Aeroacoustic Prediction and Optimization Capabilities in SU2

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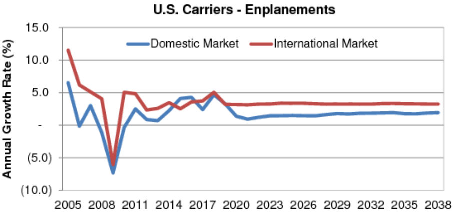
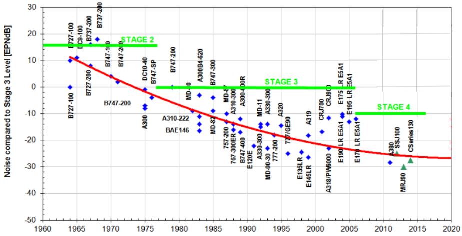
September 17, 2018

Need for Aeroacoustic Optimization

Source: FAA Forecast 2018-2038





- Latest FAA forecast: demand to air travel to DOUBLE by 2038
- Noise reduction attained in the last decade has started to plateau
- Various noise sources present at different frequencies but comparable amplitudes – must be reduced by similar amounts for discernible *overall* noise reduction
- To meet stringent 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
  - ...

(1). D. P. Lockard and G. M. Lilley, *The Airframe Noise Reduction Challege*, NASA Report 2004-213013

Review of Existing Work

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 URANS+FW-H) using discrete adjoint, Fabiano et al., 2015
- Optimal control of shear-layer noise (DNS) using continuous adjoint, Buchta et al. 2016
- Porous trailing-edge design (LES+APE) using AD-based discrete adjoint, Zhou, Gauger et al., 2016–2018
- **Optimizations involving high-fidelity and scale-resolving simulations limited to simple geometries**

Challenges

- Computationally intensive: $(N_{xyz} \sim 10^8) \times (N_{\Delta t} \sim 10^5) \implies$ CPU-hrs $\sim$?
- Large set of design variables with mostly uncharted design spaces
- Noise reducing modifications often accompanied by a marked loss of lift

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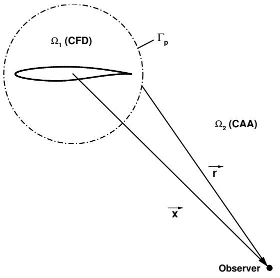
This work: Consistent and robust discrete adjoint on the basis of algorithmic differentiation (AD) to explore unconventional design concepts

A Coupled CFD-CAA Framework for Noise Prediction

A boundary integral formulation of the permeable surface **F**fowcs **W**illiams-**H**awkings (FW-H) acoustic solver is coupled with CFD solver in SU2 for efficient acoustic computations at arbitrary observer locations. [Di Francescantonio, 1997]

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

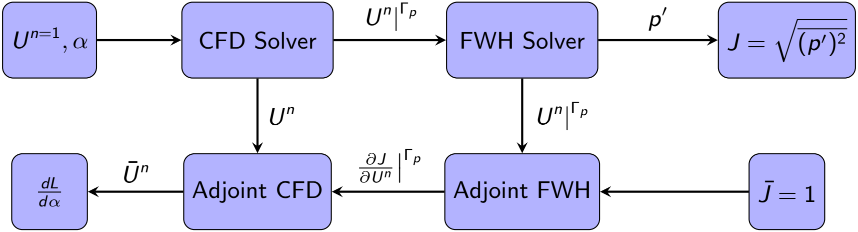


where

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

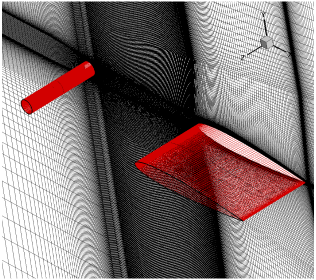
- Flow field in Ω_1 resolved by CFD
- p, ρ, u'_i on Γ_p extracted from CFD data
- p'_T & p'_L: 'thickness' and 'loading' noise source
- Quadrupole source (p'_Q) negligible for low M_∞
- $[\cdot]_{ret}$: source terms evaluated in 'retarded' time
- 2-D freq-domain formulation also implemented (Lockard, 2000)

