High-Order Finite-Difference Large-Eddy Simulations of a Supersonic Nozzle

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Introduction

- WRLES code has been used successfully for subsonic jet and mixing layer simulations
- No real experience at supersonic conditions
- Objective is to explore the capabilities of the numerical methods at supersonic conditions with shock waves

Wave Resolving Large-Eddy Simulation (WRLES)

- Block structured grids
  - Point matched overlapping interfaces to preserve accuracy
  - Limits grid topology
  - Domain decomposition for parallelization
- Hybrid parallelization
  - MPI parallelization
    - Communication between grid blocks
    - One grid block per CPU or compute node
  - OpenMP parallelization
    - Loop level parallelization within a grid block
    - Multiple cores per processor

Numerical Method

- Temporal Discretization
  - 2N low-storage explicit Runge-Kutta
  - 6-stage, 4th-order scheme of Berland et al, *Comput Fluids 2006*
- Spatial Discretization
  - 11-point dispersion relation preserving (DRP) scheme of Bogey and Bailley, *J Comput Phys 2004*
  - Skewed and/or reduced order stencils near boundaries
- Spatial Filtering
  - Provides numerical dissipation for central-difference schemes
  - 11-point DRP filter matching the spatial discretization

Computational Grid

- Based on supplied grids
- Modified for the WRLES code
  - Extruded via rotation around x-axis, resulting in O-grid cross-section
  - Increased spacing at viscous walls (not attempting to resolve turbulent boundary layer)
  - Smoothed for stability of high-order numerics
    - Rounded sharp corners on external surface
    - Added resolution in areas of curvature
    - Elliptic smoothing
  - 73 million grid points

Problems with the O-grid

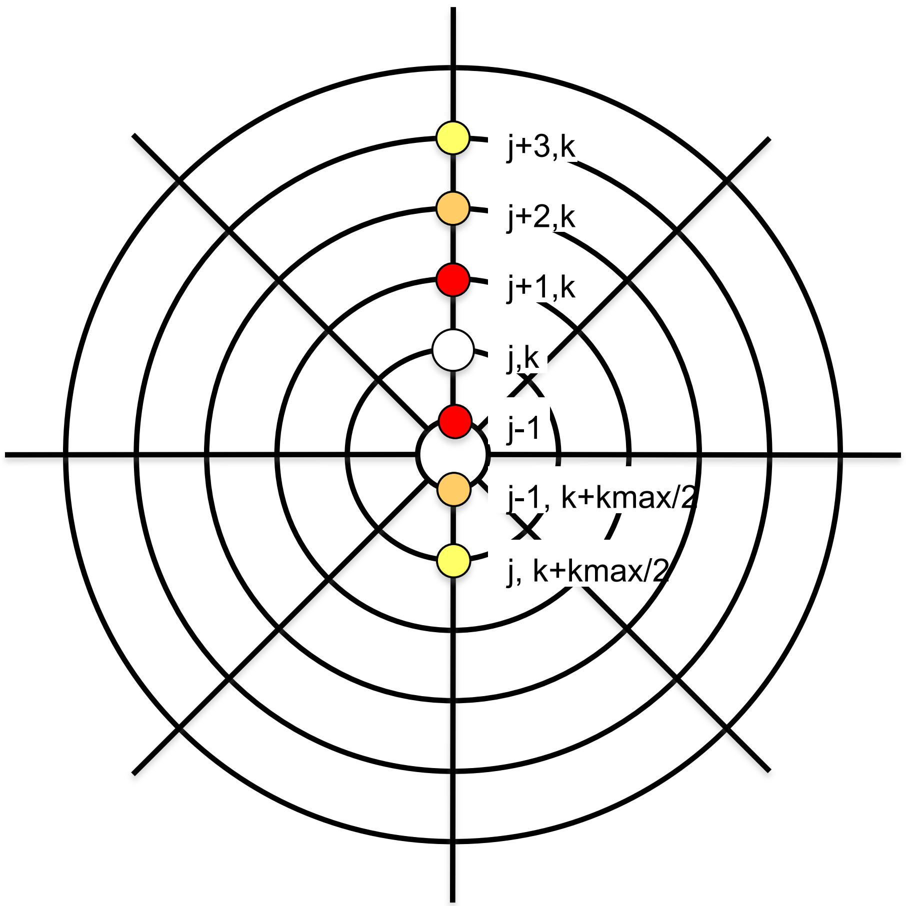
Cylindrical coordinates are a natural choice for the round jet, but there are 2 major problems

1) Centerline treatment
   - O-grid creates collapsed surface on the the centerline of the domain
   - A boundary condition or other special treatment must be applied in the center of the domain

2) Grid spacing
   - Azimuthal grid spacing scales with radius, resulting in very small cells near the centerline
   - Small cells severely restrict the time-step

