An Overview of Aeroacoustic Prediction and Design Capabilities in SU2

Beckett Y. Zhou, Nicolas R. Gauger

Chair for Scientific Computing,
TU Kaiserslautern, Germany

SU2
The Open-Source CFD Code

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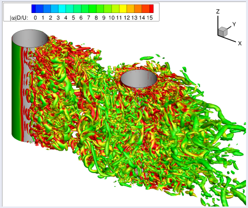
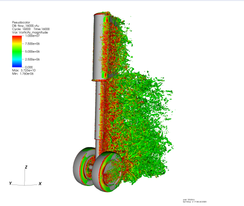
Aeroacoustic Prediction Capabilities in SU2

Turbulent Flow Simulation

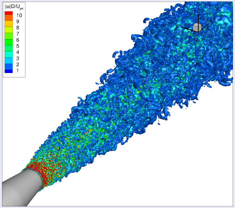
- URANS, EDDES with Shear-Layer Adaptive SGS, WMLES, DG



Tandem Cylinder



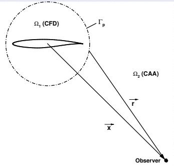
Landing Gear

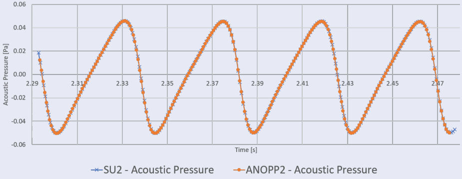


Turbulent Jet

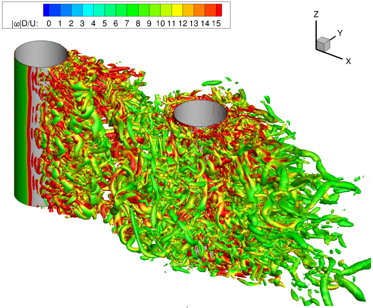
Noise Propagation

- Ffowcs Williams and Hawkings (FWH) Acoustic Analogy in 'Wind-Tunnel Formulation'

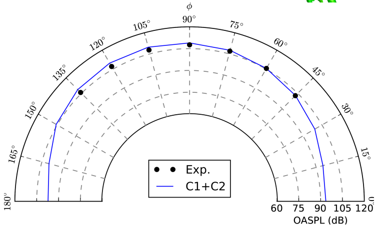




Validation: Tandem Cylinder Case from BANC-I Workshop



- SU2 aeroacoustic prediction using EDDES+FWH
- Studied in a series of experiments performed at NASA Langley.
- a prototype for interaction problems commonly encountered in airframe noise, e.g., landing gear configuration.
  - Separation of turbulent boundary layer.
  - Free shear layer roll-up.
  - Interaction of an unsteady wake of the upstream with the downstream cylinder.



Unsteady Discrete Adjoint Framework

The discretized unsteady optimization problem over N time levels:

$$\begin{aligned} \min_{\alpha} \quad & J &=& \quad f(U^{N_*}, \dots, U^N, \alpha) & \\ \text{subject to} \quad & U^n &=& \quad G^n(U^n, U^{n-1}, U^{n-2}, \alpha), & \quad n = 1, \dots, N \end{aligned}$$

α: 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:

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

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

$$KKT: \quad \begin{aligned} \frac{\partial L}{\partial \bar{U}^n} &= 0, \quad n = 1, \dots, N \qquad &\text{(State equations)} \\ \frac{\partial L}{\partial U^n} &= 0, \quad n = 1, \dots, N \qquad &\text{(Adjoint equations)} \\ \frac{\partial L}{\partial \alpha} &= 0, \qquad &\text{(Control equation)} \end{aligned}$$

Unsteady Discrete Adjoint Framework

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

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

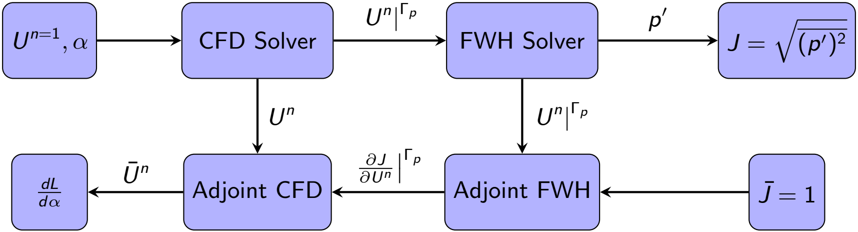
$\bar{U}^{n+1}$: converged adjoint state vector at time level $n+1$
$\bar{U}^{n+2}$: converged adjoint state vector at time level $n+2$