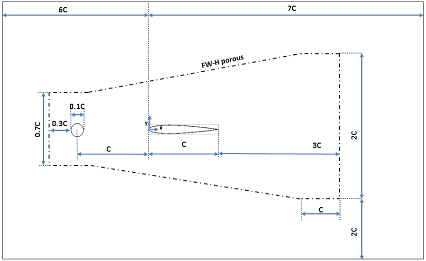
Coupled CFD-FWH Noise Prediction and Optimization Framework



- CFD Solver: $U^n = G^n(U^n, U^{n-1}, U^{n-2})$, URANS or DDES
- FWH Solver: $p'_{obs}(\vec{x}, t) = p'_T + p'_L = Fn(\, U\big|^{\Gamma_p}, \vec{x}, t)$, invoked via SU2_SOL
- Adjoint CFD: $\bar{U}^n = \bar{G}^n(\bar{U}^n, \bar{U}^{n-1}, \bar{U}^{n-2}) + (\,\frac{\partial J}{\partial U^n}\big|^{\Gamma_p})^T$
- $U^n\big|^{\Gamma_p}$: 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
- Shape optimization process fully automated in SU2
- See related publications for details on coupled adjoint formulation

Validation: 3-D Rod-Airfoil Configuration

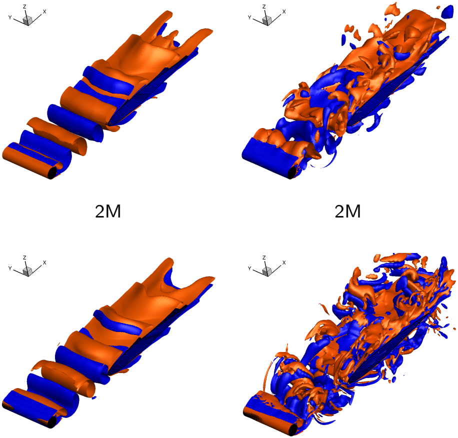




- NACA0012 airfoil section ($C = 0.1m$) with $S = 0.5C$ placed at a distance $\delta = 1.0C$ behind a cylinder of diameter $D = 0.1C$
- $U_\infty = 72m/s$, $Re_c = 4.8 \times 10^5$
- Structured mesh with ~ 6.0 million elements with refinement in rod-airfoil gap
- Nearfield acoustic sources computed by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

URANS to DDES

URANS-SA | DDES-SA

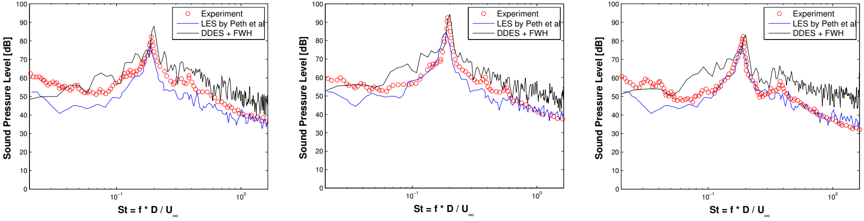


2M | 2M

4M | 4M

- URANS+Turbulence Model: well-tuned and inexepnsive in attached boundary layer but inaccurate in separated flow
- LES cost scales strongly with Re in wall-bounded flows but accurate and independnet 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

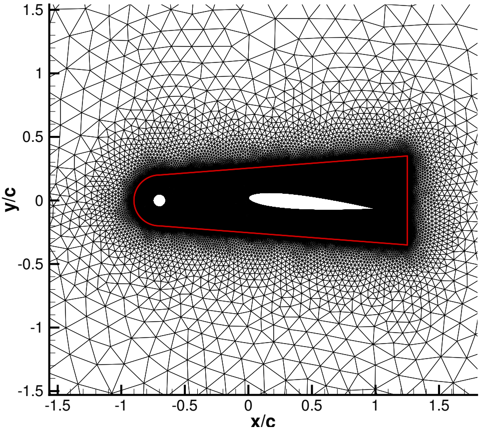
Validation: Farfield Noise Spectra



$\theta = 45^\circ$ $\theta = 90^\circ$ $\theta = 135^\circ$

- 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)

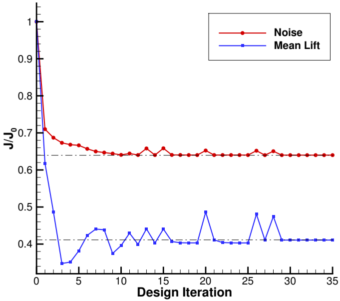
Noise Minimization of a Rod-Airfoil Configuration (2-D)