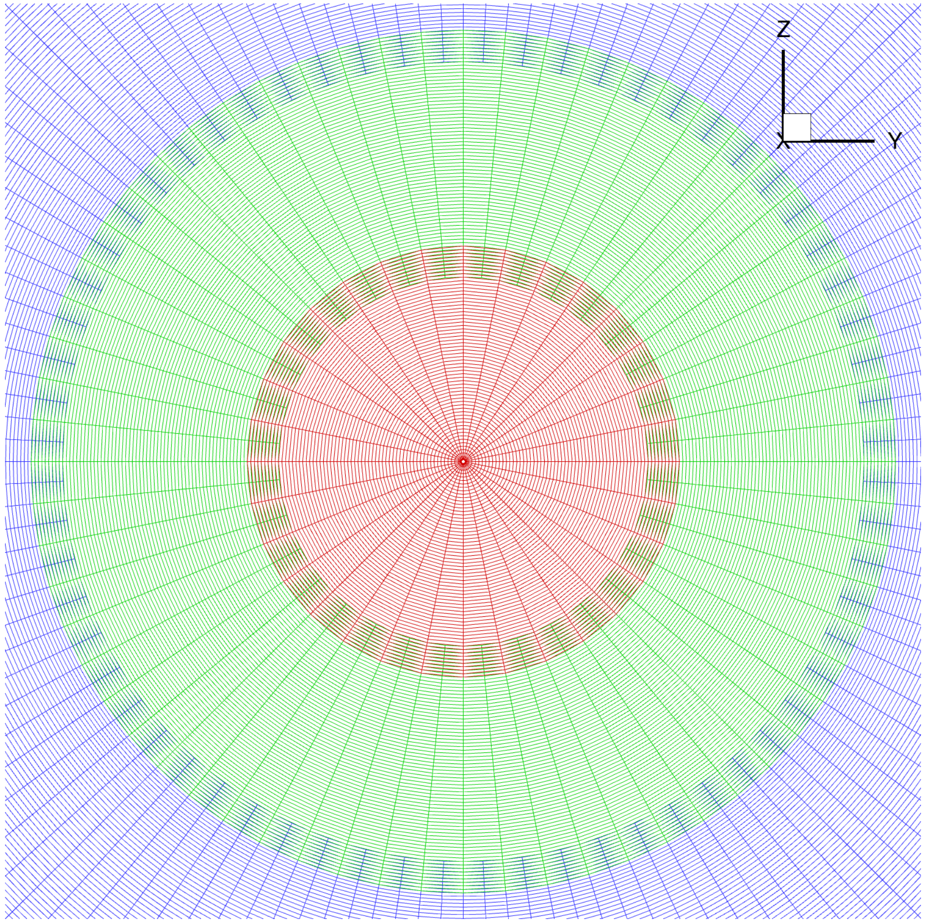
Centerline Boundary Treatment

- Construct grid with a finite cylindrical surface around centerline (not completely collapsed)
  - Creates a void around the centerline
  - The void is sized to create an evenly spaced stencil across the void
- Generate an artificial stencil across the singularity
  - Uses points on the opposite side of the void in the difference stencil
  - Removes the boundary condition
  - Increases the cell size/time-step

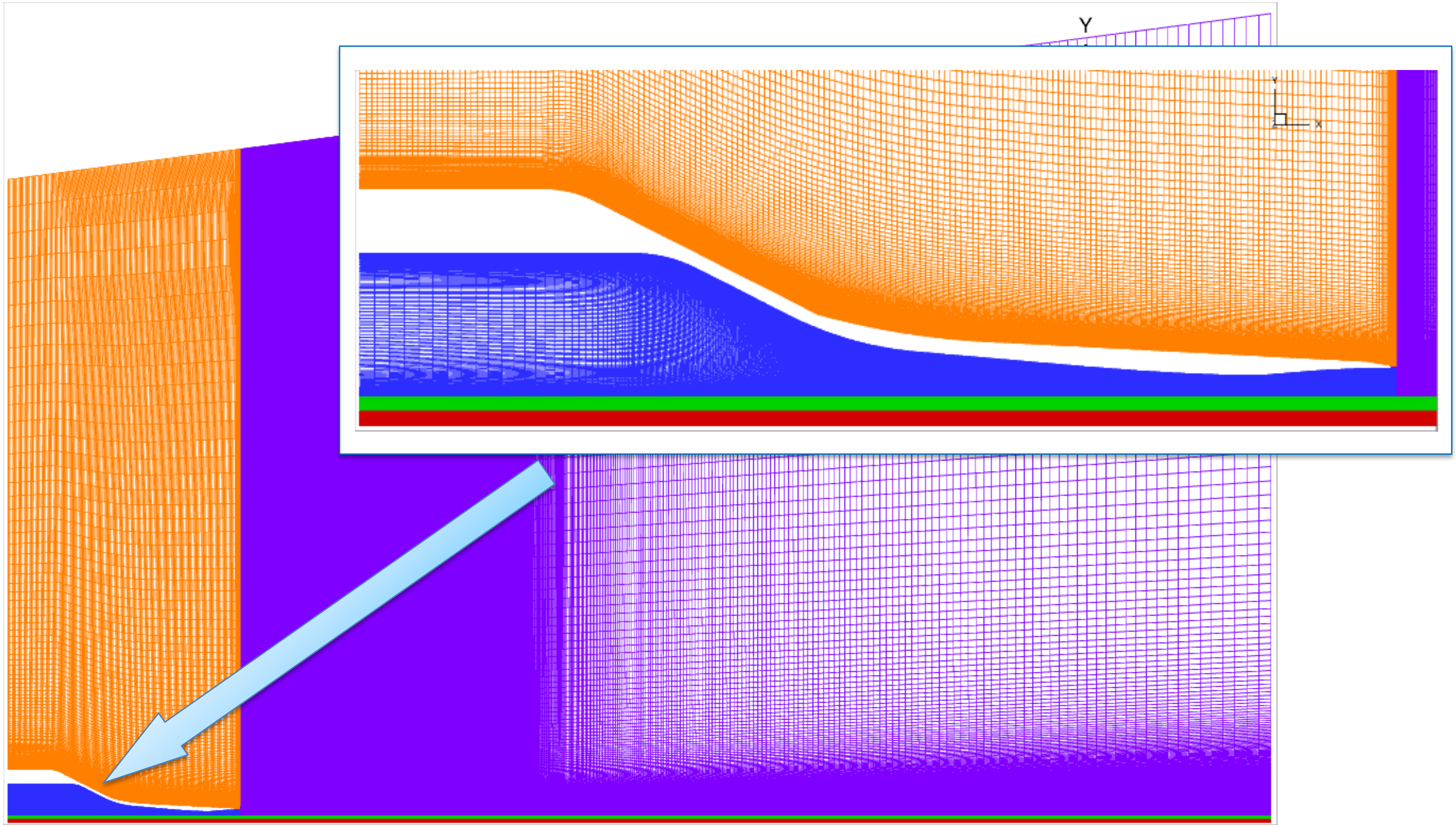


Azimuthal Resolution Reduction

- O-grid topology
  - Used in the cross-plane
  - Azimuthal spacing scales with the radius
- Small grid spacing near the axis severely restricts the time step
- New block interface
  - Azimuthal spacing is doubled across the block interface
  - 2nd and 4th order interpolation
  - Applied at radial locations of r/R_{jet} = 0.5 and 0.25
  - Provides more uniform azimuthal spacing with radius

