High-order mesh generation for CFD solvers

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Overview

• Motivation
• The spectral/hp element method
• Challenges: mesh generation
• Some results
• Conclusions
Motivation

Primary research goal is to investigate challenging external aerodynamics cases:

• High Reynolds numbers
• Complex three-dimensional geometries
• Large resolution requirements
• Transient dynamics

Using high-order spectral/hp element method
Spectral/hp element method

map from reference element

tenзор product expansion

Boundary-interior decomposition
Assembly matrix

tensor product expansion

$$\phi_p(\xi_1, \xi_2) = \psi^p_{r_p} (\eta_1) \psi^q_{r_q} (\eta_2)$$
Why high-order methods?

Rotation of Gaussian bump in linear advection equation
Why high-order methods?

• Very good numerical properties: should therefore be better at tracking long-time transient structures

• Discrete operators are dense and have rich structure: computationally efficient & scale well

but...

• Lots of specialised knowledge required

• One big challenge: mesh generation
High-order mesh generation

(in theory)

B-Rep
High-order mesh generation

Curving coarse meshes leads to invalid elements
Most existing MG packages cannot deal with this
MG pipeline to date

For complex geometries:

- Use commercial mesh generator for coarse straight-sided mesh (prism boundary, tet interior)
- Manipulate the mesh to make it high order
- Try to fix broken elements
- Pray
NACA 0012 wing tip

\[ \text{Re} = O(10^6) \]

Strong wingtip vortex difficult to capture with RANS
Existing workflow

1. Linear mesh from Star-CCM+
2. Convert to high-order
3. Output high order mesh
NACA 0012 example

- Simulations at \( \text{Re} = 1.2 \text{m} \)
- Highly unsteady, vortex dominated
- SVV-LES formulation of incompressible NS

The key feature of these studies is in their use of reduced equations or turbulence models, all of which require parameters to tune their performance. Since the underlying physical processes that dictate the development and evolution of vortices is not well understood, it is therefore difficult a priori to determine appropriate settings for these models. The aim of this work is therefore to demonstrate how an implicit LES method, in which the number of parameters is comparably very small and is used to provide additional stability, can successfully be leveraged to obtain accurate comparisons against experimental data. We appreciate that there may be different views of the definition of implicit LES. We have adopted the definition of Sagaut [13], who explicitly refers to SVV as an implicit LES model and states that "using a numerical viscosity with no...".
Despite a 70% increase in the total number of degrees of freedom. However, there is a significant difference between that of a 3rd refinement study and previous LES results by Uzun et al. [1]. In (a) and in (b) where we also show the results from the uniform grid, we can observe the growth of the vortex over the wing surface. The sudden change in trend at z/c = 0.5, may have led to a strong SVV dissipation that in turn significantly damped the early location of the secondary vortex. The resulting distribution as a benchmark for observing the convergence and providing a form of self-validation. In these tests, the polynomial order was varied; however, the main features of the flow are well captured.

Although this test case is computationally expensive to simulate, we have performed a limited resolution study of the flow physics, using the SVV-iLES and Nektar-P=5,6. The resulting number of local/global mesh degrees of freedom for 4, 6, and 8 refinement studies are 5.7M/1.5M, 16.7M/6.9M and 25.3M/11.9M respectively. The 70% increase in number of global degrees of freedom when using 7 refinement of 7 results that we present here to results at z/b = 0.5 in (a) and 0.1 in (b) compared against experimental results from Chow et al. (AIAA 1997). The number of local/global mesh degrees of freedom is 5.7M/1.5M, 16.7M/6.9M and 25.3M/11.9M respectively. The 70% increase in number of global degrees of freedom when using 7 refinement of 7 results that we present here to results at z/b = 0.5 in (a) and 0.1 in (b) compared against experimental results from Chow et al. (AIAA 1997). The number of local/global mesh degrees of freedom is 5.7M/1.5M, 16.7M/6.9M and 25.3M/11.9M respectively.

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NACA 0012 example

More complex geometries
Towards a better MG solution

Single step process from CAD to flow solution
As few user parameters as possible
Construct an octree
Smooth the octree
Relate geometry to mesh sizing

\[ \delta(R) \]
Propagate mesh specification
Our process

- OpenCascade for CAD handling
- Modified version of Triangle for surface meshing
- Modified version of TetGen for the interior volume
- Our own system for high-order manipulation
- Linear elastic PDE solver for mesh deformation

Encapsulated inside Nektar++ spectral/hp element framework
Result

Without leaving Nektar++ and only 4 user parameters for meshing

$P = 6$
$Re = 10,000$
More complex geometries
Nektar++ high-order framework

Framework for spectral(/hp) element method:

- Dimension independent, supports CG/DG/HDG
- Mixed elements (quads/tris, hexes, prisms, tets, pyramids) using hierarchical modal and classical nodal formulations
- Solvers for (in)compressible Navier-Stokes, advection-diffusion-reaction, shallow water equations, ...
- Parallelised with MPI, tested scaling up to ~10k cores

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Thanks for listening!

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