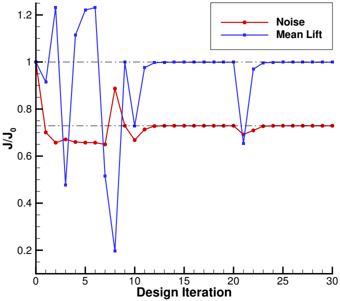
——: FWH Surface

- NACA0012 airfoil at a distance $\delta = 0.7C$ behind the cylinder
- Airfoil pitched to AoA=5°
- $U_\infty = 72m/s$, $Re_c = 4.8 \times 10^5$
- Hybrid mesh with $\sim$ 100K 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° and 135°) using frequency-domain FWH (Lockard, 2000).
- Farfield p' corresponds to $\sim$ 9 cycles of airfoil lift fluctuation
- $J^N = RMS(p')$
- Shape design via free-form deformation(FFD) $\Longrightarrow$ 256 DV's

Optimization History: Unconstrained vs. Lift-Constrained



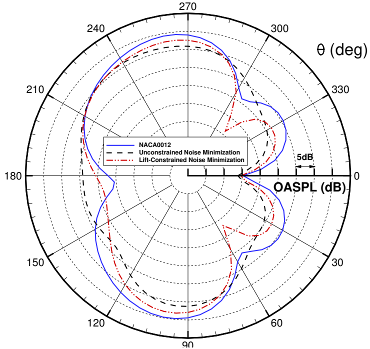
Unconstrained Noise Minimization



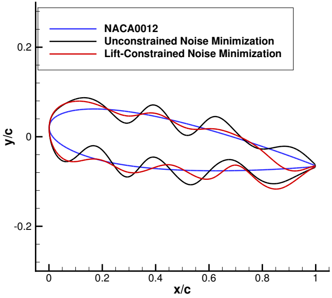
Lift-Constrained Noise Minimization

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

Directivities and Optimized Designs



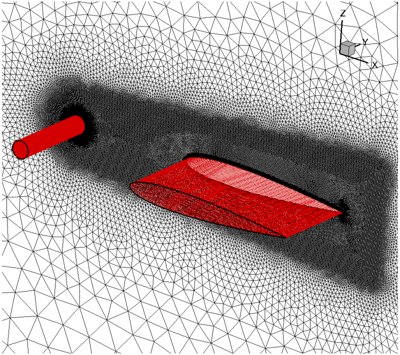
Overall Sound Pressure Level

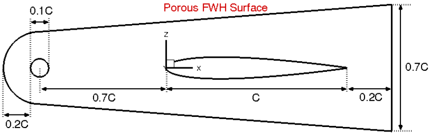


Optimized Designs

- 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)





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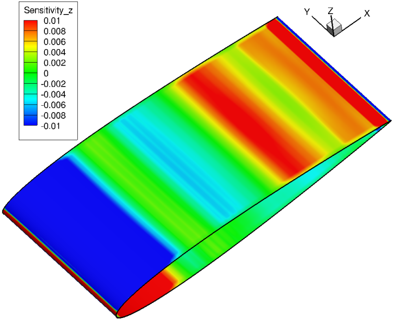
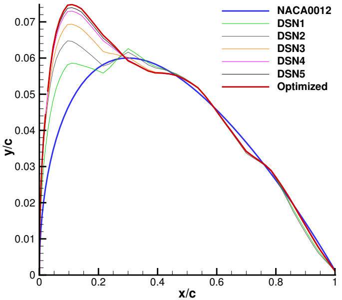
- Propagation to 3 farfield microphone positions ($r = 100C$, $\theta = 45^\circ$, 90° and 135°) using time-domain FWH.
- Farfield p' corresponds to ~ 10 cycles of airfoil lift fluctuation

Optimization History



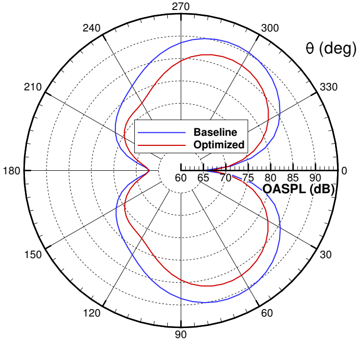
Surface noise sensitivity in normal direction