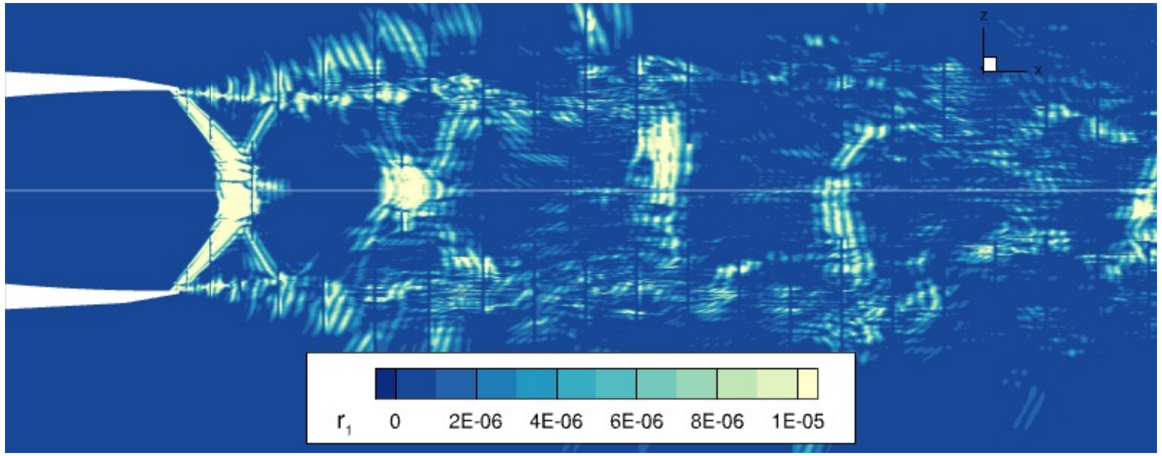


Computational Grid

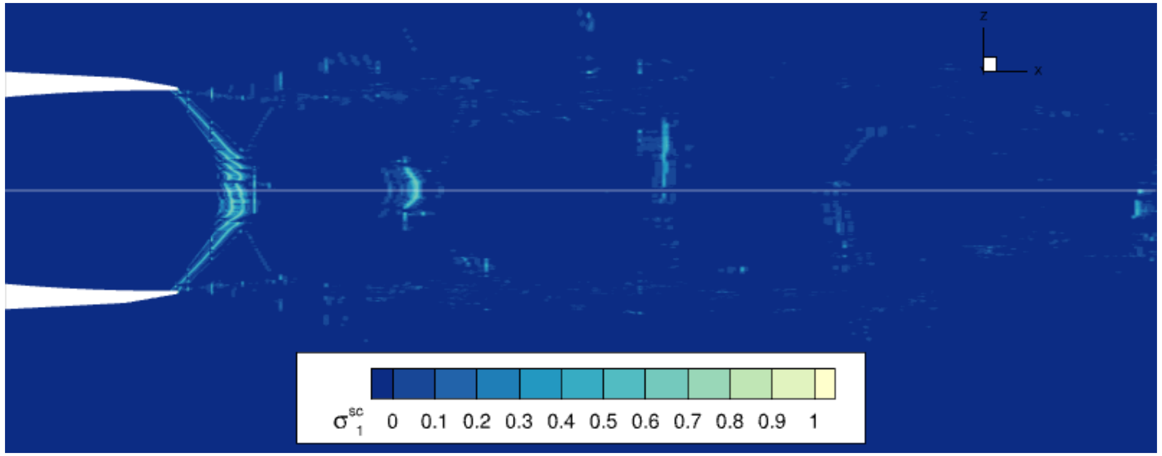


Shock Capturing Filter

- Removes spurious oscillations due to shocks/discontinuities which lead to numerical instability
- Bogey et al, *J Comput Phys 2009*
- 2nd order filter applied at shock location
  - Jameson type sensor to detect shocks, based on pressure gradient
  - Threshold parameter to activate filter
    - Value determined by trial-and-error
    - Set as high as possible to avoid damping turbulent structures

