Research Directions in Unsteady Aerodynamics

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Boeing Commercial Airplanes

*with Strelets and Squires
Outline

• Theory: )-:

• Computational Fluid Dynamics
  – Resolved and modeled motion in ~ LES
  – SRANS; 2DURANS; 3DURANS; DES; LES
  – Resolution issue in DES/LES publications
  – Different “kinds” of unsteadiness?

• Diversion: LES of Jets and their Noise

• Experiments
  – Motivation
  – Number of dimensions
  – Transition
  – Circular cylinder, a wish list

• Summary
  (other diversion: DNS of a LEBU?)
Computational Fluid Dynamics

• Resolved and modeled motion in ~ LES
  – Ideally, the split follows clear filtering or averaging operation
  – Concretely, the split is controlled by the eddy viscosity, be it called RANS or SGS
  – Fundamental difficulty in LES remains “wall modeling”
    • QDNS, Quasi-Direct Numerical Simulation (e.g., channel at Re$_\tau$ = 1000, with $\nu_t / \nu \sim < 2$) is un-interesting. Aim at $\Delta z^+ = 1000$, then $10^4$!
      • Accounting for the filter is especially tricky.

• Acronyms
  – RANS
    • Steady: SRANS
    • Unsteady: URANS
      – Two-dimensional: 2DURANS
      – Three-dimensional: 3DURANS (even in 2D geometry)
  – DES (3D Unsteady, boundary layers by RANS)
  – LES (3D Unsteady, boundary layers by LES, due in 2045, EVEN with wall modeling)
Resolved Solution in Different Approaches

- SRANS
- 2D URANS
- LES or DES, coarse grid
- LES or DES, fine grid

Cylinder with laminar separation

By Strelets group
DES of F-15 at 65° α

Courtesy of Forsythe, Squires, Wurtzler

BL Grid, RANS model

Vorticity colored
With pressure

Re = 13.6 × 10^6; lift, drag, moment within 5% 10^7 cells/side, Cobalt code, US DOD CPU
Turbulent CFD: Resolution Issue

• RANS
  – Grid convergence is easy to define…
  – And easy to achieve, even to “overkill”

• DES, LES
  – Grid convergence is not easy to define
  – The order of numerical convergence is unclear
  – We “know” a flow field with more, smaller eddies is “better”
  – It is difficult to please journal editors, as author or reviewer
  – Ideally, we’d show a neat LES, and run one 16 times bigger, simply as a check…

• DNS
  – Grid convergence again easy to define
  – We limit ourselves with the Reynolds number
  – We never “overkill” (almost never…)

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Different “kinds” of unsteadiness?

• Driven by boundary conditions
  – Low-frequency. No particular trouble
  – Medium- or high-frequency. Trouble for RANS

• Spontaneous
  – All turbulent flows have unsteadiness
  – Some have a “gross” unsteadiness, e.g., vortex shedding
    • Exists even in non-turbulent cases (e.g., cylinder at Re = 100)
    • Easy to capture, even in 2D CFD
    • Not as simple as it seems
    • Strong modulations destroy the motivation for phase-averaging.
      Seen in LES/DES, AND in Cantwell-Coles Expt.
  • 2DURANS is easy, highly periodic… and inaccurate!
Force Histories on a Circular Cylinder

---- Case 1
- - - Case 2

Laminar Separation
Forces Averaged over 2*D spanwise
The prospects for 3D URANS

• Work with Shur, Strelets, Travin, and Squires
• 3D simulations in 2D geometries, with periodicity
• Prompted by findings of Vatsa and Singer
• We used to expect RANS would force 2D
• Will show cylinder (airfoil and square-cylinder act similar)
• Findings:
  – Most often, the three-dimensionality survives
  – It is much less fine-grained than in DES or LES
  – It does not improve with grid refinement
  – The global results (pressures, drag) are much better than from 2D URANS…
  – But they depend on the spanwise period and the RANS model, and usually do not catch up to DES
The “Look” of DES and 3DURANS Flow past a Cylinder, Laminar Separation

DES, period repeated  
URANS, single period
Prediction of Jet Noise from First Principles

• Work with Shur and Strelets in St-Petersburg
• Turbulence:
  – LES
  – ~ 2 million points, on a PC
  – SGS model disabled, for now
• Sound:
  – Ffowcs-Williams/Hawkings formula, “adapted”
  – Permeable surface close to jet
• Performance:
  – Able to treat dual nozzles in co-flow, hot jets, chevrons, and imperfectly-expanded jets with shocks
  – Accurate within 2-3dB over a relatively wide range
  – Limited to Strouhal number ~ 2 (300Hz, for 777)
Turbulence + Shock Cells in Sonic Jet
by Shur & Strelets

