Aeroacoustic Optimization Capabilities in the Open-Source SU2 Solver

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SU2
The Open-Source CFD Code

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Challenges in Airframe Noise Reduction
– An Optimal Design Perspective

- Various noise sources present at different frequencies but comparable amplitudes – must be reduced by similar amounts for discernible overall noise reduction
- $J^N = \text{rms}(p') (=\text{OASPL})$ misleading
  - Must target broadband component!
  - EPNLdB (2-10kHz range)
  - Strong requirement on CAA solver
- To meet aggressive noise reduction goals, it is insufficient to only reduce high-lift and landing gear noise – trailing edge scattering (‘lower bound’) must be reduced.\(^{(1)}\)
- Require efficient simulation and design tools to explore innovative and unconventional configurations and control strategies
  - Porous TE
  - LE and TE serrations
  - ...

Review of Existing Work

State of the Art on Aeroacoustic Simulation

- ‘Direct’ noise computation via DNS/LES computationally intractable for far-field observer locations (strong disparity between hydrodynamic and acoustic length scales at low \( M_\infty \))
- A hybrid two-stage approach allows for more efficient noise prediction
- Near-body turbulent flow field resolved using LES/DES/URANS
- Noise signal propagated to far-field using linearized Euler or integral methods such as Ffowcs Williams-Hawkings (FW-H)
- Predictive capabilities must be used to influence design!

Computational Cost: \( (N_{xyz} \sim 10^8) \times (N_{\Delta t} \sim 10^5) \implies \text{CPU-hrs} \sim ? \)

Existing Work on Aeroacoustic Optimization – A Non-Exhaustive List

- Airfoil design in turbulent flow (2D URANS+FW-H) using discrete adjoint, Rumpfkeil & Zingg, 2010
- Helicopter blade design (3D Euler+FW-H) using discrete adjoint, Fabiano et al., 2015
- Porous trailing-edge design (LES+APE) using AD-based discrete adjoint, Zhou, Gauger et al., 2015, 2016
- Optimizations involving high-fidelity and scale-resolving simulations limited to simple geometries
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This work: Consistent and robust discrete adjoint on the basis of algorithmic differentiation (AD) to explore unconventional design concepts
SU2 – An Open-Source Multi-Physics Analysis and Design Tool

- Open source multi-physics solver suite
- URANS: FV method with various flux discretization schemes (JST, AUSM, etc) and turbulence models (SA & SST) implemented
- Dual-time stepping for time-accuracy
- Dynamic grid movement capability
- SLSQP optimizer (SciPy), initially implemented with continuous adjoint

Active development on various disciplines by many groups around the world
- Stanford University (original solver, continuous adjoint, etc)
- TU Kaiserslautern (CFD-CAA coupled solver, AD-based discrete adjoint)
- TU Delft & Politecnico di Milano (Turbomachinery applications)
- Imperial College (Aero-structural analysis)
- Technological Institute of Aeronautics (DDES, IDDES, etc)

Latest Version (v6.0 Falcon) released in Feb. 2018
Aeroacoustic Simulation and Optimization in SU2 – The Past, Present, and Future

Past

- 2D URANS + FWH in frequency domain
- Noise minimization on various 2D configurations

Present

- 3D FWH in both time and frequency domain, coupled with URANS and DDES
- Noise minimization with 3D URANS + FWH, final analysis using DDES + FWH
- Preliminary validation against experiment using DDES + FWH

Future

- Minimization of broadband noise with DDES + FWH
- (U)RANS with stochastic noise generation (SNGR / fRPM / ASR)

AVIATION 2016

SCI-TECH 2017
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A Coupled CFD-CAA Framework for Noise Prediction

A boundary integral formulation of the permeable surface Ffowcs Williams-Hawkings (FW-H) acoustic solver is coupled with CFD solver in SU2 for efficient acoustic computations at arbitrary observer locations. [Di Francescantonio, 1997]

\[
p'_{obs}(\vec{x}, t) = \left[ \int_{\Gamma_p} \left( \frac{\rho_\infty \dot{U} \cdot \hat{n}}{4\pi r} \right)_{ret} d\Gamma_p + \frac{1}{c} \int_{\Gamma_p} \left( \frac{\dot{F} \cdot \hat{r}}{4\pi r} \right)_{ret} d\Gamma_p + \int_{\Gamma_p} \left( \frac{F \cdot \hat{r}}{4\pi r^2} \right)_{ret} d\Gamma_p \right] + p'_Q \tag{1}
\]

where

- \( U_i = \rho u'_i / \rho_\infty \),
- \( F_i = \left[ (p - p_\infty)\delta_{ij} - \tau_{ij} + \rho u'_i u'_j \right] \hat{n}_j \),