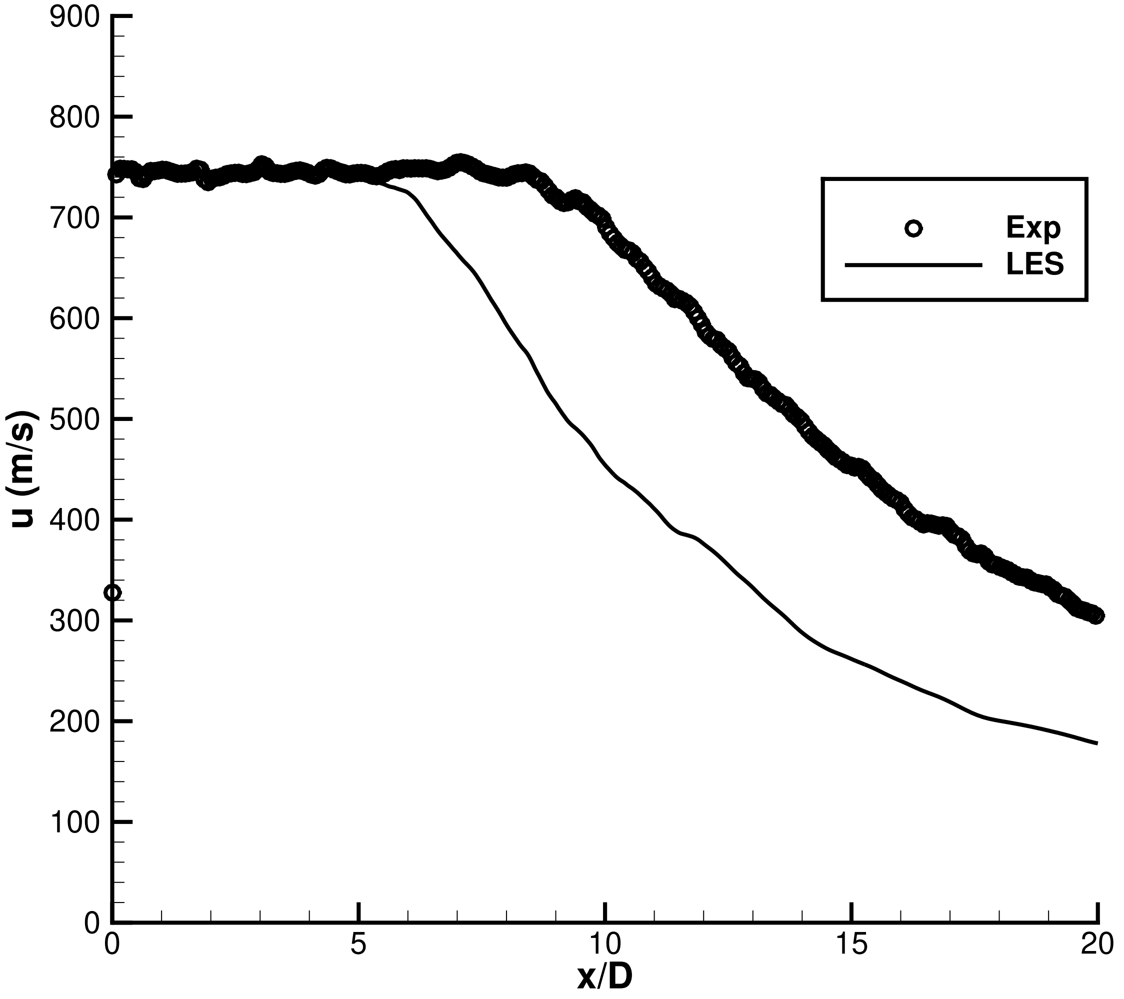


Pressure Gradient Parameter

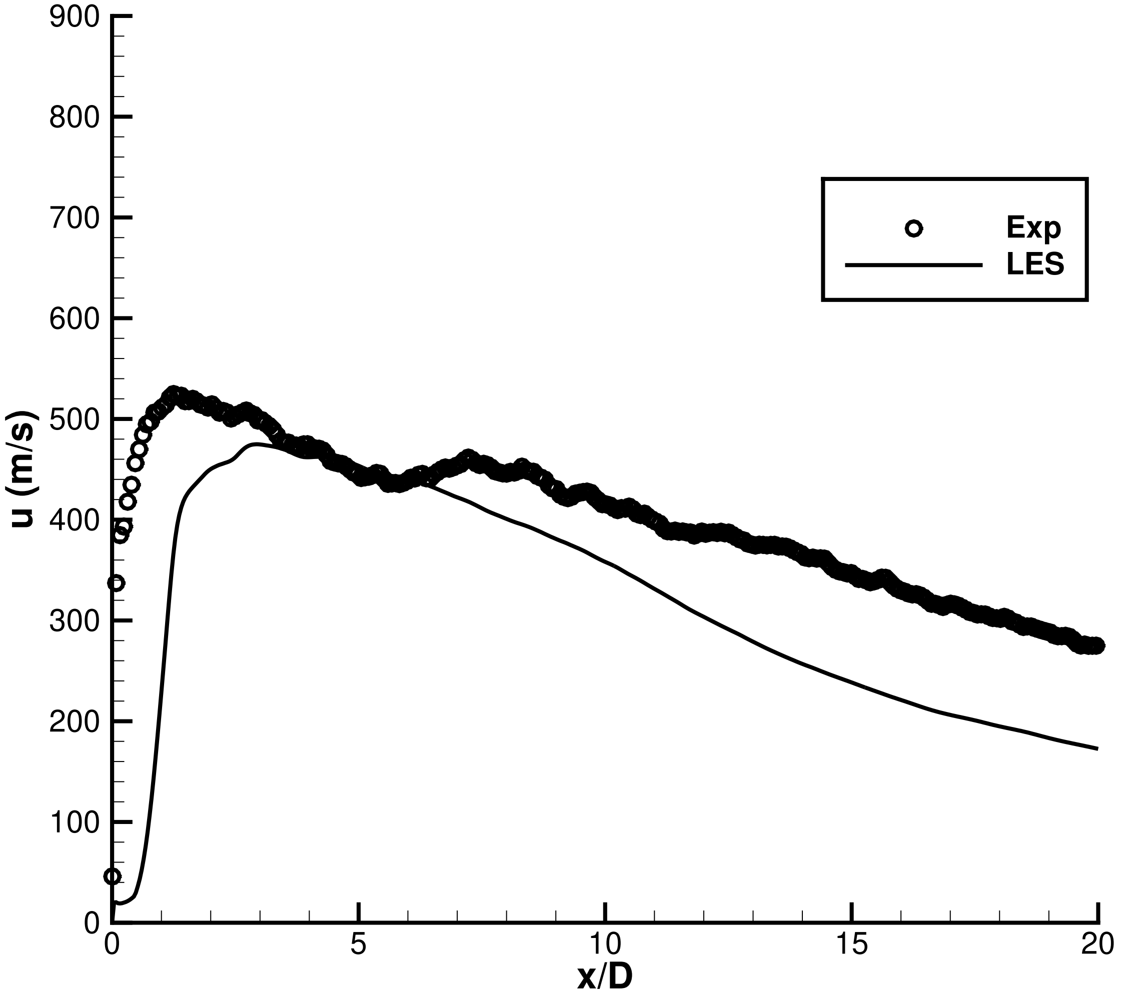


Filtering Coefficient

Case 2 – Streamwise Velocity

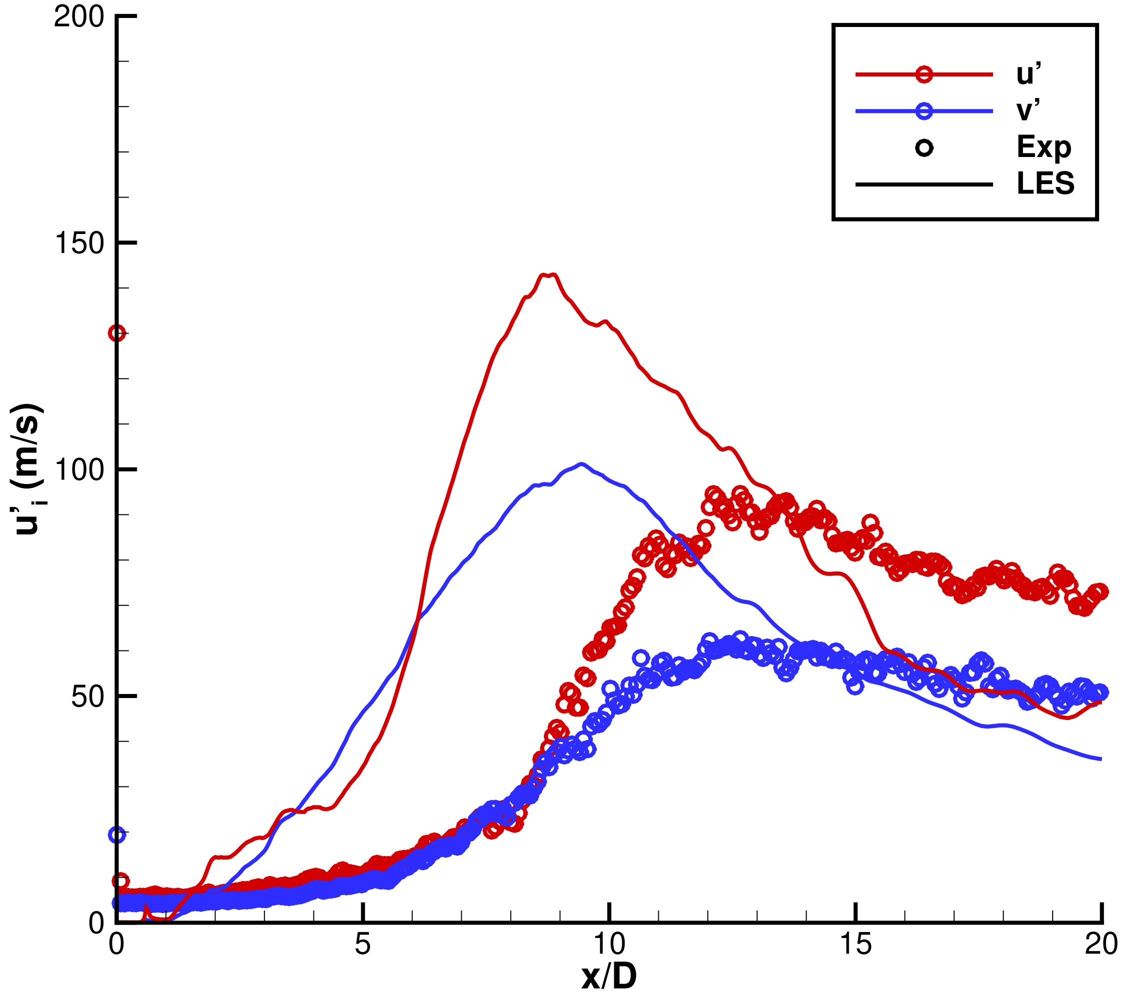