Design Evolution

- 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

Aeroacoustic Analysis Based on DDES-FWH



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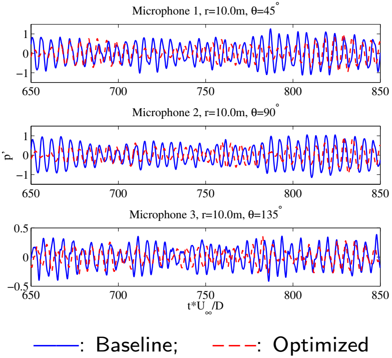
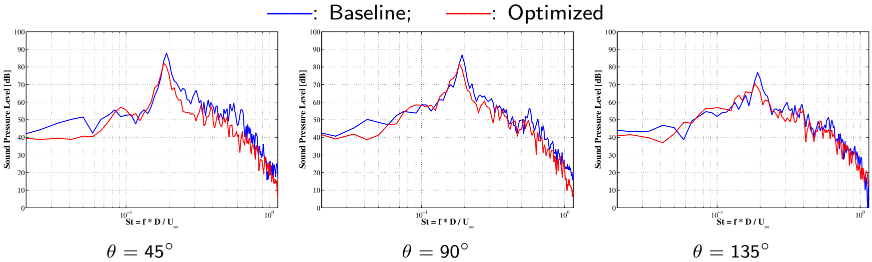


- Sample collection after 50 flow passage times
- 15000 samples corresponding to $\sim$ 40 cycles of lift fluctuations on airfoil
- J^N reduced by $\sim$ 45% (compared to 33% with URANS-FWH)
- OASPL: omni-directional noise reduction, up to 6dB

Farfield Noise Spectra (R = 100C)

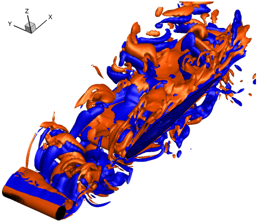


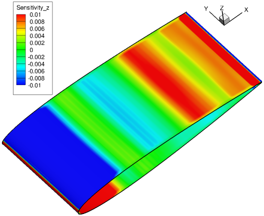
- Peak frequency $St = 0.19$ well-captured in baseline configuration
- Peak SPL reduced by 5-6 dB
- Broadband reduction not omni-directional, but at least peak SPL not shifted towards higher frequency
- To minimize broadband noise, J^N must be re-defined to target high-frequency component $\implies$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

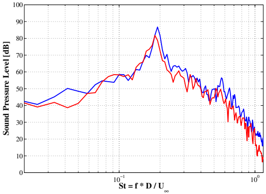
Summary and Future Work

Current Aeroacoustic Prediction and Optimization Capabilities

- 2D&3D URANS/DDES-FWH aeroacoustic solver implemented in SU2
- Adjoint-based aeroacoustic design optimization enabled by a discrete adjoint solver based on algorithmic differentiation (AD)
- Validation against experiment: tone well-captured; broadband to be improved







Related Publications

- A Discrete Adjoint Framework for Unsteady Aerodynamic and Aeroacoustic Optimization, **AIAA-2015-3355**
- A Discrete Adjoint Approach for Jet-Flap Interaction Noise Reduction, **AIAA 2017-0130**
- Reduction of Airframe Noise Components Using a Discrete Adjoint Approach, **AIAA-2017-3658**
- An Efficient Adjoint-based Framework for Airframe Noise Reduction, AIAA Journal, In Preparation

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Open Question: What about broadband noise?

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Open Question: What about broadband noise?

- 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

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  - 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
- Synthetic-turbulence-type methods (e.g. SNGR) for noise generation based on (U)RANS solutions at lower cost (Part II)
  - Joint work with Lars Davidson's group at Chalmers University since April 2018

Adjoint-based Broadband Noise Minimization using Stochastic Noise Generation

Beckett Y. Zhou[1], Leonard V. Lopes[2], Nicolas R. Gauger[3],

Hua-Dong Yao[4], Shia-Hui Peng[4], Lars Davidson[4]

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[2]NASA Langley Research Center, USA
[3]Chair for Scientific Computing, TU Kaiserslautern, Germany
[4]Chalmers University of Technology, Sweden

