Subgrid-scale models for large-eddy simulation of rotating turbulent channel flows

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Introduction

Conclusions

• Rotating turbulent flows form a rich and challenging test case for large-eddy simulation

• Our new nonlinear subgrid-scale model improves predictions of the Reynolds stress anisotropy
Introduction

Rotating turbulent flows

Ubiquitous in nature and engineering
Introduction

Challenge

• Coriolis force
  – Conserves total kinetic energy
  – Transports energy from small to large scales of motion, reduces viscous dissipation of kinetic energy
  – Anisotropy

Why a challenge?

• Large-eddy simulation
  – Eddy viscosity models: focus on dissipation
  – Our focus: also capture transport effects
Large-eddy simulation

A new nonlinear subgrid-scale model

\[ \tau^{\text{mod}} = -2\nu_e S_{\text{eddy viscosity}} + \mu_e (S\Omega - \Omega S)_{\text{nonlinear}} \]

- Describes dissipation
- Models well established
- ‘Stable part’ of gradient model
- Nondissipative
- Nondynamic coefficients based on vortex stretching magnitude

\[ \nu_e = C_\nu \delta^2 \sqrt{2|S|} * f(|S\omega|^2) \quad \mu_e = C_\mu \delta^2 * g(|S\omega|^2) \]

- Nonlinear term represents energy transport in rotating homogeneous isotropic turbulence

Silvis et al. (2017), Phys. Fluids 29, 015105
Silvis et al. (2016), APS DFD Meeting
Large-eddy simulation

Code

- Incompressible Navier-Stokes solver
- Finite-volume method on a staggered grid
- Pressure projection method
- One-leg explicit second-order time integration method

- Second-order symmetry-preserving spatial discretization
  - Kinetic energy conservation by ...
    - convection
    - Coriolis force
    - nonlinear term of subgrid-scale model

Remmerswaal (2016), MSc thesis, University of Groningen
Spanwise-rotating plane-channel flow

Description

- Domain size: $2\pi d \times 2d \times \pi d$
- Periodic in $x$ and $z$ directions
- Constant pressure gradient in $x$ direction
- Rotation about the spanwise axis

- Characterized by

\[
Re_\tau = \frac{u_\tau d}{\nu} \approx 395
\]
\[
Ro^+ = \frac{2\Omega d}{u_\tau} = 0 - 1000
\]

Grundestam et al. (2008), *J. Fluid Mech.* 598, 177
Spanwise-rotating plane-channel flow

Typical observations: $Ro^+$ dependence

- Mean velocity
  - Linear slope $\sim Ro^+$
  - Flow laminarizes with $Ro^+$

- Reynolds shear stress
  - ‘Turbulent’ and ‘laminar’ side
  - Flow laminarizes with $Ro^+$

\[ Re_\tau \approx 395, \quad Ro^+ = 0 - 1000 \]
\[ n_x \times n_y \times n_z = 128 \times 256 \times 128 \]
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Spanwise-rotating plane-channel flow

Typical observations: resolution dependence

- Mean velocity
  
  Ample opportunity for LES, even at $Re_\tau \approx 395$

- Streamwise stress anisotropy
  
  Traceless subgrid-scale models: Reynolds stress anisotropy
  
  Turbulent bursts
  
  Focus on ‘turbulent’ side

$Re_\tau \approx 395, Ro^+ = 100$

Winckelmans et al. (2002), Phys. Fluids 14, 1809
Spanwise-rotating plane-channel flow

Typical observations: resolution dependence

- Mean velocity
  
  \[ \langle u_1 \rangle^+ \]

  \[ x_2/d \]

  \[ 0 \] \[ 0.5 \] \[ 1 \] \[ 1.5 \] \[ 2 \]

  \[ 0 \] \[ 50 \] \[ 100 \]

  - Ample opportunity for LES, even at \( Re_\tau \approx 395 \)

- Streamwise stress anisotropy

  \[ \sigma_{11}^+ \]

  \[ x_2/d \]

  \[ 0 \] \[ 0.5 \] \[ 1 \] \[ 1.5 \] \[ 2 \]

  \[ -5 \] \[ 0 \] \[ 5 \]

  - Traceless subgrid-scale models: Reynolds stress anisotropy
  - Turbulent bursts
  - Focus on ‘turbulent’ side

  \[ Re_\tau \approx 395, Ro^+ = 100 \]

Winckelmans et al. (2002), Phys. Fluids 14, 1809
Numerical results

Large-eddy simulation with new nonlinear model

- Mean velocity

\[ \langle u_1 \rangle^+ \]

- Observations
  - Dynamic Smagorinsky model provides best prediction
  - Eddy viscosity model close to no-model result
  - Nonlinear model does not improve or deteriorate this result
  - Similar observations for \( Ro^+ = 50, 75, 100, \ldots, 250 \)
  - Similar observations for \( n_x \times n_y \times n_z = 64^3 \)

\[ Re_\tau \approx 395, \ Ro^+ = 100 \]
Numerical results

Large-eddy simulation with new nonlinear model

• Streamwise stress anisotropy

• Observations
  – Dynamic Smagorinsky prediction much less good
  – Nonlinear model improves shape and magnitude of stresses a lot
  – Similar observations for \( Ro^+ = 50, 75, 100, \ldots, 250 \), for the same model constants
  – Similar observations for \( n_x \times n_y \times n_z = 64^3 \), for the same model constants

\[ Re_\tau \approx 395, \quad Ro^+ = 100 \]
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\[ Re_\tau \approx 395, \ Ro^+ = 100 \]
Summary and outlook

Conclusions

• Spanwise-rotating turbulent plane-channel flows
  – A rich test case
  – Ample opportunity for large-eddy simulation

• New nonlinear subgrid-scale model
  – Improves predictions of the Reynolds stress anisotropy
  – No negative effects on the mean velocity

Outlook

• Further study of the nonlinear subgrid-scale model
  – Combine dynamic Smagorinsky model with nonlinear term
  – Combine with different subgrid characteristic length scale, $\delta$
Thank you for your attention!

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