- Flow field in \( \Omega_1 \) resolved by CFD
- \( p, \rho, u'_i \) on \( \Gamma_p \) extracted from CFD data
- \( p'_T \) & \( p'_L \): ‘thickness’ and ‘loading’ noise source
- Quadrupole source (\( p'_Q \)) negligible for low \( M_\infty \)
- \([\cdot]_{ret}\): source terms evaluated in ‘retarded’ time
- 2-D freq-domain formulation also implemented (Lockard, 2000)
AD-based Unsteady Discrete Adjoint Framework

Consider a system of semi-discretized PDEs as follows:
\[
\frac{dU}{dt} + R(U) = 0
\]

\(U\): spatially discretized state vector
\(R(U)\): is the discrete spatial residual vector.

Second-order backward difference is used for time discretization:
\[
R^*(U^n) = \frac{3}{2\Delta t} U^n + R(U^n) - \frac{2}{\Delta t} U^{n-1} + \frac{1}{2\Delta t} U^{n-2} = 0, \quad n = 1, \ldots, N
\]

Dual-time stepping method converges \(R^*(U^n)\) to a steady state solution at each time level \(n\) through a pseudo time \(\tau\):
\[
\frac{dU^n}{d\tau} + R^*(U^n) = 0
\]

Implicit Euler method is used to time march the above equation to steady state:
\[
U^n_{p+1} - U^n_p + \Delta \tau R^*(U^n_{p+1}) = 0, \quad p = 1, \ldots, M
\]
The resultant nonlinear system can be linearized around $U^n_p$ to solve for the state $U^n_{p+1}$:

$$U^n_{p+1} - U^n_p + \Delta \tau \left[ R^* (U^n_p) + \frac{\partial R^*}{\partial U} \bigg|_p (U^n_{p+1} - U^n_p) \right] = 0, \quad p = 1, \ldots, M$$

This can be written in the form of a fixed-point iteration:

$$U^n_{p+1} = G^n(U^n_p, U^{n-1}, U^{n-2}), \quad p = 1, \ldots, M, \quad n = 1, \ldots, N$$

$G^n$: an iteration of the pseudo time stepping
$U^{n-1}$: converged state vector at time level $n - 1$
$U^{n-2}$: converged state vectors at time level $n - 2$

The fixed point iteration converges to the numerical solution $U^n$:

$$U^n = G^n(U^n, U^{n-1}, U^{n-2}), \quad n = 1, \ldots, N$$
The discretized unsteady optimization problem over $N$ time levels:

$$\min_{\alpha} \ J = f(U_{N*}, \ldots, U^N, \alpha)$$

subject to

$$U^n = G^n(U^n, U^{n-1}, U^{n-2}, \alpha), \quad n = 1, \ldots, N$$

$\alpha$: vector of design variables. $J$ is evaluated between $N_* \leq n \leq N$. One can express the Lagrangian associated with the above constrained optimization problem as follows:

$$L = f(U_{N*}, \ldots, U^N, \alpha) - \sum_{n=1}^{N} [((\bar{U}^n)^T (U^n - G^n(U^n, U^{n-1}, U^{n-2}, \alpha))]$$

$\bar{U}^n$: adjoint state vector at time level $n$.

$$\frac{\partial L}{\partial \bar{U}^n} = 0, \quad n = 1, \ldots, N \quad \text{(State equations)}$$

$$KKT: \quad \frac{\partial L}{\partial U^n} = 0, \quad n = 1, \ldots, N \quad \text{(Adjoint equations)}$$

$$\frac{\partial L}{\partial \alpha} = 0, \quad \text{(Control equation)}$$
AD-based Unsteady Discrete Adjoint Framework

