Detached-Eddy Simulation of a Linear Compressor Cascade with Tip Gap and Moving Wall*)

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Motivation and Objectives

• Vortex-dominated endwall flows are typical of aircraft engines fans and compressors and affect both the aerodynamic efficiency of the engine and the noise it generates

• The internal unsteadiness of the tip-clearance flows and a wide range of important scales make their numerical modeling a great physical and computational challenge

  ➢ A promise of RANS-based CFD approaches as applied to vortex-dominated flows is vague, even with DRSM; for highly loaded turbomachinery blade rows in near stall and stalled airfoil performance such approaches are not “good enough”

  ➢ Even a “perfect” RANS model “by definition” would provide only mean flow characteristics which is not sufficient for noise prediction

  ➢ An LES is potentially capable of both predicting mean flow parameters and resolving most of the energy containing vortices, but is still far from affordable for complex flows typical of turbomachinery
Motivation and Objectives

- This situation and, also, promising results obtained with DES for a wide range of vortex-dominated separated flows makes it a tempting alternative to an LES

- A long-term objective of the project is to formulate strategies of DES implementation for these types of flows, which are tangibly more complex

- The specific flow considered is a linear compressor cascade with a tip gap and moving end wall (“Virginia Tech Cascade”) studied in the experiments of W.J. Devenport with coauthors
Flow Geometry

Plan view of the cascade wind tunnel (all dimensions in millimeters)
Flow Geometry

Cross section through the cascade taken along the inlet flow direction
VTC Flow IS a Challenging Test for DES

• The regime is not stalled, with no massive separation over the blade
• After crossing the inter-blade passage, the tip leakage vortex may interact with the boundary layer of the “next” (downstream) blade. This means that the vortex with some “turbulent content” (resolved turbulence) may mingle with the attached TBL treated in RANS mode. This situation is not typical of DES applications in the external aerodynamics
• An interaction is also possible of the tip-clearance vortex and tip separation vortex with the spanwise trailing-edge vortices. This imposes severe demands on the numerical resolution in the blades’ near wake region
• The tip gap is narrow (1.65% of the blade height, less than the incoming BL thickness) and so a very fine grid is needed inside the clearance. This may cause premature switch of DES to its LES eddy-viscosity level (“GIS”) in the BL on the moving wall. Therefore:
  - DDES or “F₂” option of DES should be turned on
Problem Setup

Symposium on Hybrid RANS-LES Methods

The setup strictly corresponds the experimental flow conditions

- Tripping of the incoming BL $X/c_a = -0.412$
  (BL thickness is about gap height)
- Tripping at 10% of Blade chord, $C$
- Slip/Non-Slip Boundary ($X/c_a = -0.71$)
- Still/moving endwall boundary $X/c_a = -0.137$
Coarse and Fine Grids

“Coarse” grid (~1.8M nodes)

“Fine” grid (~5M nodes)

- 2 times more cells in x-y plane
- Lower cell aspect ratio
- Additional refinement in the region downstream of the blade

- Edge of the moving end-wall coincides with grid-line
- z-step is reduced
- Fine-grid “trace” of blade tip is removed (lower cell aspect ratio in LES region)
Baseline RANS Computations

- S-A and Wilcox RANS computations are carried out on the “coarse” grid with no-slip and free-slip BC’s at the upper (“hub”) wall

**SA, no-slip upper wall**

**Wilcox, no-slip upper wall**

**Wilcox, free-slip upper wall**

Effect of turbulence model and problem statement on the velocity field in the near wake $X/c_a=1.51$

- Effects of turbulence model and BC’s at the upper (“hub”) wall are quite noticeable, and the latter is probably overestimated
- DES is carried out with the use of Wilcox model in half-domain (the blade wake being smooth in the center region)
**DES and RANS Flow-Patterns**

- **y/c=0.015 (inside clearance)**
- **y/c=0.12**
- **y/c=0.30**

Vorticity from RANS and DES solutions

- Visible difference between the two approaches
  - RANS solution is smooth and reveals mostly the tip clearance vortex (TCV)
  - DES solution, along with the TCV, reflects a wide range of fine-scale turbulence, including the vortices shed by the blade trailing edge.
Details of DES Solution in TE Area