Numerical “schlieren” from LES of under-expanded sonic jet

Movie not available
Broad-band Noise
due to Shock Cells in Sonic Jet
LES and Experiment

Sound Intensity, dB

Observer Angle

Rear

Front

SONIC UNDER-EXPANDED JET

SUPERSONIC PERFECTLY EXPANDED JET

Under-expanded sonic and perfectly-expanded supersonic jets with $M_{\text{FULLY-EXPANDED}} = 1.372; T_{\text{FULLY-EXPANDED}} = 1$
Experiments

• Motivations
  – DNS, “Definitive Numerical Simulation” not possible
    • Geometry
    • Reynolds number
    • Small perturbations that control transition
      – Inflow
      – Noise
      – Surface
    • New, finer quantities needed
      – Far-field noise
      – Flow structure over very large scales
  – Study the instrumentation, not the flow?

• Two or three dimensions?
  – “3D issues” were already big at the Stanford Olympics
  – The value of “2D” flows is much lower because of:
    • Higher CFD power
    • Higher accuracy standards
Situation of the Circular Cylinder

• This flow is a Classic
  – Simple shape
  – Sensitive to transition, smooth-wall separation, and massive separation
  – Has odd flow regimes, such as permanent asymmetry
  – Good place to make CFD fail!

• The experimental job is not finished
  – Experiments disagree tangibly:
    • For Reynolds numbers in the millions
    • Just where we thought we had simpler physics!
  – Transition and separation appear mingled, even at $4 \times 10^6$
    • Or else, we have reattachment, and turbulent re-separation?
    • Current RANS turbulence modeling is at a loss
    • RANS can do “Laminar Separation” OR “Turbulent Separation”
    • A “microscopic” DNS of the separation region could be neat
Pressure on Circular Cylinder, Reynolds number in the Millions

The two best experiments differ by $C_p \approx 0.3$, which gives CFD a place to hide!

DES, with various grids and models. Early transition 2000

Van Nunen 1974 $7.6 \times 10^6$

Roshko 1961 $8.5 \times 10^6$
Skin Friction on Circular Cylinder, Reynolds number in the Millions

DES, fully Turbulent BL, Re = 3 \times 10^6

Expt, free transition, Re = 3.6 \times 10^6
A Wish List for the Circular Cylinder

• Reynolds number all the way:
  – From inception of drag crisis, \( \sim 10^5 \)
  – To fully-turbulent boundary layers, \( \sim ?? \) \( 10^6 \)

• Wind tunnel:
  – High aspect ratio. We could do the CFD with side walls
  – Acceptable blockage and Mach number

• Transition:
  – Natural
  – Tripped, at moderate Reynolds number, \( \sim 10^5 \)
  – Tripped on one side, compared with natural asymmetry

• Measurements:
  – Pressure and skin friction
  – Unsteady forces
  – Spanwise correlation
  – Reynolds stresses?
Summary

• “Unsteadiness” is all over turbulence
• Turbulence simulations bring up “strategic decisions”:
  – what to resolve, what to model?
  – beware of simplistic concepts of unsteadiness
• Sadly, the practice with RANS and SGS models
  – rarely is clearly tied to a filter
  – especially with wall modeling, which is a must
• Transition is the most delicate aspect in some cases

• Experiments must be very well-documented
• Being 2D is not that helpful any more
• They may often be limited by instrumentation
• Transition needs to be understood/dictated
• The circular cylinder remains a fabulous sand-box
“Industrial” Direct Numerical Simulation: a Large-Eddy Break-Up (LEBU) device

- Work with Travin and Strelets
- Motivation
  - Aerodynamic noise in airliner cockpits
  - Value of a small, passive, simple device
  - Applicability to other vehicles?
- Objectives
  - Reduce wall pressure fluctuations of TBL (one that is attached to start with)
  - Reach benefit of several dB
  - Beat “rule of thumb” that a TBL recovers in 10 $\delta$
Turbulence-Damping Device

(ignore red circles)
“Industrial” Direct Numerical Simulation: a Large-Eddy Break-Up (LEBU) device

• Approach
  – DNS at $R_\theta \sim 1000$ (OK, since focus is on $St_\delta < 1$)
  – Multi-block high-order implicit code
  – Turbulent inflow by simplified Lund-Wu-Squires recycling; uses up less than 5 $\delta$

• Findings
  – Vortex generators tried first. They reduce TKE, as expected, but not the wall pressure rms
  – LEBU, looking like “highway bridge”, lowers $p'$ rms by 30% (or 3dB), but only over ~ 30cm
  – We have not optimized the design

• Experiment
  – In wind tunnel, with extensive measurements + structural model of window
  – In flight!
Effect of LEBU in Turbulent Boundary Layer
Effect of LEBU in Turbulent BL

Pressure rms

Pressure spectra

1/3-octave