for a Single Circumferential Row of Receivers

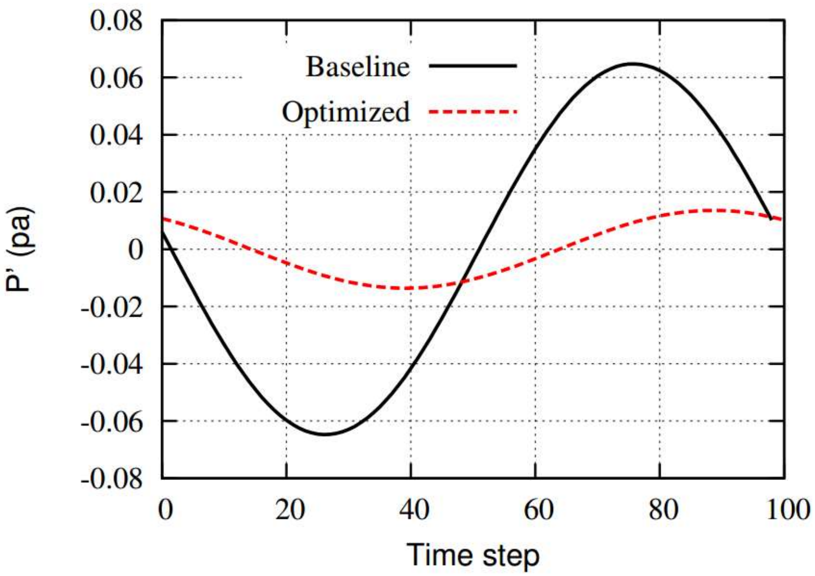


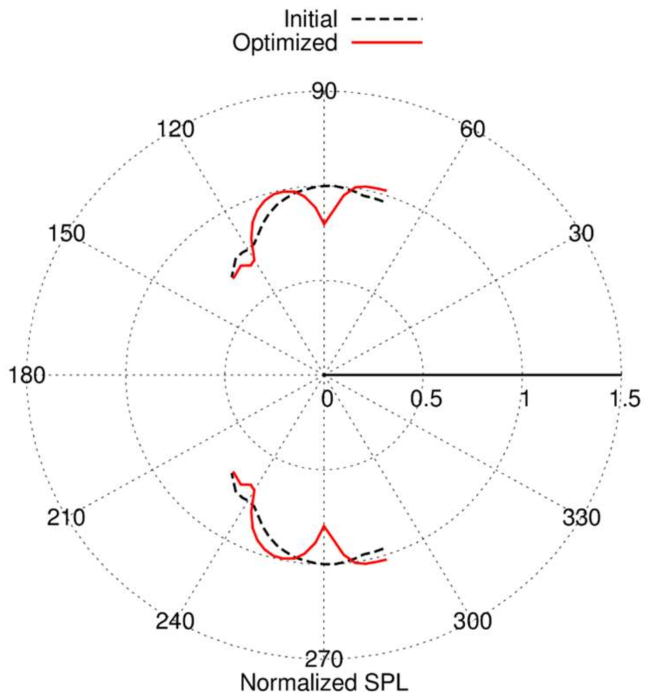


~70% reduction in the noise objective

Optimization for a Single Circumferential Row of Receivers

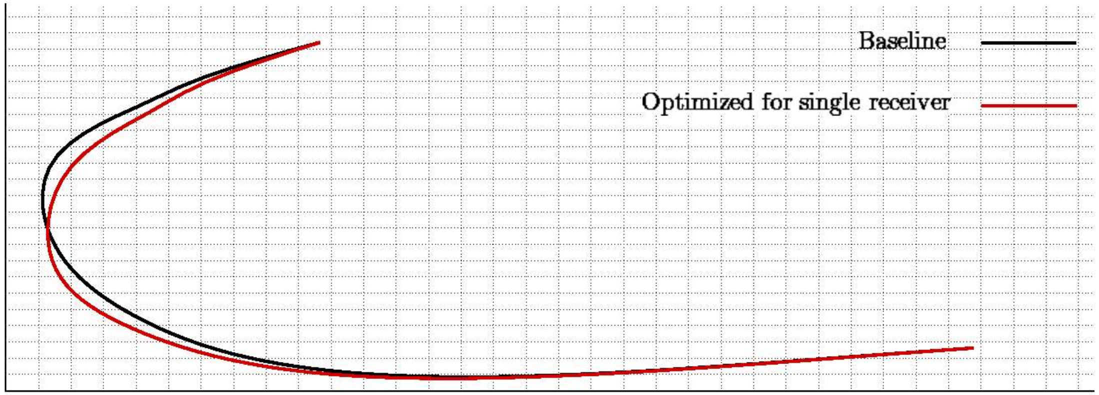
- Reduced amplitude of sound pressure.
- Slightly worse aerodynamic performance. ~0.6% increase in Pt loss.
- Directional noise reduction.