The unsteady discrete adjoint equations can be derived in the fixed point form as:

\[
\bar{U}^n_{i+1} = \left( \frac{\partial G^n}{\partial \bar{U}^n} \right)^T \bar{U}^n_i + \left( \frac{\partial G^{n+1}}{\partial \bar{U}^n} \right)^T \bar{U}^{n+1} + \left( \frac{\partial G^{n+2}}{\partial \bar{U}^n} \right)^T \bar{U}^{n+2} + \left( \frac{\partial J}{\partial \bar{U}^n} \right)^T, \quad n = N, \ldots, 1
\]

\[\bar{G}^n(\bar{U}^n, \bar{U}^{n-1}, \bar{U}^{n-2})\]

\(\bar{U}^{n+1}\): converged adjoint state vector at time level \(n + 1\)
\(\bar{U}^{n+2}\): converged adjoint state vector at time level \(n + 2\)

The unsteady adjoint equations above are solved backward in time. The sensitivity gradient can be computed from the adjoint solutions:

\[
\frac{dL}{d\alpha} = \frac{\partial J}{\partial \alpha} + \sum_{n=1}^{N} \left( (\bar{U}^n)^T \frac{\partial G^n}{\partial \alpha} \right)
\]

- High-lighted terms computed using **Algorithmic Differentiation** in reverse mode
- Reverse accumulation used at each time level to ‘tape’ the computational graph for AD
- Adjoint iterator inherits the same convergence properties as primal iterator
- G includes: turbulence model, grid movement, limiters, etc
- AD implementation details see Albring et al. AIAA-2016-3518
Coupled CFD-FWH Noise Prediction and Optimization Framework

- **CFD Solver:** \( U^n = G^n(U^n, U^{n-1}, U^{n-2}) \)
- **FWH Solver:** \( p'_\text{obs}(\vec{x}, t) = p'_T + p'_L = F_n(U|\Gamma_p, \vec{x}, t) \)
- **Adjoint CFD:** \( \bar{U}^n = \bar{G}^n(\bar{U}^n, \bar{U}^{n-1}, \bar{U}^{n-2}) + \left( \frac{\partial J}{\partial U^n} |_{\Gamma_p} \right)^T \)
- **\( U^n|_{\Gamma_p} \):** Flow variables at time step \( n \) on the FWH surface \( \Gamma_p \)
- **\( \frac{\partial J}{\partial U^n} |_{\Gamma_p} \):** sensitivity of the noise objective with respect to flow variables evaluated on the FWH surface \( \Gamma_p \)
Verification of FWH Solver (2D)

- 2-D circular cylinder in subsonic, turbulent flow
- \( M_\infty = 0.25, \ Re = 5 \times 10^6 \)
- Turbulent flow computed by URANS
- Acoustics computed by 2-D freq-domain FWH (Lockhard, 2000)
- 3 mics placed in radial direction and 3 mics in circumferential direction
- \( p' \) at mic positions compared (URANS-FWH vs. Direct URANS)

<table>
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<th>Microphone No.</th>
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<th>( \theta )</th>
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<td>5D</td>
<td>90°</td>
</tr>
<tr>
<td>6</td>
<td>5D</td>
<td>135°</td>
</tr>
</tbody>
</table>
Verification of 2-D FWH Solver (Circumferential Direction)

- Microphone 4, \( r=5D, \theta=45 \text{ deg} \)
- Microphone 5, \( r=5D, \theta=90 \text{ deg} \)
- Microphone 6, \( r=5D, \theta=135 \text{ deg} \)

- : Direct URANS; – – – : URANS-FWH; - - - : Hanning Window

- Excellent match in frequency
- Slight mismatch in amplitude – Hanning window (to enforce periodicity) is energy-preserving, NOT amplitude-preserving
Verification of 2-D FWH Solver (Radial Direction)

Microphone 1,  \( r=3D, \theta=90 \) deg

Microphone 2,  \( r=6D, \theta=90 \) deg

Microphone 3,  \( r=12D, \theta=90 \) deg

- : Direct URANS;  -- : URANS-FWH;  - - - : Hanning Window

- Excellent match in frequency
- Discernible amplitude difference in furthest mic (\( r=12D \)) due to mesh coarsening (damping of static pressure signal in URANS)
Verification of FWH Solver (3-D)