Centerline

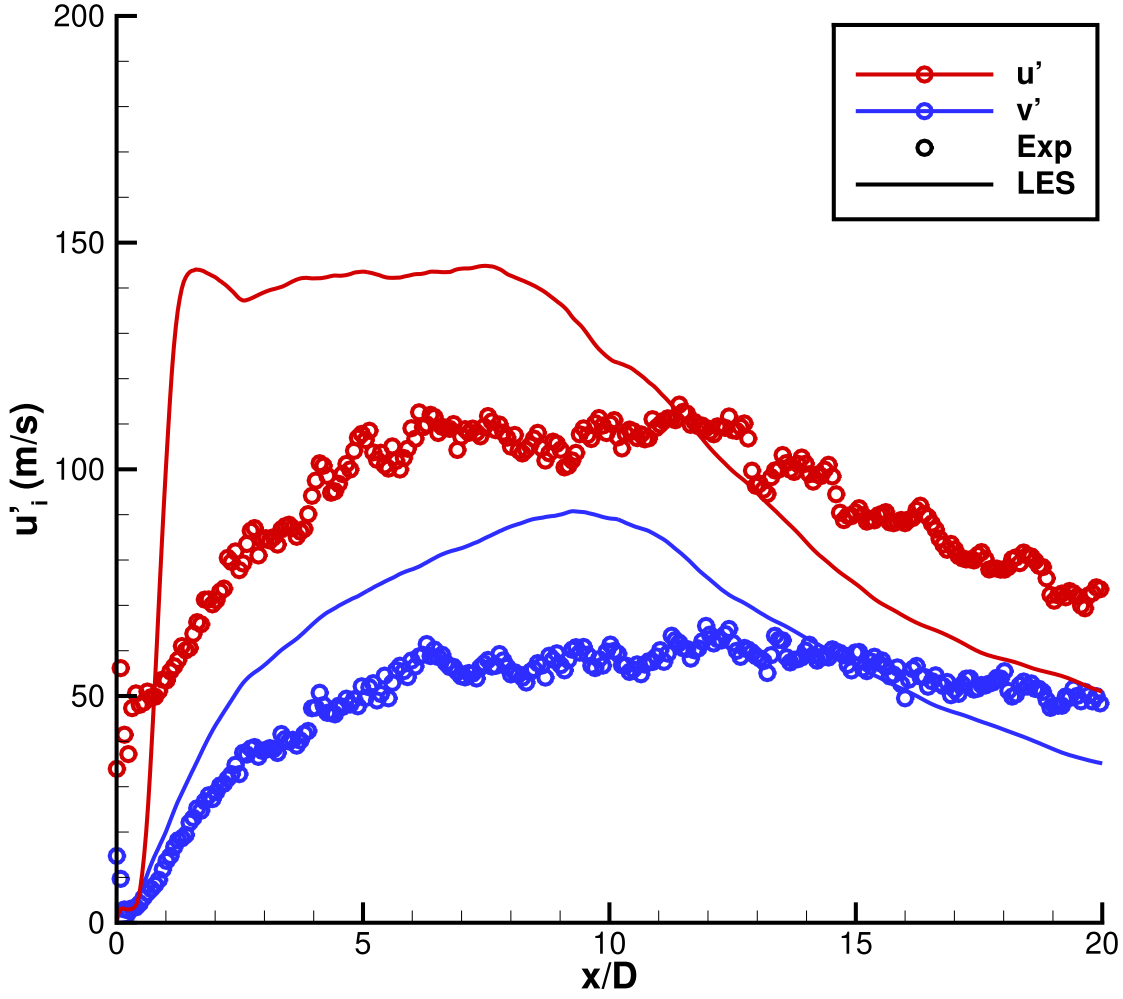


Lipline

Case 2 – Turbulence Intensities



Centerline



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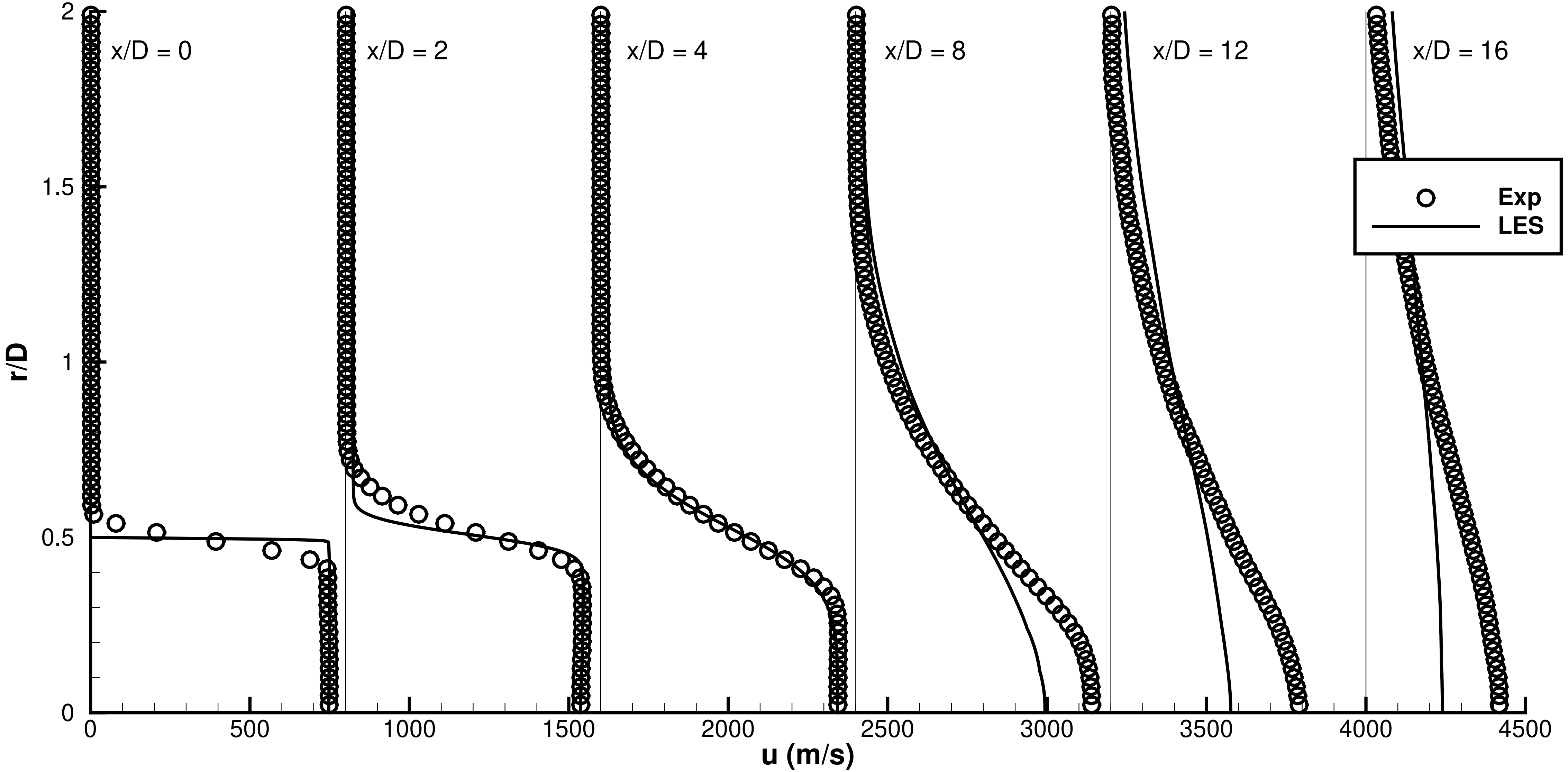