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

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

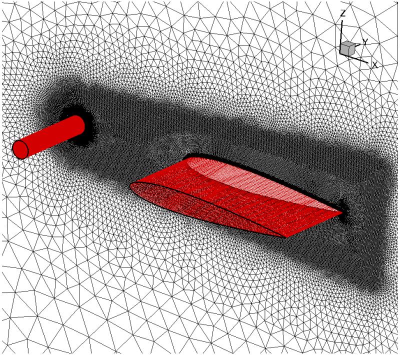
- High-lighted terms computed using Algorithmic Differentiation (AD) in reverse mode
- Reverse accumulation used at each time level to ‘tape’ the computational graph for AD
- G includes: turbulence model, grid movement, limiters, etc
- Adjoint iterator $\bar{G}$ inherits the same convergence properties as primal iterator
- AD implementation details see Albring et al. AIAA-2016-3518

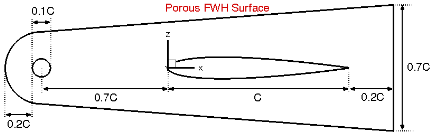
Coupled CFD-FWH Noise Prediction and Optimization Framework



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

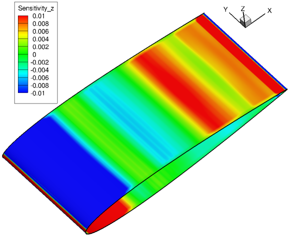
Minimization of Rod-Airfoil Interaction Noise



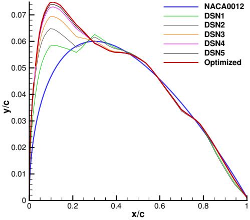


- NACA0012 airfoil section with $S = 0.5C$ placed at a distance $\delta = 0.7C$ behind the cylinder
- $U_\infty = 72m/s$, $Re_c = 4.8 \times 10^5$
- Nearfield acoustic source computed by URANS+SA
- Propagation to 3 farfield microphone positions ($r = 100C$, $\theta = 45^\circ$, 90° and 135°) using time-domain FWH.
- $J^N = RMS(p')$, averaged over 3 mic positions
- 225 FFD design variables allow for smooth morphing of airfoil section
- Noise minimization performed to determine *optimal* shape morphing of the airfoil section to reduce interaction noise

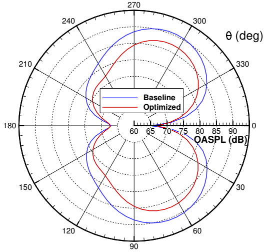
Noise Minimization of a Rod-Airfoil Configuration



Surface Noise Sensitivity



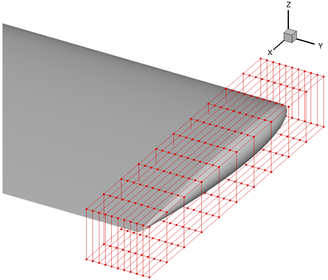
Design Evolution

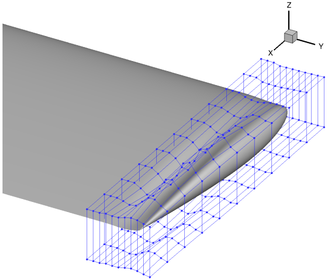


Overall Sound Pressure Level

- Advantage of adjoint-based method: identification of regions of high design sensitivities
- 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 – coherent vortices impinging on the airfoil LE due to URANS simulation
- OASPL: omni-directional noise reduction, up to 6dB
- Details in: AIAA-2017-3658

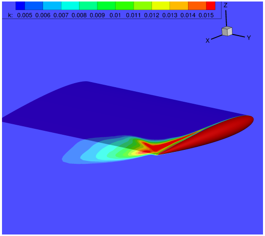
Flap Side-Edge Broadband Noise Minimization