- Monopole source at origin
- Acoustic source on FWH surface analytically computed
- Propagation to farfield with both time- and frequency-domain FWH
- Excellent agreement between FWH-propagated signal and analytical signal at 3 farfield positions
- Slight mis-match in amplitude for frequency-domain FWH due to windowing
- Farfield $p' \propto 1/r$ scaling law perfectly observed

Analytic: (——)
Time-domain FWH: (– – –)
Frequency-domain FWH: (· · ·)
Validation: 3-D Rod-Airfoil Configuration

Vorticity Iso-surfaces ($\omega_z D/ U_\infty = \pm 1$)

- NACA0012 airfoil section in the turbulent wake of a circular cylinder
- Representative test case for interaction noise of various airframe components
- Good benchmark test case with tonal (cylinder shedding) and broadband (turbulent wake breakdown & impingement) components
- Farfield noise measurement made by Jacob et al.

Measurement by Jacob et al.
URANS to DDES

- URANS+Turbulence Model: well-tuned and inexpensive in attached boundary layer but inaccurate in separated flow
- LES cost scales strongly with Re in wall-bounded flows but accurate and independent of Re in separated zones
- Delayed Detached Eddy Simulation (DDES): RANS in boundary layer; LES in separated region (Spalart et al., 2006)
- More refinement → more turbulent content (LES-like behaviour)
- Crucial for broadband noise prediction

Beckett Y. Zhou et al.  
Aeroacoustic Optimization in SU2
Validation: 3-D Rod-Airfoil Configuration

- NACA0012 airfoil section \((C = 0.1m)\) with \(S = 0.5C\) placed at a distance \(\delta = 1.0C\) behind a cylinder of diameter \(D = 0.1C\)
- \(U_\infty = 72m/s\), \(Re_c = 4.8 \times 10^5\)
- Structured mesh with \(\sim 6.0\) million elements with refinement in rod-airfoil gap
- Nearfield acoustic source computed by DDES+SA
- Propagation to 3 farfield microphone positions \((r = 18.5C, \theta = 45^\circ, 90^\circ\) and \(135^\circ)\) using time-domain FWH.
- Farfield \(p'\) computed based on 28,500 samples, \(\sim 38\) cycles of airfoil lift fluctuation
Validation: Farfield Noise Spectra

- Good agreement with measurement around the spectral peak: tonal frequency $St = 0.19$ and peak SPL well-captured
- Low frequency error: installation effect not modeled in simulation (also noted by Giret et al. 2012)
- Broadband range over-predicted (work in progress)
  - Excessive mesh coarsening after impingement and in airfoil wake (switch back to RANS mode)
  - Spurious noise from neglecting quadrupole source (Greschner et al. 2008)
Validation: Farfield Noise Spectra

- URANS-based results over-predict peak SPL by up to 15dB
- Tonal frequency also off by $\sim 20\%$
- Turbulent wake breakdown in rod-airfoil gap region not resolved by URANS
Noise Minimization of a Rod-Airfoil Configuration (2-D)

- NACA0012 airfoil at a distance $\delta = 0.7C$ behind the cylinder
- Airfoil pitched to $\text{AoA}=5^\circ$
- $U_\infty = 72\, \text{m/s}$, $Re_c = 4.8 \times 10^5$
- Hybrid mesh with $\sim 100\text{K}$ elements with refinement within FWH surface
- Nearfield acoustic source computed by URANS+SA
- Propagation to 3 farfield microphone positions ($r = 100C$, $\theta = 45^\circ$, $90^\circ$ and $135^\circ$) using frequency-domain FWH (Lockard, 2000).
- Farfield $p'$ corresponds to $\sim 9$ cycles of airfoil lift fluctuation
- $J^N = \text{RMS}(p')$
- Shape design via free-form deformation (FFD) $\implies$ 256 DV’s
Optimization History: Unconstrained vs. Lift-Constrained

- Aeroacoustic and aerodynamic design objectives directly competing
- Unconstrained noise minimization: \(\sim 36\%\) noise reduction accompanied by marked loss of lift (\(\sim 59\%\)!
- Lift-constrained noise minimization: more modest noise reduction (\(\sim 27\%\)) but mean lift maintained at baseline level
Acoustic Fields