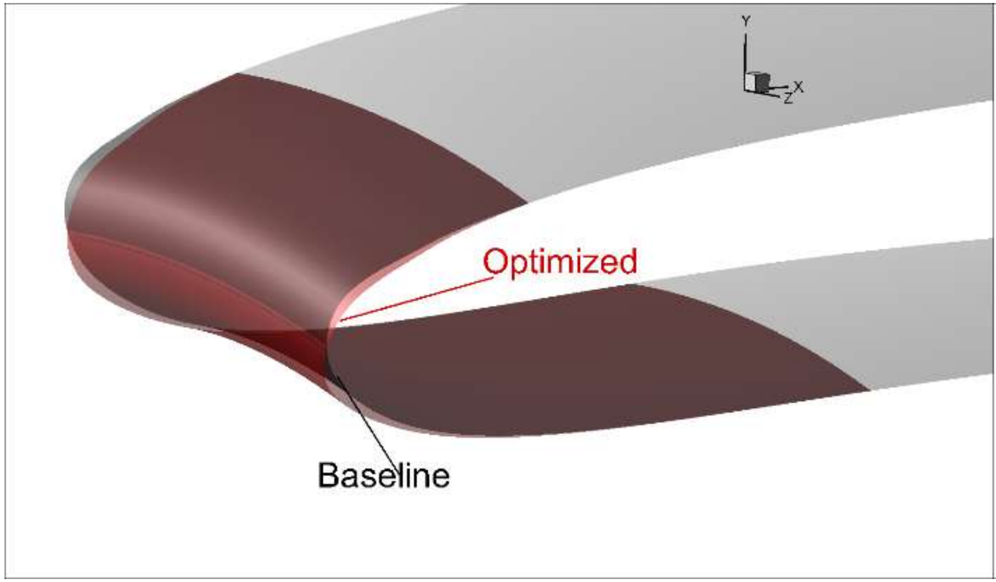


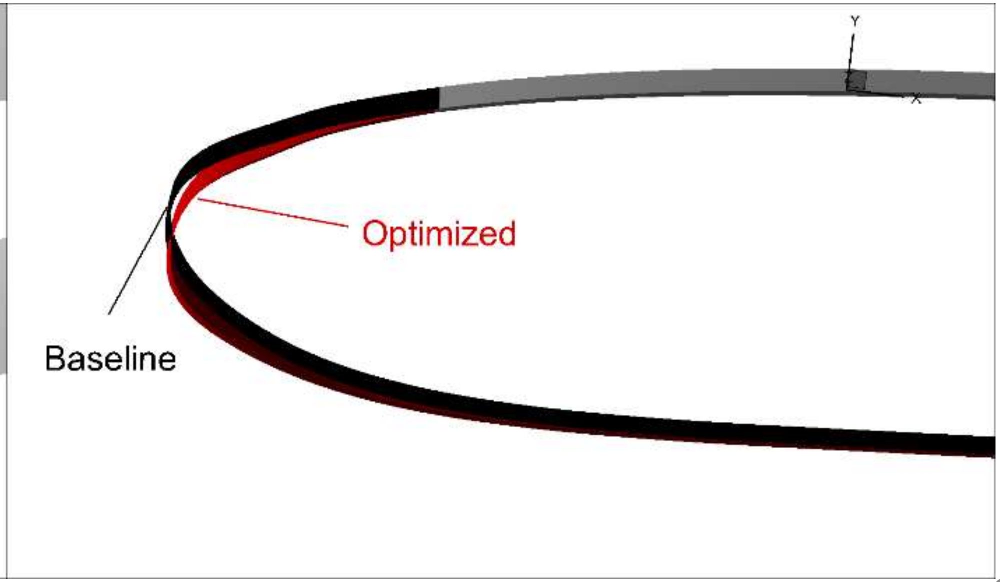


Max reduction ~10 dB

Optimization for a Single Circumferential Row of Receivers







