Multi-Physics Capabilities in SU2

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... and many others in the SU2 Community

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SU2

The Open-Source CFD Code

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Multi-Physics Capabilities in SU2

Aeroacoustics

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# Aeroacoustic Simulation and Optimization in SU2

## Turbulent Flow Simulation
- URANS
- DDES

## Acoustic Propagation
- 2D: frequency-domain permeable-surface Ffowcs Williams-Hawkings (FWH) of Lockard, 2000
- 3D: time-domain solid- and permeable-surface FWH (Formulation F1A of Farassat)

## Special for Broadband Noise
- RANS coupled with stochastic noise generation (SNG)

## Adjoint-based Optimization
- Coupled URANS-FWH/RANS-SNG discrete adjoint based on algorithmic differentiation (AD)
Aeroacoustic Simulation and Optimization in SU2
– The Past, Present, and Future

Initial Work

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

AVIATION 2016 (AIAA 2016-3369)  
SCI-TECH 2017 (AIAA 2017-0130)
Aeroacoustic Simulation and Optimization in SU2 – The Past, Present, and Future

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

Ph.D. Thesis
- 3D fixed-source FWH, coupled with URANS and DDES
- Noise minimization with 3D URANS + FWH, final analysis using DDES + FWH
- Preliminary validation against experiment using DDES + FWH

Current
- Extension to moving-source FWH in 3D (Formulation F1A of Farassat)
- (U)RANS with stochastic noise generation (RANS-SNG)
**Coupled CFD-FWH Noise Prediction and Optimization Framework**

- **CFD Solver:** \( U^n = G^n(U^n, U^{n-1}, U^{n-2}) \)
- **FWH Solver:** \( p'_\text{obs}(\vec{x}, t) = p'_T + p'_L = F_n(U^n|\Gamma_p, \vec{x}, t) \)
- **Adjoint CFD:** \( \tilde{U}^n = \tilde{G}^n(\tilde{U}^n, \tilde{U}^{n-1}, \tilde{U}^{n-2}) + (\frac{\partial J}{\partial U^n}|_{\Gamma_p})^T \)
- \( U^n|_{\Gamma_p} \): 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 \( \Gamma_p \)
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Baseline Rod-Airfoil
Unconstrained Noise Min.
Lift-Constrained Noise Min.

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Aeroacoustic Simulation and Optimization in SU2
Extension to 3D Moving-Source FWH

- Fixed-source FWH extended to full F1A formulation of Farassat
- Test case: rotating and translating sphere ($M_\infty = 0.5$, RPM=812 about $\hat{x}$)
- URANS-FWH result validated against static CFD pressure and NASA-ANOPP2

*On-Going Work: Omur Icke, Andy Moy, Beckett Y. Zhou, Oktay Baysal, Leonard V. Lopes and Boris Diskin
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 ($\epsilon$ or $\omega$) 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. (circa. 2000)

What RANS-SNG Method IS and ISN’T

- NOT designed to predict broadband noise to an \textit{absolute} level
- 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
Trailing-Edge Noise Minimization (SciTech 2019)

BBN source minimization performed with and without aerodynamic constraint

Shape optimization effectively reduces trailing-edge broadband noise source

In progress: verification of results with scale-resolving simulations

Details in: AIAA-2019-0002
Flap Side Edge Broadband Noise Minimization
Aeroacoustic Simulation and Optimization in SU2

Reference Publications


Future Work

- Aeroacoustic optimization of rotor and propeller blades
- Propagation of SNG noise source using high-order SU2-DG solver
- Machine learning for SNG using LES data
Multi-Physics Capabilities in SU2

Fluid-Structure Interaction

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**Coupled FSI Solver**

- Fully **Implicit**, coupled solver
- ALE Formulation
- Geometrical **Non-Linearity**
- Complex material model
- Consistent **interpolation** on domain-filling discretizations
- Elastic solver for **mesh movement**
- Fully **differentiated** using AD

First Paper:

Coupled FSI Solver
Coupled FSI Adjoint Solver based on Algorithmic Differentiation

For details of coupled-adjoint formulation:


Coupled FSI Adjoint Solver based on Algorithmic Differentiation

Electro-mechanically Actuated Membrane Wings


Optimal Actuation of Dielectric Membrane Wings using High-Fidelity Fluid-Structure Modelling
AIAA paper 2017-0857, presented at Scitech 2017

FSI Solution → Input → Non-linear Solver → Output → Performance

- Large Deformations
- Non-linear Material Model
- Electric effects
- Viscous flow
Shape Optimization of FSI

Optimization problem

Area ($A \geq A_0$), lift ($c_l = 0.5$), and deformation ($\delta_{TE} \leq \delta_{max}$) constrained, drag minimization. Constraints at low Mach number (0.25), objective at high (0.75).

