Introduction

- The objective of this work is to prove the capability of STAR-CCM+ as a Computational Fluid Dynamics (CFD) software in the analysis of airfoil aero-acoustic and far-field noise propagation.
- This work in this report focuses on the aeroacoustic performance of a NACA0012 series airfoil.
- Test conditions for the airfoil are listed on the following slide.
- The goal is to determine the peak sound pressure level (SPL) relative to 3rd octave frequency bands and the frequency that produces the peak SPL.
- Frequency range of interest for this analysis is between 1 kHz and 1000 kHz.
- The work outlined in this report is based on the following publication:
  - NASA Reference Publication 1218, July 1989
    Airfoil Self-Noise and Prediction
    Thomas F. Brooks, D. Stuart Pope and Michael A. Marcolini
- Documented results for SPL are plotted in 3rd octave frequencies bands in figure 52 of the NASA publication. The solid black line represents the experimental results.
Experimental Data

Test Conditions:

- Freestream Mach Number: 0.208 (71.3 m/s)
- Freestream Temperature: 300 K
- Freestream Reynolds Number: 1.13E6 (at 0.2286 m)
- Freestream Viscosity: 1.71E-5 Pa-s
- Airfoil Angle of Attack: 7.3 degrees
- Airfoil Chord Length: 0.2286 m
- Airfoil Span: 0.4572 m
- Trailing edge thickness: 0.001c
Airfoil and Computational Domain

- Airfoil: NACA0012
- Angle of Attack 7.3 degrees
- Airfoil Span: 0.1286 m
- Freestream Diameter: 2.4 m
- Trailing Edge Thickness: 0.001c (2.286E-4 m)
Mesh Continuum (Air)

- Mesh Models:
  - Surface Remesher
  - Trimmer
  - Prism Layer Mesher
- Reference Values:
  - Thickness of near Wall Prism Layer: 1E-5 m
  - Base size: 4 mm
  - Maximum cell size: 1600%
  - Number of prism layers: 20
  - Prism layer thickness: 5 mm
  - Surface size:
    - Relative minimum size: 1 mm
    - Relative target size: 2 mm
  - Template Growth Rate:
    - Default growth rate: Slow
    - Boundary growth rate: Medium
Mesh Volumetric Controls

Cylinder 1

Cylinder 2

1 mm

2 mm
Volume Mesh

- Section Cut: Z=0.05715 m
- Prism Layers: 20
- Prism Layer Thickness: 5 mm
- Prism Layer Stretching: 1.28
- Predominantly hexahedral cells in the free stream domain.
Steady State Physics

- Physics Models:
  - Air
    - Three Dimensional
    - Steady State
    - Ideal Gas
    - Segregated Flow Solver
    - Segregated Energy Solver
    - K-Omega SST Turbulence
    - All Y+ wall Treatment
    - Aeroacoustics
    - Broadband Noise Sources
    - Lilley Sources

- Reference Values:
  - Reference pressure: 101325 Pa

- Initial Conditions:
  - Static Pressure: 0.0 Pa (gage)
  - Static Temperature: 300K
  - Turbulence Intensity: 0.01
  - Turbulent Viscosity Ratio: 10
  - Velocity: [71.3, 0, 0] m/s
Boundary Conditions

Boundary Conditions:
- Free Stream:
  - Mach Number: 0.208
  - Static Temperature: 300 K
  - Turbulence Intensity: 0.01
  - Turbulent Viscosity Ratio: 10
Steady State Lift and Drag Coefficients

- Force coefficients:
  - Published:
    - Lift Coefficient: 0.800
    - Drag Coefficient: 0.0113
  - Simulation:
    - Lift Coefficient: 0.792
    - Drag Coefficient: 0.0180
  - Reference values:
    - Area: 2.96557E-2 m²
    - Velocity: 713 m/s
    - Density: 1.17683 kg/m³
Steady State Mesh Cutoff Frequency

- Mesh Cutoff Frequency measures the mesh’s ability to capture a given frequency:
  - Formulation is based on turbulent kinetic energy and cell volume.
  - This tells us that the mesh is red is capable of capturing 1000 Hz.
  - ISO surface shown is MCF = 1000 Hz.

\[
F_{MC} = \frac{\sqrt{2k}}{2V^{\frac{1}{3}}} (Hz)
\]
Unsteady LES Physics

- Air:
  - Three Dimensional
  - Implicit Unsteady
    - Discretization: 2nd Order
  - Ideal Gas
  - Segregated Flow Solver
    - Convection: Bounded-Central
  - Segregated Energy Solver
  - LES Turbulence
    - Wale Subgrid Scale Model
  - All Y+ Wall Treatment
  - Aeroacoustics
    - Fwocs Williams-Hawkings

- Reference Values:
  - Reference pressure: 101325 Pa

- Initial Conditions:
  - Started from Steady State RANS calculation.
Time Step and Duration

Calculate the time step based on the highest frequency to be resolved:

\[
TimeStep[s] = \frac{1}{10 * MaximumFrequencyResolution[Hz]}
\]

- Highest frequency to be resolved: 10,000 Hz
- Time step: 1E-5 s

Calculate the duration based on the minimum frequency to be resolved:

\[
Duration[s] = \frac{20}{MinimumFrequencyResolution[Hz]}
\]

- Minimum frequency to be resolved: 1,000 Hz
- Duration: 0.02 s
Unsteady LES Lift and Drag Coefficients

- Force coefficients:
  - Published:
    - Lift Coefficient: 0.800
    - Drag Coefficient: 0.0113
  - Simulation:
    - Lift Coefficient: 0.8428
    - Drag Coefficient: 0.0122
  - Reference values:
    - Area: 2.96557E-2 m²
    - Velocity: 713 m/s
    - Density: 1.17683 kg/m³

- Viewing the lift and drag coefficients on a per iteration basis allows us to ensure convergence within the time step.
- 15 inner iterations are used to achieve convergence within the time step.
Scalar Contours

Solution Time = 0.0601
Time Level = 6010
Pressure Probes

- Pressure probes around the airfoil surface at mid-span track pressure fluctuations as a function of time.
- Pressure probes are numbered 1-18 from the leading edge of the airfoil past the trailing edge of the airfoil.
- Tracking pressure allows us to determine when the pressure fluctuations become stable.