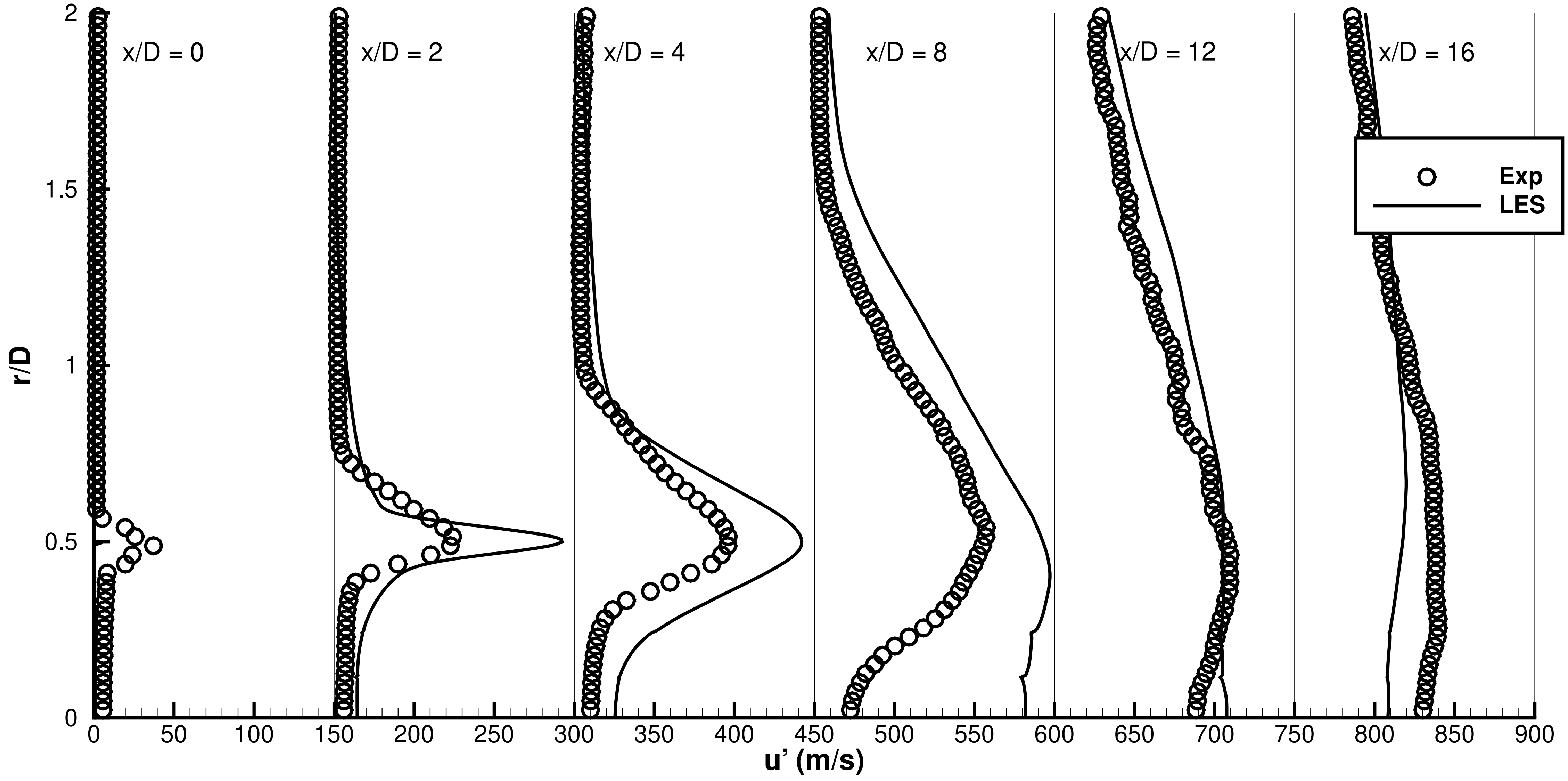
Case 2 – Radial Profiles of Streamwise Velocity



subsequent profiles shifted by 800 (m/s)

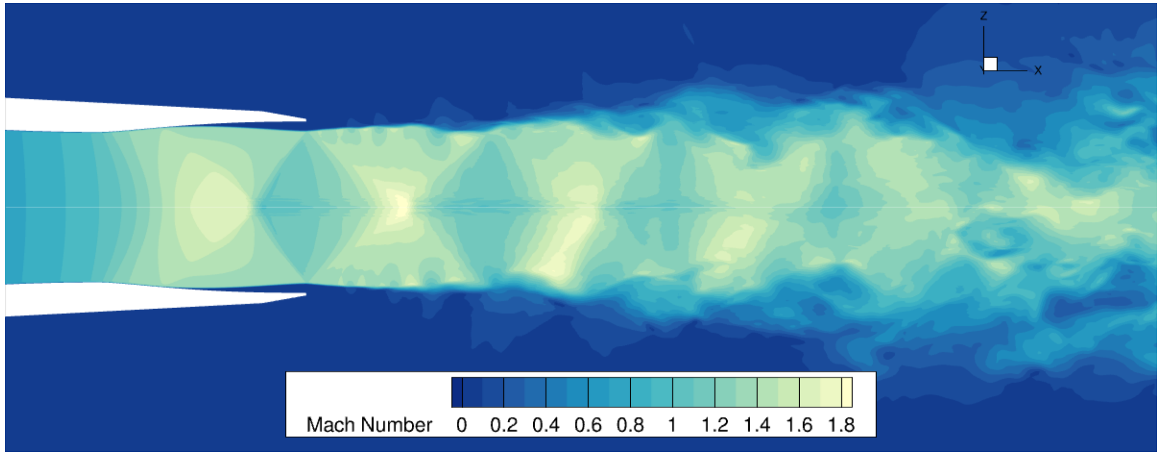
Case 2 – Radial Profiles of Streamwise Turb. Int.