SU2
The Open-Source CFD Code

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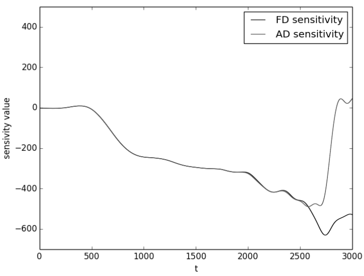
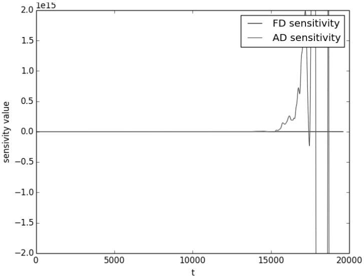
Motivation

- Broadband noise prediction: scale-resolving simulations (DNS, LES or at least DES) needed to resolve noise source + wave propagation (LEE, APE or FW-H)
- For efficient design optimization, necessary to use adjoint-based methods
- A fundamental obstacle: regularization problem encountered in adjoint computation of scale-resolving simulations (Blonigan and Wang, 2012)



First 3000 Δt's



Full Horizon

Figure: Divergence of sensitivities observed in a jet noise application by Oezkaya et al. (FD: Finite Difference; AD: Algorithmic Differentiation)

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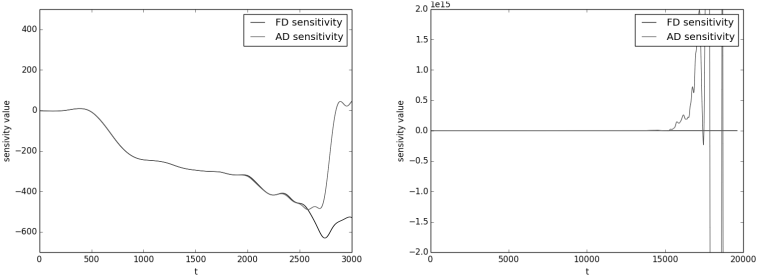

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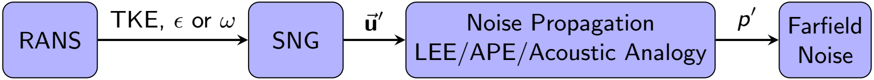
Figure: Divergence of sensitivities observed in a jet noise application by Oezkaya et al. (FD: Finite Difference; AD: Algorithmic Differentiation)

A 'middle-ground' between RANS-based approaches and scale-resolving simulations needs to be found

RANS-SNG Broadband Noise Assessment Framework

Basic Idea

Use stochastic noise generation (SNG) to reconstruct the turbulent velocity field based on turbulence kinetic energy (TKE) and dissipation rates (ϵ or ω) estimated by a preceding RANS computation.



- Pioneering work in RANS-SNG by Bechara et al. and Bailly et al. in the 1990s
- Method improved by the works of Billson et al., Casalino and Barbarino, and di Francescantonio et al. in recent years.
- Similar idea to the RANS-RPM approach of Ewert et al. at DLR (circa. 2000)

What RANS-SNG Method IS and ISN'T

- Fast assessment of broadband noise source characteristics and trends for design optimization
- A method to circumvent the regularization issue plaguing adjoint solutions for scale-resolving simulations
- NOT designed to predict broadband noise to an *absolute* level

Stochastic Noise Generation

A space-time turbulent velocity field can be expressed as a sum of N_F random Fourier modes:

$$\vec{u}\left(\vec{x},t\right) = 2\sum_{n=1}^{N_F} \hat{u}_n cos\left[\vec{k}_n \cdot \left(\vec{x} - \vec{U}t\right) + \psi_n\right]\vec{\sigma}_n$$

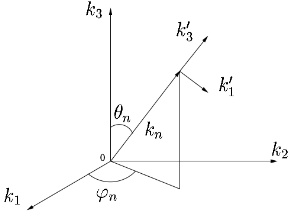
$\hat{u}_n$, $\vec{k}_n$, ψ_n and $\vec{\sigma}_n$ are statistical velocity magnitude, wave number vector, phase and direction associated with the n^{th} Fourier mode, convecting in a mean velocity $\vec{U}$

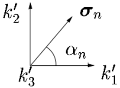
The vector $\vec{k}_n$ is generated randomly on a sphere with radius k_n, based on two polar angles φ_n and θ_n

The velocity vector $\vec{\sigma}_n$ is constrained to lie in a plane orthogonal to $\vec{k}_n$ with an angle α_n