*Preliminary Results from Pedro Gomez & Rafael Palacios (Imperial College London)
Shape Optimization of FSI

*T.E. displacement constrained to 10mm

*T.E. displacement constrained to 6mm

*Preliminary Results from Pedro Gomez & Rafael Palacios (Imperial College London)
Topology Optimization of FSI

Fixed external shape of the 6 mm case, elasticity modulus doubled, weighted objective (80% drag, 20% mass).

*Preliminary Results from Pedro Gomez & Rafael Palacios (Imperial College London)
Multi-Physics Capabilities in SU2

Conjugate Heat Transfer

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Heated Cylinder in Fluid Flow – A Multi-Zone Problem

Let

- $G^{(1)}$ be a **RANS solver** and
- $G^{(2)}$ a **heat solver**,

both coupled by transferring temperature and heat flux data at their interface.

- $D = 0.5\,\text{m}$, $D_c = 0.25\,\text{m}$
- $V_\infty = 3.4\,\frac{\text{m}}{\text{s}}$, $\text{Re} = 40$
- $T_\infty = 288.15\,\text{K}$, $T_c = 350\,\text{K}$
- same material properties, except $\lambda_s = 5\lambda_f$
3D Test Case

- Heated aluminum cylinder (height/diameter: 5mm/2mm)
- Coolant: water with inflow conditions set at 0.25 m/s, 300K (incompressible solver)
- 4W heat load applied at tip of the pin
- Equilibrium at mean tip temperature of 319K (good agreement with FLUENT)
Coupling under Unsteady and Turbulent Flow Conditions

By its dual-time stepping approach,

- a steady simulation can easily be turned into an unsteady one

and by its modular design,

- other kinds of solvers can be chosen easily.

In the example, change the Reynolds number to 1000 and (optionally) set

`KIND_TURB_MODEL= SA`
`HYBRID_RANSLES= SA_EDDES`
Transient Conjugate Heat Transfer

Based on a Strouhal number of 0.21, we expect a frequency of 1.4Hz, so let us repeat the CHT test case with physical time steps of 0.03s (in total 45s).

(Initial temperature of the cylinder set to 288.15K.)
Now that we are able to compute accurate primal solutions, can we use our solver to also compute accurate gradients?

Yes, by discrete adjoint solutions based on the same fixed point iterator $G$. 
Discrete Adjoint for Multi-Zone Problems

From an abstract point of view,

$$\lambda = \nabla_u \tilde{J}(X, U) + D_u \tilde{G}^T(X, U) \cdot \lambda$$

also is covering the case where $G$ is the combination of several $G^{(k)}$, i.e. we need an implementation of

$$\lambda_{(k)}^{(n+1)} = \frac{\partial \tilde{J}^T}{\partial u_{(k)}}(X, U) + \frac{\partial G^T}{\partial u_{(k)}}(X, U) \cdot \lambda^{(n)}$$

Though attention has to paid to evaluate all derivatives correctly (the full vectors $\lambda$ and $\partial G / \partial u_{(k)}$, involving cross dependencies, appear on the right side).
Adjoint Sensitivities for Conjugate Heat Transfer

In our 2D-CHT example,

- \( \frac{\partial}{\partial u^{(1)}} G^{(2)} \) constitutes the heat solver’s dependence on the heat fluxes and
- \( \frac{\partial}{\partial u^{(2)}} G^{(1)} \) constitutes the flow solver’s dependence on the temperature distribution at the interface,

giving the coupled adjoint solution \((\lambda_1, \lambda_2)\). E.g., for \( J \) being the heat flux, the deduced sensitivities have contributions from both zones:
Conjugate Heat Transfer in SU2