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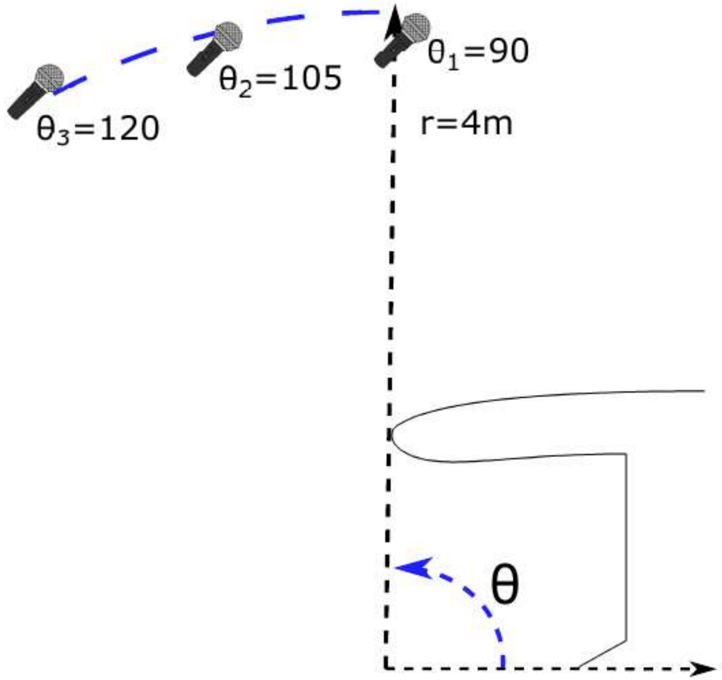
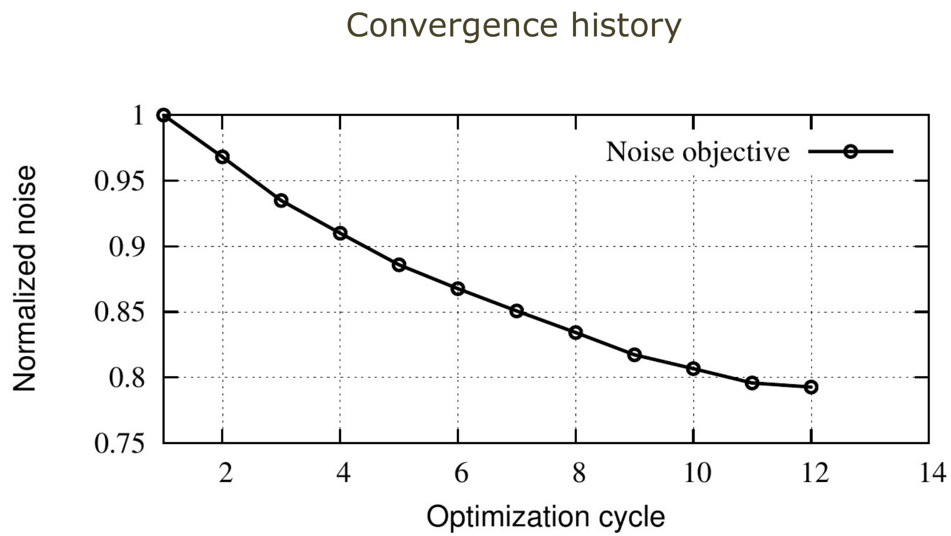
Optimization for Three Circumferential Rows of Receivers

