Direct Numerical Simulations of Turbulent Flow Past Airfoils and Flat Plate Trailing Edges

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Outline

• Introduction/Motivation
• Governing equations
• General features of DNS code
• Results:
  – Simulations of flat plate trailing edges
  – Simulations of NACA0012 aerofoils
• Early-user experience on HECToR
• Summary/Outlook
Introduction

• For modern aircraft in approach, fan noise and airframe noise main contributors of perceived noise on the ground

• Aerofoil noise from onshore wind turbines considerably limits their public acceptance despite economical and political need for renewable energy production

• Trailing edges one of main sources of noise, in particular for low Mach numbers

→ A detailed understanding of TE noise beneficial for design of quieter aircraft, propulsion systems and wind turbines
Introduction

Goal of present research:

**conduct DNS of turbulent flows past trailing edges**

- Investigate hydrodynamic field in the vicinity of trailing edge
- Evaluate broadband noise in far field
- Provide insight in mechanisms of sound generation
Introduction

What is DNS?

• Governing equations for fluid motion (Navier-Stokes equations) solved without modelling

• All length- and time-scales need to be resolved by the numerical grid and the time integration

• Important non-dim parameter: Reynolds number
  → ratio of inertial over viscous effects of a fluid

• for increasing Re, range of length/time scales larger in particular size of smallest scales decreases
  → grid resolution needs to be finer, especially at walls
Introduction

• Solving the full N-S equations to directly compute both far-field sound and near-field hydrodynamics desirable
  
  - With DNS avoid difficulties of commonly used hybrid approaches (coupling of numerical methods, storage of intermediate data, sensitivity to integration surfaces)
  - Uncertainties in turbulence models for noise prediction eliminated

Cases:

1. To reduce cost, consider infinitely thin flat plate with turbulent B-L on one side as generic example of sharp TE

2. Full airfoil geometry – limit is the total size of simulation → higher complexity of flow requires smaller Reynolds number
Governing equations

• Assume fluid to be ideal gas with constant specific heats
• Solve compressible continuity, momentum and energy equations in general coordinates
• Molecular viscosity through Sutherland’s law
• Pressure through equation of state

→ Five coupled nonlinear PDE that need to be solved on each grid-point for every iteration
Numerical Method

Code based on PCHAN / SBLI code

- 4th-order accurate centred scheme
- Carpenter 4th-order accurate boundary scheme
- 4th-order accurate low-storage Runge-Kutta
- no upwinding, artificial dissipation, or explicit filtering
- stability by: entropy splitting of nonlinear terms / Laplace formulation of viscous terms
- nonreflecting zonal characteristic boundary condition → highly effective / free of coefficients
Optimising Code for HPCx

• Number of allocated 3D arrays minimised

• Mass libraries linked and used for mathematical operations (e.g. $1/\rho$, $T^{1/2}$, etc)

• Redundant copying of data eliminated

• Reordered loops

→ achieved more than 50% increase of performance
Results – Flat plate

DNS of 3-D turbulent boundary layer

- Total: $106 \cdot 10^6$ points
- Memory size: ~ 59 Gb
  - Divided into 16 x 32 = 512 CPUs
- Require at least 80,000 iterations
  - 300,000 AUs
Results – Flat plate

Contours of spanwise vorticity in vicinity of TE

Iso-surfaces of Q coloured by streamwise vorticity
Results – Flat plate

Skin friction in vicinity of the trailing edge – important for drag prediction

Spanwise correlation length – used in models for noise prediction

Good agreement of theory with DNS data
Results – Flat plate

Main objective is investigation of trailing edge noise

Is trailing edge noise represented accurately by DNS?

- top side: TE noise superposed with noise of B-L and inflow
- bottom side: TE noise only

Key advantage of DNS with turbulent B-L on one side only
Results – Flat plate

To derive modified theory – assumed 2-D sound radiation

μ₀=16.2

• No spanwise variation at lower frequencies
• Spanwise variation at frequencies μ₀≥60

μ₀=85

At lower frequencies 2-D radiation assumption appears valid
Results – Airfoil

DNS of NACA-0012 airfoil, $\alpha=5^\circ$:

- $M=0.4$, $Re_c=50,000$

- Complex grid (variety of flow regimes):
  - Laminar boundary layer and separated shear layer
  - Transition to turbulence
  - Turbulent boundary layer and turbulent near-wake

Iso-contours of streamwise vorticity
Results – Airfoil

DNS of NACA-0012 airfoil at $\alpha=5^\circ$: $M=0.4$, $Re_c=50,000$

- large domain size
- resolve acoustic waves
- resolution requirement: 2571x693x96 points
  $\Rightarrow$ $170 \cdot 10^6$ points
  $\Rightarrow$ Memory size $\sim 94$ Gb

- anti-symmetric radiation
- additional noise sources

512 CPU
$\Rightarrow$ 500,000 AUs (HPCx)
Results – Airfoil

DNS of NACA-0012 airfoil at $\alpha=5^\circ$: $M=0.4$, $Re_c=50,000$

- Acoustic pressure for individual frequencies
  - $\mu_0 \approx 2.0$
  - $\mu_0 \approx 3.7$
  - $\mu_0 \approx 9.7$

- For specific frequencies sound radiation anti-symmetric
- Additional sources present – not predicted by TE theories

→ Ongoing research
Results – Airfoil

Effect of low energy forcing on lift and drag

• Forcing added to trigger transition (3DF):
  - \( C_L \) increases
  - \( C_D \) stays approximately the same

• When forcing removed (3DU):
  - \( C_L \) stays approximately the same as case in forced case
  - Pressure drag, and hence total \( C_D \), increases significantly

Presence of forcing increases L/D by 23%
Early-user experience HECToR

• Took HPCx version of DNS code
  → compiled without modifications to source code on HECToR

• Due to significantly larger number of CPUs available:
  code was modified such that domain can be decomposed into larger number of sub-domains

→ Porting went smoothly and took less than half a day
Early-user experience HECToR

Mixing layer

Two streams with velocity ratio of 10:1 mix downstream of a splitter plate → generic example for many applications with shear layers, e.g. jets

2D Case:

- 4000x512 points → 1.1Gb memory
- 12.29 CPU s/step (64x16=1024 CPU)
  - 10.24 CPU s/step (128x16=2048 CPU) → superlinear speed-up due to cache-effects?
Early-user experience HECToR

Mixing layer – full 3D case

- $4000 \times 512 \times 225 = 460 \times 10^6$ points $\rightarrow$ 258Gb memory (biggest CFD simulation run in the UK to date?)
- 225 planes x 12.29 CPU s/step = 2,765 CPU s/step vs 10,553 CPU s/step (actual)
Early-user experience HECToR

NACA-0006 airfoil

- 2586x691x96
  - = 171x10^6 points
- Distributed on
  32x32=1024 CPUs
- 3,280 CPU s/step

- vs 4,217 CPU s/step
  HPCx (512 CPU)

→ better performance than on HPCx for large job
Summary

• Direct Numerical Simulations of turbulent flows performed on HPCx and HECToR

• Simulations lead to improved modelling of flow in vicinity of trailing edges

• Elements of currently used prediction models for noise validated using DNS data

• Additional noise sources observed in DNS → bases for next project?

• Porting of code to HECToR without problems performance better than HPCx for large number of CPUs
END