Zoomed fragments of vorticity contours in the blade trailing edge area

- Inside the tip-gap and somewhat above ($y/c_a < ~0.15$) no regular vortex structures are observed:
  - dominant vortical structure is TCV coming from the upstream blade and interacting with the smaller, tip-separation, vortices
- At $y/c_a = 0.3$ the trailing edge vortex shedding is dominant:
  - at least qualitatively, DES provides its fairly good representation (shear layer roll-up, vortex pairing, and formation of small chaotic vortices further downstream)
- At $y/c_a = 0.8$, due to grid coarsening, the simulation under-resolves the shedding process (predicts formation of regular “quasi-laminar” vortices)
Delayed DES Functionality

\[
\nu_t^{\text{RANS}} \quad \nu_t^{\text{DDES}} \quad (1-F_d)
\]

- Major part of the clearance gap is sheltered: \((1-F_d)\) “red”
- Above the gap the shielding function is active only in the blade’s boundary layers
• Although the major part of the tip-gap area is “sheltered” from the LES mode of DES, a thin non-shielded area does exist:
  ➢ turns out to be enough to switch to LES mode and unlock the shear layer instability
In terms of the mean flow prediction, DES does not surpass RANS and is even somewhat inferior to it.
Comparison of DES and RANS with the Data

In the experiment the pressure is measured over the blade mid-span ($y/c_a = 0.915$)

- RANS and DES agree well with the experiment in the central part of the blade (at $y/c_a > 0.15$ the mean flow is close to 2D), and return close pressure distributions
- Close to the gap, the pressure varies very fast, especially at the “pressure side” of the blade, and at the edge of the blade ($y/c_a = 0.03$) the two approaches differ significantly
Comparison of DES with CTR LES
(You et al, CTR, 2003, a grid of 20 M nodes)

Contour plots of mean streamwise velocity at $y/c_a = 0.0018, 0.183, 0.366$ and $0.641$

- LES and DES solutions are close to each other, although some details of the velocity field are different
  - LES separates earlier, probably because it can’t resolve the blade TBL
  - at the $y=0.0018c_a$ cut, DES solution has visually pronounced regions of low and high velocity (shown by a circle), while in the LES there are no such structures
Comparison of DES with CTR LES


DES, 5M nodes

LES, 8M nodes

LES, 20M nodes

Time-averaged spanwise velocity contours at y/ca 0.008

- DES captures all the major vortical structures revealed by LES and, in some respects, is closer to the “fine” grid LES than to the “coarse” grid one:
  - predicts the location of TCV close to that of the fine-grid LES (in the coarse grid LES the origin of the vortex is shifted downstream, resulting in a corresponding shift in its position)
  - On the other hand, DES predicts somewhat stronger TCV and stronger and more regular tip-separation vortices (marked by the circle); in this sense it is closer to the coarse grid LES.
In general, the fine-grid LES seems to provide for a somewhat better resolution of the vortical structures than DES does. As a result:

- TCV (A) and counter-rotating passage (B) vortices in DES remain “compact” up to the tip-gap of the next blade and their interaction with each other (wrapping of the passage vortex around the TCV) is more pronounced.
- In DES the “horseshoe” vortex (D) is large and smooth, while in LES this vortex is not seen (this also can affect the TCV originating from this region). In DES this area is treated in RANS mode while in LES a recycling procedure similar to that of Lund et al is applied.

Comparison of DES with CTR LES

Swirl isosurface feo LES and DES  
Top view of the swirl isosurface from DES

A – Tip Clearance Vortex; B – Counter-Rotating Vortices; C - Tip-Separation Vortices  D – Horse-Shore Vortex
**Comparison of DES with CTR LES**

Mean streamwise velocity normalized by the local maximum velocity at $x/c_a = 1.51$

- Comparable accuracy of mean flow prediction with, may be, some superiority of LES
Conclusions

• DES based on $k-\omega$ Wilcox model is performed for VTC with a moving wall on a grid with 5M nodes
• The test is challenging for DES: in addition to tip separation, it includes tip-clearance vortex - blade boundary layer interaction and trailing edge vortex shedding
• DES proves to be capable of capturing the major unsteady physics of the flow
• With the current grid, DES does not surpass RANS in terms of mean flow prediction and is comparable with LES on 20M nodes grid:
  ➢ grid-independent solutions are probably out of reach, and may take an order of magnitude more grid points, if not more
• DES for highly loaded turbomachinery blade rows in near stall and stalled airfoil conditions seems to be manageable

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