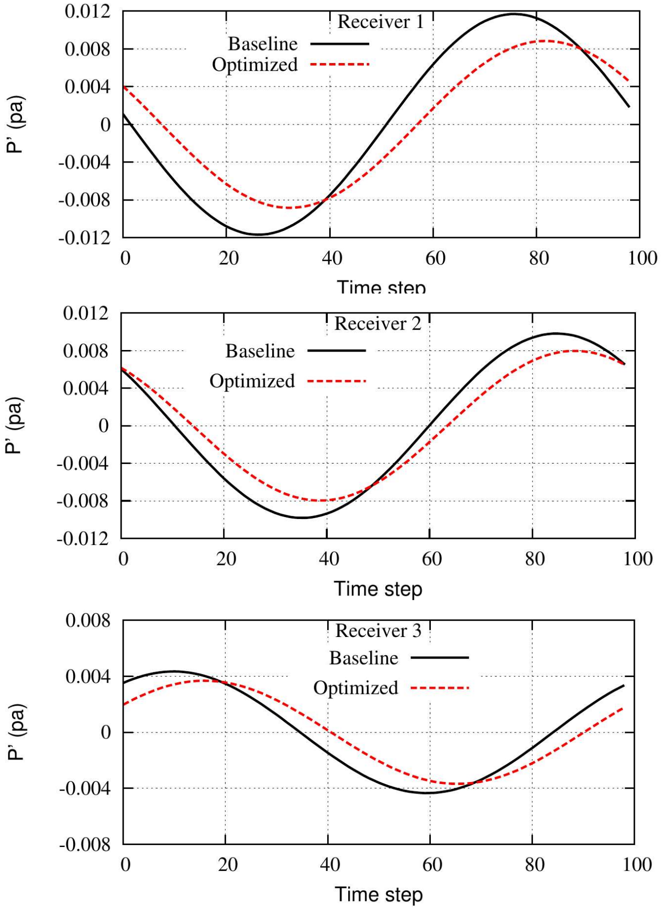


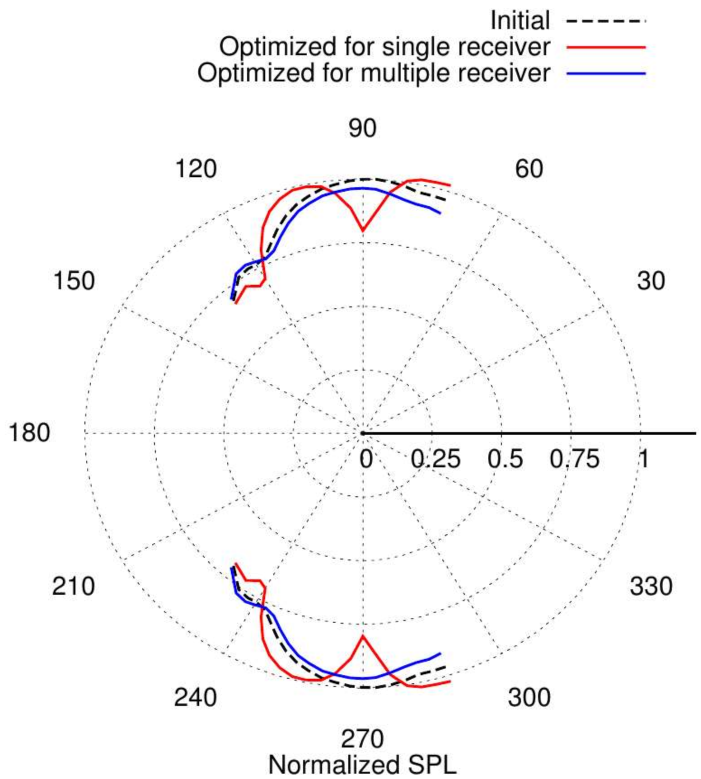


~20% reduction in the noise objective

Better (~0.12%) aerodynamic performance

Optimization for Three Circumferential Rows of Receivers





Max reduction ~2.5 dB

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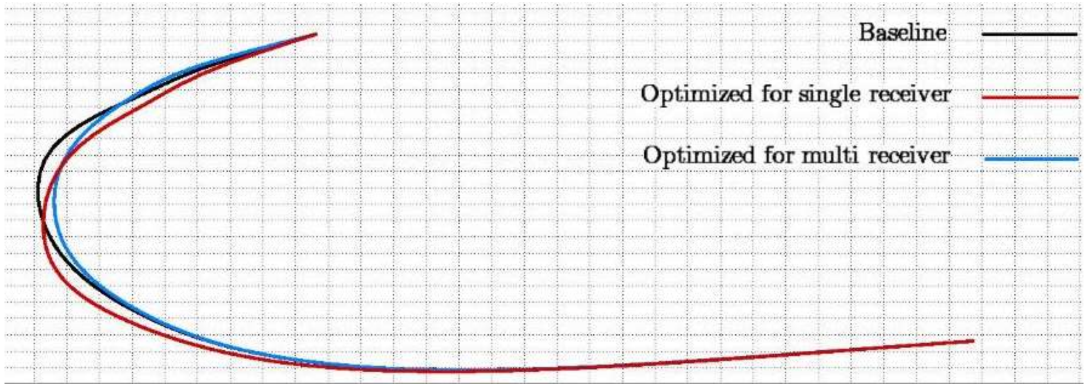
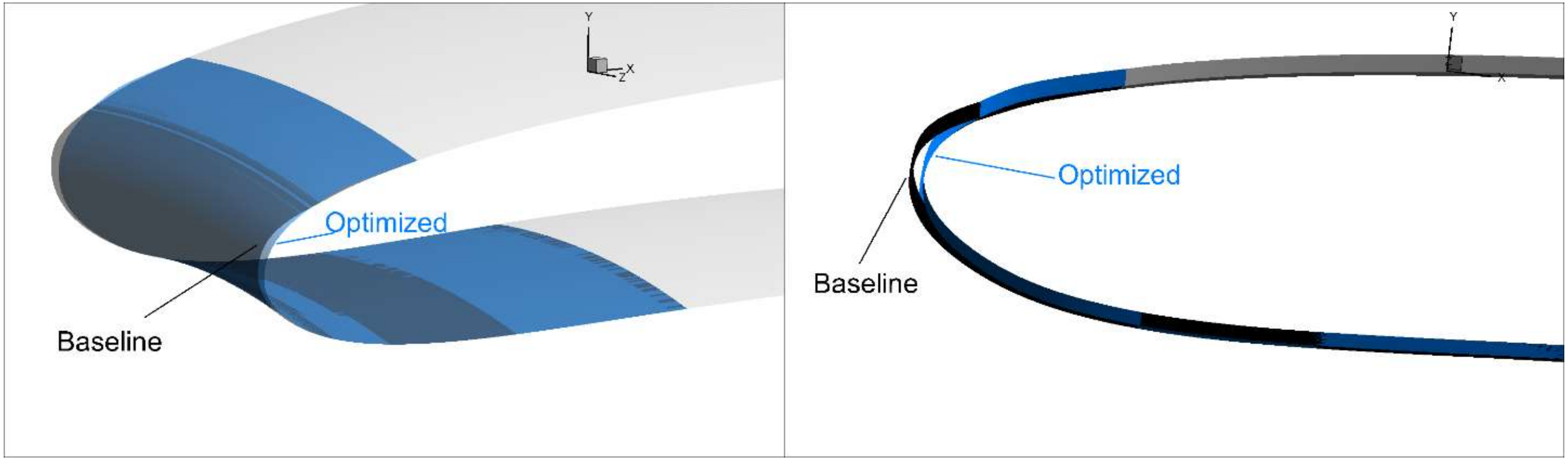
Optimization for Three Circumferential Rows of Receivers





Conclusion

- A previous implementation of the permeable version of the FW-H analogy in the frequency domain, for 2D problems, is extended and verified in 3D.
- Differentiation of the FW-H analogy is verified by comparison to analytical solution of sound field from a monopole source.
- Overall optimization tool runs on NVIDIA GPUs.
- Flow and adjoint are solved in a rotation frame of reference (steady).
- The unsteady fields of flow and adjoint solutions are achieved by rotation of the steady fields.
- The previous step overcomes the problems of large memory requirement and long solution time.
- Aeroacoustic shape optimization performed for both single and multiple receiver locations.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 769025.

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