- Re-computed on finer meshes for better resolution
- Dilatation field: provides a qualitative comparison of the radiated acoustic waves
Directivities and Optimized Designs

- Noise reduction in all directions with exception of shallow upstream angles
- Surface waviness in both noise-minimized and lift-constrained-noise-minimized designs
- Noted in works of other groups, mostly in spanwise waviness along LE
Noise Minimization of a Rod-Airfoil Configuration (3-D)

- NACA0012 airfoil section with $S = 0.5C$ placed at a distance $\delta = 0.7C$ behind the cylinder
- $U_\infty = 72\,m/s$, $Re_c = 4.8 \times 10^5$
- Hybrid mesh with $\sim 2.8$ million elements with refinement within permeable FWH surface
- Nearfield acoustic source computed by URANS+SA
- Propagation to 3 farfield microphone positions ($r = 100C$, $\theta = 45^\circ$, $90^\circ$ and $135^\circ$) using time-domain FWH.
- Farfield $p'$ corresponds to $\sim 10$ cycles of airfoil lift fluctuation
Optimization History

- 33% reduction in $J^N = \sqrt{(p')^2}$ after 9 design iterations
- No aerodynamic or geometric design constraints applied
- Clear farfield noise reduction in all three directions ($\theta = 45^\circ$, $90^\circ$ and $135^\circ$)
Optimization History

Surface noise sensitivity in normal direction

- Does not collapse the airfoil as one would expect
- Optimizer introduces streamwise waviness on both upper and lower surfaces
- No spanwise variation in surface sensitivities – due to coherent vortices impinging on the airfoil LE due to URANS simulation
- Scale-resolving simulations required to model turbulent wake breakdown
DDES Simulation of Nearfield Acoustic Sources

- Hybrid mesh with 4 million elements with extra refinement in cylinder wake region to encourage RANS-LES switch
- Surface waviness ‘surpresses’ noise-generating vortical structures from the airfoil surface
Acoustic Results Based on DDES-FWH

- Sample collection after 50 flow passage times
- 15000 samples corresponding to ~ 40 cycles of lift fluctuations on airfoil
- $J^N$ reduced by ~ 45% (compared to 33% with URANS-FWH)
- OASPL: omni-directional noise reduction, up to 6dB
Farfield Noise Spectra ($R = 100C$)

- Peak frequency $St = 0.19$ well-captured in baseline configuration
- Peak SPL reduced by 5-6 dB
- Broadband reduction not omni-directional, but at least peak SPL not shifted towards higher frequency
- To minimize broadband noise, $J^N$ must be re-defined to target high-frequency component $\Rightarrow$ perform optimizations directly with DDES-FWH in the loop
LE and TE Modifications

- LE and TE serration/waviness already shown to have acoustic and aerodynamic benefits

Adjoint Optimization with DDES+FHW?

- Can they be further optimized?
- More importantly, can noise reduction be achieved with aerodynamic design constraints at practical flow regimes ($Re \sim 10^7$)?

Credit: Fish et al. Integrative and Comparative Biology, 2008

Summary and Future Work

Summary

- 2D & 3D FW-H acoustic solver implemented in SU2, coupled with URANS and DDES
- Adjoint-based aeroacoustic design enabled by a discrete adjoint solver based on algorithmic differentiation (AD)
- Aeroacoustic and aerodynamic design objectives shown to be competing
- Streamwise surface waviness observed in optimized airfoil with 5-6 dB noise reduction (scale-resolving methods required to exploit spanwise variations)
- Validation against experiment: tone well-captured; broadband to be improved
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- Adjoint-based noise minimization to tackle broadband noise – much more challenging to remove/reduce than tonal noise
  - Challenge #1: Mesh size for DDES $\sim O(10^{7-8})$ for large, complex geometries
  - Challenge #2: Need for regularization due to chaotic LES content
- Joint work with Lars Davidson’s group at Chalmers University to commence in April 2018
- Can URANS-SNGR-FWH provide ‘accurate enough’ characterization of farfield noise (compared to DDES-FWH) for optimization?
- SU2-ANOPP2 coupling for propeller design (joint work with Len Lopes, NASA Langley)
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