The magnitude $\hat{u}_n$ of each mode is computed so that the turbulence energy spectrum $E(k_n)$ corresponds to the energy spectrum for isotropic turbulence, giving:

$$\hat{u}_n = \sqrt{E\left(k_n\right)\Delta k_n}$$





Probability distributions of the four random angles necessary for the stochastic generation of $\vec{u}(\vec{x},t)$:

$\mathcal{P}(\varphi_n) = 1/(2\pi)$	$0 \leq \varphi_n \leq 2\pi$
$\mathcal{P}(\theta_n) = (1/2)sin(\theta_n)$	$0 \leq \theta_n \leq \pi$
$\mathcal{P}(\psi_n) = 1/(2\pi)$	$0 \leq \psi_n \leq 2\pi$
$\mathcal{P}(\alpha_n) = 1/(2\pi)$	$0 \leq \alpha_n \leq 2\pi$

Stochastic Noise Generation

The energy spectrum is assumed in the form of Von Kármán-Pao isotropic turbulence spectrum as

$$E(k) = \frac{2A}{3}\frac{K}{k_e}\left(\frac{k}{k_e}\right)^4 exp\left[-2\left(\frac{k}{k_\eta}\right)^2\right]\left[1+\left(\frac{k}{k_e}\right)^2\right]^{(-17/6)}$$

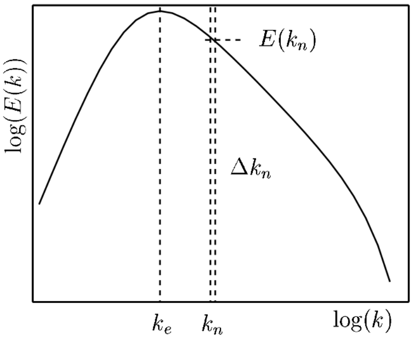
K: turbulence kinetic energy

$k_e = 0.747/L_T$: wavenumber of the maximum energy determined by the turbulent length scale L_T from RANS ($L_T = c_1 u'^3/\epsilon$, where $u' = \sqrt{2K/3}$)

$k_\eta = \epsilon^{1/4}\nu^{-3/4}$: wavenumber of the Kolmogorov scale.

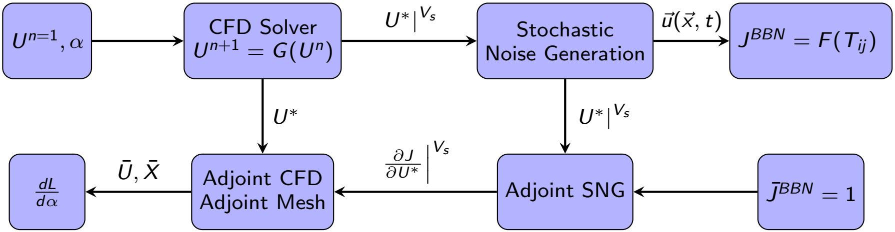
ϵ: turbulence dissipation rate

Constants $A \simeq 1.453$ and $c_1 = 1.0$.