- Viewing the pressure fluctuations on a per iteration basis allows us to ensure convergence within the time step.
- Only 8-10 inner iterations are required to achieve convergence within the time step. This is less restrictive than the force convergence requirement.
FWH Receivers

- Receiver locations listed in NASA publication:
  - M1: [ 0.2286 , 1.22 , 0.05715 ] m
  - M2: [ 0.2286 , -1.22 , 0.05715 ] m
  - M4: [-0.3814 , 1.05655 , 0.05715 ] m
  - M5: [ 0.8386 , 1.05655 , 0.05715 ] m
  - M7: [-0.3814 , -1.05655 , 0.05715 ] m
  - M8: [ 0.8386 , -1.05655 , 0.05715 ] m

- For the sake of acoustic analysis, a single observer point located at receiver point M1 is used for spectra analysis.

- The time it takes the pressure fluctuations to propagate from the FWH surface to the FWH receiver depends on speed of sound of the surrounding media and distance between the surfaces and receivers.

\[
\text{Time}[s] = \frac{\text{Distance}[m]}{\text{Speed of Sound}[m/s]} = \frac{1.22}{340} = 0.00359[s]
\]

- Sufficient duration of the analysis is required to wash out any transient effects in the receiver data and must also be sufficient to capture 0.02 s of statistically stable data.
Sound Pressure Level (LES)

- Receiver data processed using a Fourier Transform of sound pressure level versus 3rd octave frequency bands.

- A factor must be added to the overall SPL to account for the variation in span from the experimental airfoil to the analysis airfoil:

\[
SPL[dB] = 10 \log_{10} \left( \frac{L_{\text{Experiment}}}{L_{\text{Analysis}}} \right) = 10 \log_{10} \left( \frac{0.4572}{0.1286} \right) = 5.5[dB]
\]

- Simulation Peak SPL: 65.5 dB
  - Exact center frequency: 1589.9 Hz
- Experiment Peak SPL: 67 dB
  - Exact center frequency: 1258.9 Hz
Setup & Run Statistics (LES Analysis)

- **Compute Resources:**
  - Processor: Intel Xeon
  - RAM per processor: 2 Gb
  - Number of processors: 40
  - Processor Speed: 2.6 Ghz
  - Number of compute cells: 9.5 M
  - Operating System: LINUX 64-bit

- **Total run time:**
  - Simulated Time: 0.04 s
  - Wall Clock Time: 89 hrs (3.7 days)
  - Wall Clock Time per Iteration: 5.34 s
  - Wall Clock Time per Time Step: 80.1 s (15 inner iterations)
- Sound Pressure Level Results (1000 – 10000 Hz frequency range):
  - Experiment Peak SPL: 67 dB
  - Simulation Peak SPL: 65.5 dB (2% difference)
  - Peak frequency: 1589.9 Hz (1 band difference)
- Setup and simulation time for LES analysis: 4 days
A similar acoustic analysis was performed using a unsteady RANS turbulence model (K-Omega SST).

The objective was to determine if using a URANS based turbulence model will predict the correct frequency at which the peak sound pressure level is achieved. In a similar manner, the receiver data is processed using a Fourier Transform to obtain a sound pressure level versus 3rd octave band frequencies.

The SPL was then adjusted to account for the span of the experimental airfoil.

Simulation Peak SPL: 60.5 dB

- Exact center frequency: 1258.9 Hz

Experiment Peak SPL: 67 dB

- Exact center frequency: 1258.9 Hz
Conclusion

- Though the main focus of this work was within the 1 kHz to 10 kHz frequency range, increased resolution of the acoustic spectra at frequencies below 1 kHz can be gained by running the analysis for a longer duration. This will allow for a sampling of acoustic data that is greater than 0.02 s.
- It is speculated that the accuracy of the acoustic spectra at frequencies below 1 kHz can be influenced by the span wise length of the analysis airfoil.
- The results of the analysis shows good correlation with experimental data in the 1 kHz to 10 kHz frequency range for the stated free stream test conditions.
Additional Work

- The mesh was modified to remove the boundary layer mesh at the trailing edge of the airfoil.
- Cell quality at the blunt trailing edge was improved by removing the boundary layer mesh which resulted in better quality trim cells at the trailing edge as compared to highly skewed prism layer cells.
- In addition to improving cell quality, the overall cell count in the volume mesh was reduced from 9.5 million cells to 5.9 million cells. This is a reduction of 38% in the volume mesh.
- This model was analyzed using the same LES approach as with the first model.
- As shown in the sound pressure level plot below, the results for the new mesh are comparable to the results for the initial mesh.
- The overall run time is significantly reduced from approximately 5.34 seconds per iteration to 3.5 seconds per iteration which for the same number of inner iterations reduces the overall run time from 89 hours to 58 (a 34% reduction).