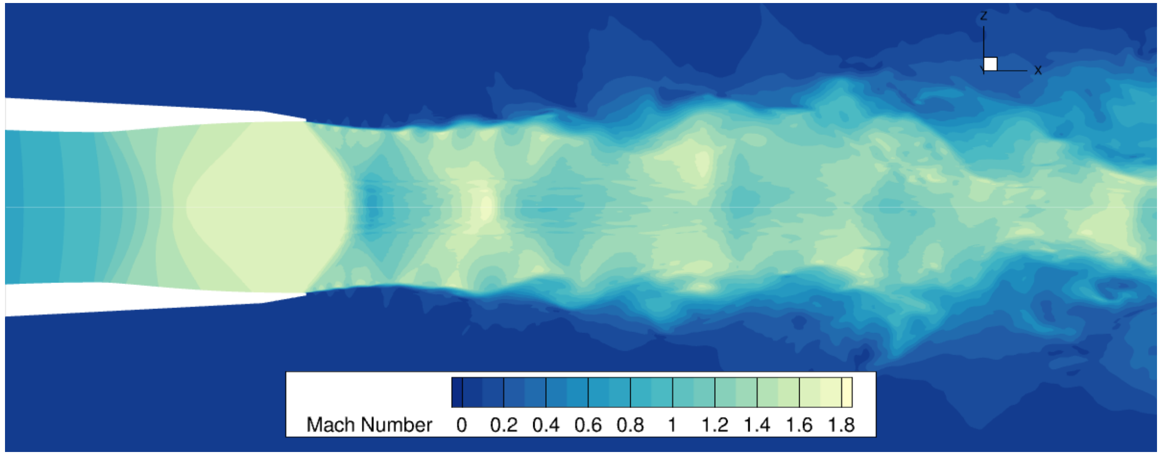
subsequent profiles shifted by 150 (m/s)

Case 4 Wall Boundary Conditions

- Near-wall grid is not sufficient to resolve turbulence
- Nozzle boundary layers are essential laminar
- For case 4, the flow separates downstream of the throat, resulting in an expansion at the nozzle exit
- A case with slip walls was run to keep the flow attached, resulting in a shock at the nozzle exit