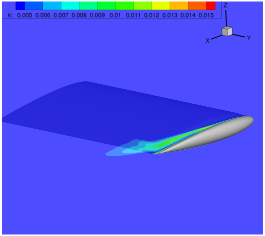


- Broadband noise source modeled by RANS + Stochastic Noise Generation (SNG)
- NACA0012 single element wing section with round tip
- Similar underlying noise generation mechanism as that of flap side-edge
- $M_\infty = 0.175$ ($V_\infty = 60m/s$)
  $Re_c = 1.0 \times 10^6$
  $AoA = 12^\circ$, $AR \sim 1.5$
- RANS solution computed with SST $k - \omega$ turbulence model
- SNG and sensitivities evaluated in the tip region
- Frequency range targeted in SNG: 1-10 kHz
- Only allow geometry in tip region ($y \geq 1.35C$) to change
- Details in: AIAA 2019-2697

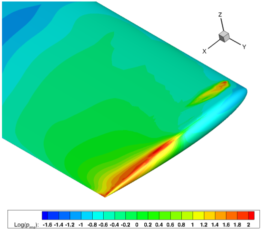
Flap Side-Edge Broadband Noise Minimization



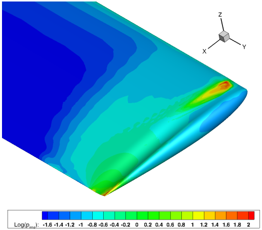
Baseline TKE



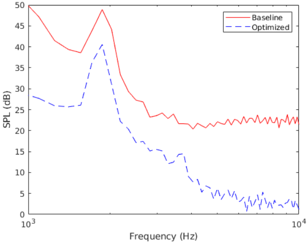
Optimized TKE



Baseline p'_{RMS}



Optimized p'_{RMS}

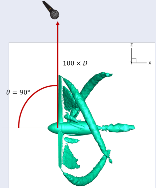


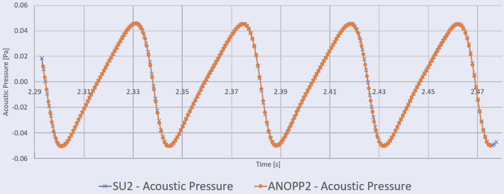
Farfield Noise Spectrum

Current and Future Effort

Extend existing FWH implementation to full F1A for moving sources

- NASA funded project aimed at developing adjoint-based noise minimization capabilities for propeller and rotor configurations
  - Omur Icke, Andy Moy and Oktay Baysal (Old Dominion University)
  - Leonard V. Lopes (NASA Langley)
  - Beckett Y. Zhou (TU Kaiserslautern)
  - Boris Diskin (National Institute of Aerospace)
- Currently implemented in V6; Integration with V7 this summer





Aeroacoustic Development 'Wish List'

- Advance-in-time method for FWH solver
- Couple SU2-DG to solve LEE/APE for near-field propagation (duct acoustics)
- Low-fidelity aeroacoustic models (e.g. Tam & Auriault model for jet noise)

Aeroacoustic Prediction and Optimization in SU2

Acknowledgements

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Related Publications

- **B. Y. Zhou**, T. Albring, N. R. Gauger, C. R. da Silva, T. D. Economon, and J. J. Alonso, "*An Efficient Airframe Noise Reduction Framework via Adjoint-based Shape Optimization*", AIAA Journal (Under Review)
- R. O. Icke, O. Baysal, A. Moy, L. Lopes, **B. Y. Zhou**, and B. Diskin, "*Toward Adjoint-Based Aeroacoustic Optimization for Propeller and Rotorcraft Applications*", In AVIATION 2020 Forum, No. 2020-3140, Reno, NV, 2020.
- **B. Y. Zhou**, N. R. Gauger, H. Yao, S. Peng, and L. Davidson, "*Adjoint-based Broadband Noise Minimization using Stochastic Noise Generation*", In 25th AIAA/CEAS Aeroacoustics Conference, No. 2019-2697, Delft, 2019.
- **B. Y. Zhou**, T. Albring, N. R. Gauger, C. R. da Silva, T. D. Economon, and J. J. Alonso, "*Reduction of Airframe Noise Components Using a Discrete Adjoint Approach*", In 18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, No. 2017-3658, Denver, CO, 2017.
- **B. Y. Zhou**, T. Albring, N. R. Gauger, T. D. Economon, F. Palacios, and J. J. Alonso, "*A Discrete Adjoint Framework for Unsteady Aerodynamic and Aeroacoustic Optimization*", In 16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, No. 2015-3355, Dallas, TX, 2015.

Thank you for your attention