Reference


Future Work

- Couple CHT and turbomachinery functionalities for cooled turbine blade optimizations
Multi-Physics Capabilities in SU2

NonEquilibrium MOdels (SU2-NEMO)

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Basis of SU2-NEMO

Initial efforts by Sean Copeland (PhD, 2015, Stanford University): “A Continuous Adjoint Formulation for Hypersonic Flows in Thermochemical Nonequilibrium”

- continuum, steady, viscous, multi-component, gas mixture in thermochemical nonequilibrium
- Transport properties
  - Diffusion — Fick’s Law w/ closure terms
  - Viscosity — Newtonian fluid w/ Stokes’ Hypothesis
  - Thermal Cond. — Fourier’s Law
- Transport coefficients: Blottner/Eucken + Wilke’s semi- empirical mixing rule
- Landau-Teller vibrational relaxation with Park’s limiting cross section
- Finite-rate chemistry (Arrhenius-type)
- Derivation of continuous adjoint system
Coupling with Mutation++

Mutation++: An open-source library developed at VKI, designed to couple with conventional CFD codes to provide thermodynamic, transport, chemistry, and energy transfer properties associated with subsonic to hypersonic flows.

- Thermodynamic properties
- Multicomponent transport properties
- Finite rate chemistry in thermal nonequilibrium
- A robust multiphase equilibrium solver
Hypersonic Double Wedge Configuration

a) Temperature [K]  
b) Numerical Schlieren

- Mach 9
- Nonequilibrium shock interference patterns
- 5-Species, (79% N2, 21% O2) freestream
Towards Hypersonic Vehicle Design

- Grid independence study on X43-like hypersonic vehicle and access-to-space systems
On-Going Efforts

- Implementation of subsonic, characteristic-based outlet boundary
- Validation and verification of Navier-Stokes solver/boundary conditions (Space shuttle wing or Mars entry vehicle)
- Discrete adjoint sensitivity (Validate using RAM-C II case)
- Verify TNE2 source terms at low speed/temperature regimes
- Transitional flow prediction using RANS-style modeling
Multi-Physics Capabilities in SU2

Helicopter Blade Kinematics

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Helicopter Blade Kinematics in Forward Flight

In forward flight, experience a blade normal velocity which depends on the azimuthal position:

\[ M_n(\psi) = M_{tip} \frac{r}{R} + M_\infty \sin \psi = M_{tip} \left( \frac{r}{R} + \mu \sin \psi \right) \]

The differences in the blade normal velocities combined with the requirement that the rotor does not produce pitching or rolling moments is the main challenge.

Flapping hinge introduced eliminating the rolling moment which arises in forward flight. Flapping causes large Coriolis moments in the plane of rotation and the lag hinge is provided to relieve these moments. Lastly the pitching hinge allows the blade to be pitched.
Helicopter Blade Kinematics in Forward Flight

- Modeled within SU2 using a helicopter fixed-frame of reference
- Blades are rotating around the z-axis
- The order of the flapping, lead-lag and pitching motion is important.
- Created a new grid movement type called ROTORCRAFT
- At each iteration, apply the blade rotation as a volumetric grid movement
- Then apply the blade kinematics as a surface movement.
Helicopter Blade Kinematics in Forward Flight

- New config options required for a ROTORCRAFT simulation
Helicopter Blade Kinematics in Forward Flight

- Caradonna-Tung rotor with untwisted NACA0012 airfoil, rotating CCW
- Mesh available in TestCase folder
Helicopter Blade Kinematics in Forward Flight

Reference


Future Work

- Validate the flow field of the resultant blade kinematics. HART-II experimental test campaign has been selected. This experimental test case will also allow us to assess the acoustics produced from the main rotor in descending flight when strong BVI is present.

- Once at a stage where there is complete verification of the method and validation of the results there will be a pull request to merge the feature_ROTORCRAFT branch into the main release branch.

- Modeling the elastic nature of the rotor blades is also being considered through the coupling of the open-source multibody dynamics software, MBDyn with SU2 using the open-source coupling library, preCICE.

- Rotor blade shape optimization to improve aerodynamic and aeroacoustic performance (joint work with Beckett Y. Zhou, TU Kaiserslautern)