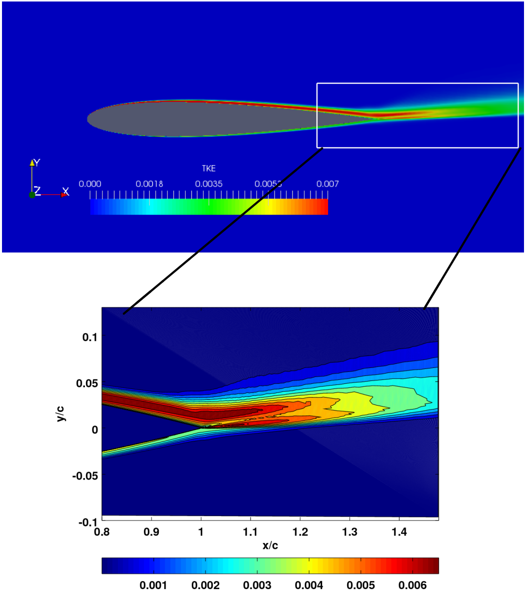
K and ϵ extracted from RANS solution

Adjoint-Based RANS-SNG Noise Reduction Framework



- $U^*|^{V_s}$: Turbulent flow variables extracted from the user-defined noise source region V_s.
- J^{BBN}: a function of stochastically generated Lighthill's stress tensor (T_{ij})
- $\frac{\partial J}{\partial U^*}\Big|^{V_s}$: sensitivity of the broadband noise objective with respect to turbulent flow variables extracted from V_s
- Adjoint CFD: $\bar{U} = \frac{\partial}{\partial U} G^T(U, X)\bar{U} + (\frac{\partial J}{\partial U^*}\Big|^{V_s})^T$
- The effect of the turbulent flow variables (k, ϵ or ω) in the source region V_s on the broadband noise design objective J^{BBN} is 'transmitted' through the term $\frac{\partial J}{\partial U^*}\Big|^{V_s}$, which is accumulated to the flow adjoint iterator in evaluating the coupled adjoint of RANS-SNG

Airfoil Self-Noise and Design Sensitivities

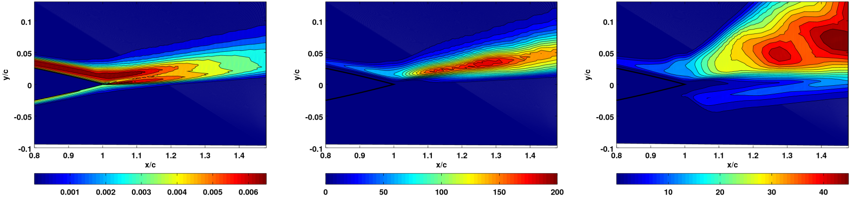


- 2-D NACA0012 airfoil
- $M_\infty = 0.2$
  $Re_c = 6.0 \times 10^6$
  $AoA = 8^\circ$
- RANS solution computed with SST $k - \omega$ turbulence model
- Steady aerodynamic results validated against experiment
- TKE and ω extracted from RANS solution
- SNG and sensitivities computed in the focus region: $x \in [0.8, 1.5], y \in [-0.1, 0.15]$
- Frequency range: 1-5 KHz
- Both primal and adjoint computations implemented in open-source solver SU2, fully parallelized.

TKE, $T_{i,j}$, and Sensitivity Distributions

$$\mathcal{J}^{BBN} = \left|\left| \frac{1}{V_s} \frac{1}{N_t} \sum_{m=1}^{N_x} \sum_{n=1}^{N_t} \mathbf{T}(\vec{x}_m, t_n) \Delta V_m \right|\right|^{Frob}$$

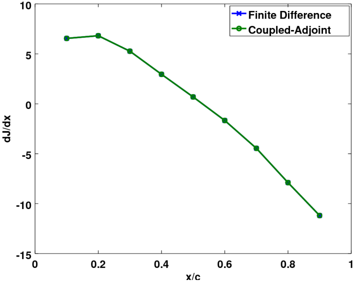
where $\mathbf{T} = T_{ij} = \rho u_i u_j$ and $||\cdot||^{Frob}$ is the Frobenius norm of a tensor.



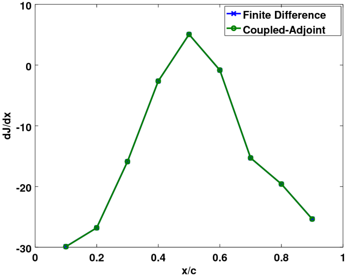
TKE $\qquad$ $||\bar{T}||^{Frob}$ $\qquad$ $\frac{\partial \mathcal{J}^{BBN}}{\partial K}$

- While the peak TKE is located in the turbulent boundary layer, the broadband noise source is actually located further down in the wake and more importantly, so is the peak sensitivity region
- It would not be effective to directly target the high-TKE regions in the boundary layer.
- Shape optimization should be conducted to morph the shape so as to reduce the TKE **in the wake**, where the strong quadrupole sources are.

Coupled-Sensitivity Validation



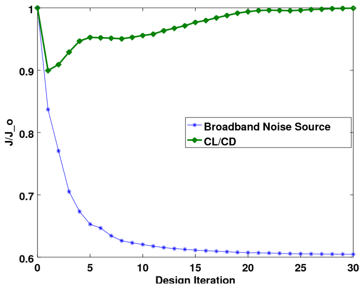
Pressure Side



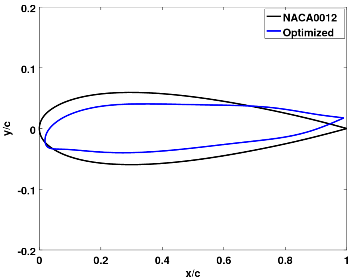
Suction Side

- Airfoil surface parameterized with 18 Hicks-Henne bump functions (9 on each surface) to enable shape deformation
- $\frac{dJ}{dx}$: design sensitivity of the broadband noise source (as predicted by RANS-SNG) with respect to the 18 shape design variables
- Coupled adjoint sensitivity validated against finite difference ($\delta = 10^{-6}$)

Broadband Noise Source Minimization



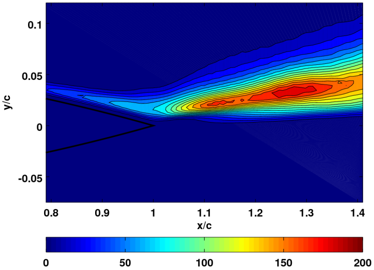
Optimization History



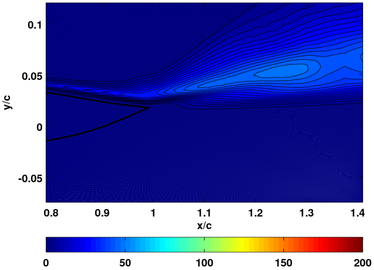
Design Comparison

- Shape parameterized with 484 FFD design variables
- Optimization process fully automated in SU2
- Broadband noise minimization performed for 30 design iterations, leading to $\sim 40\%$ reduction in design objective
- No apparent loss of aerodynamic efficiency, even though no aerodynamic constraints are applied.
- Can impose aerodynamic or geometric design constraints.

Broadband Noise Source Minimization



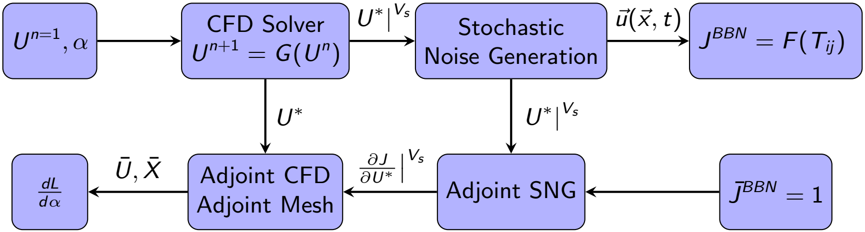
Baseline



Optimized

- Comparison: Frobenius norm of the time-averaged Lighthill's stress tensor in the trailing-edge region
- Shape optimization effectively removes broadband noise source
- Peak BBN source ($||\bar{T}||^{Frob}$) reduced by $\sim 75\%$
- This should be verified by a scale-resolving simulation
- Related publication: Towards Adjoint-based Broadband Noise Minimization using Stochastic Noise Generation, SciTech 2019

Next Steps



- Compare baseline and optimized configurations in terms of far-field BBN with LES-FWH solutions (quasi-2D)
- SNG for anisotropic turbulence
- Wave equation to propagate BBN source to solid/permeable FWH surface for far-field noise prediction
- Application to 3-D cases:
  - Optimal slat setting for a 30P30N configuration
  - Optimal shape design for flap side edge noise reduction
  - Serrated trailing edge design
  - Engine chevron design for jet noise reduction
- Extend to unsteady formulation: URANS-SNG framework for rotor/propeller broadband noise design

Future of SU2-CAA

Synergistic Activities

- NASA: Rotor/propeller noise reduction and coupling of SU2 with ANOPP2
- Collaborators/Users:
  - Stanford University: DDES+FWH and validation against experiments
  - Embraer S.A.: jet-flap interaction, propeller noise reduction, etc.
  - Chalmers: RANS-SNG method for BBN
  - Polimi: Rotor icing detection via aeroacoustics
  - TU Cottbus: Wind-tunnel tests for baseline and optimized RANS-SNG designs
  - TU Berlin: Airfoil trailing-edge noise prediction

SU2 Development Plans and Suggestions

- FWH with moving surfaces for rotor/propeller noise
- Sliding mesh capability with discrete adjoint
- SLSQP optimizer change
- LES with explicit SGS (request from users)
- Lattice Boltzmann Method
- Unsteady aero-structural capabilities