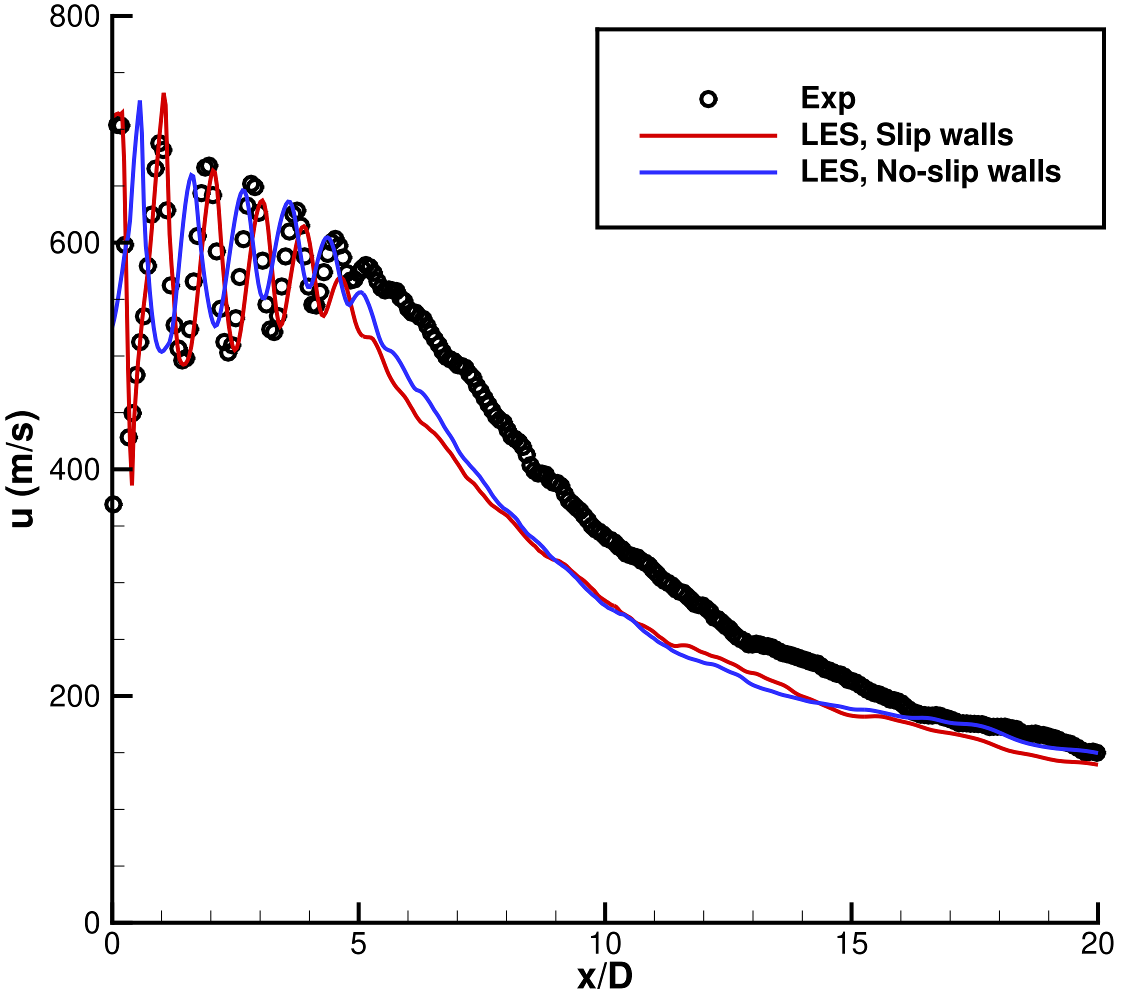


No-slip walls

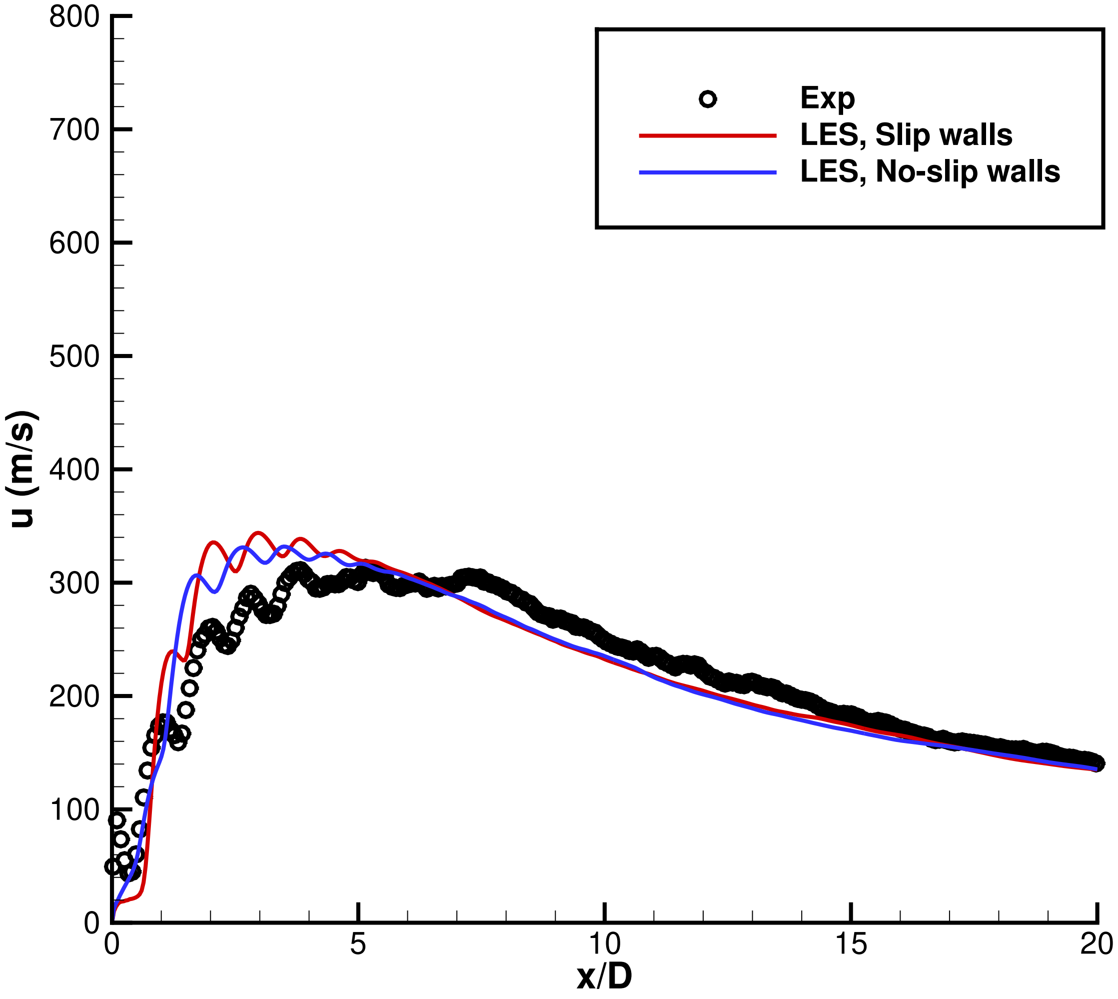


Slip walls

Case 4 – Streamwise Velocity



Centerline



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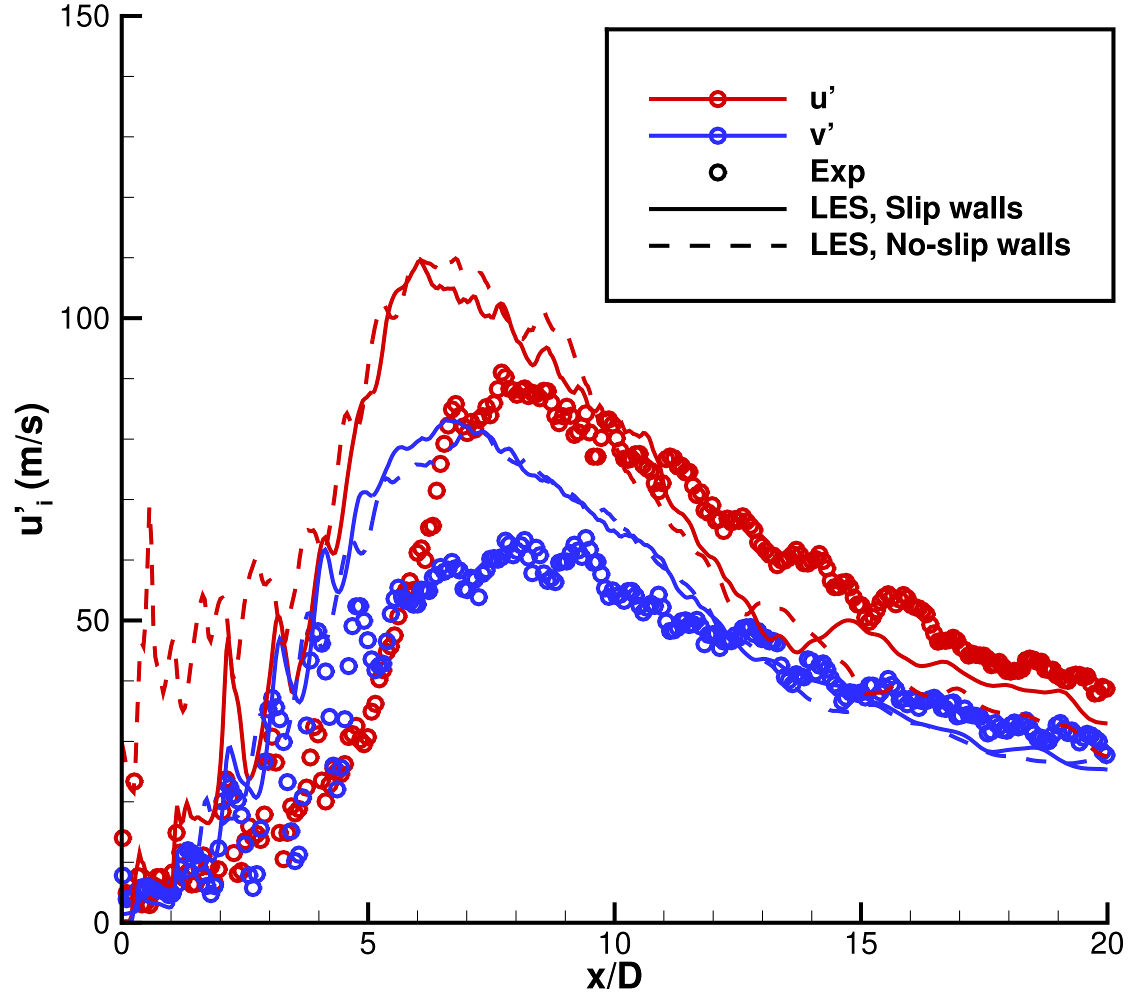
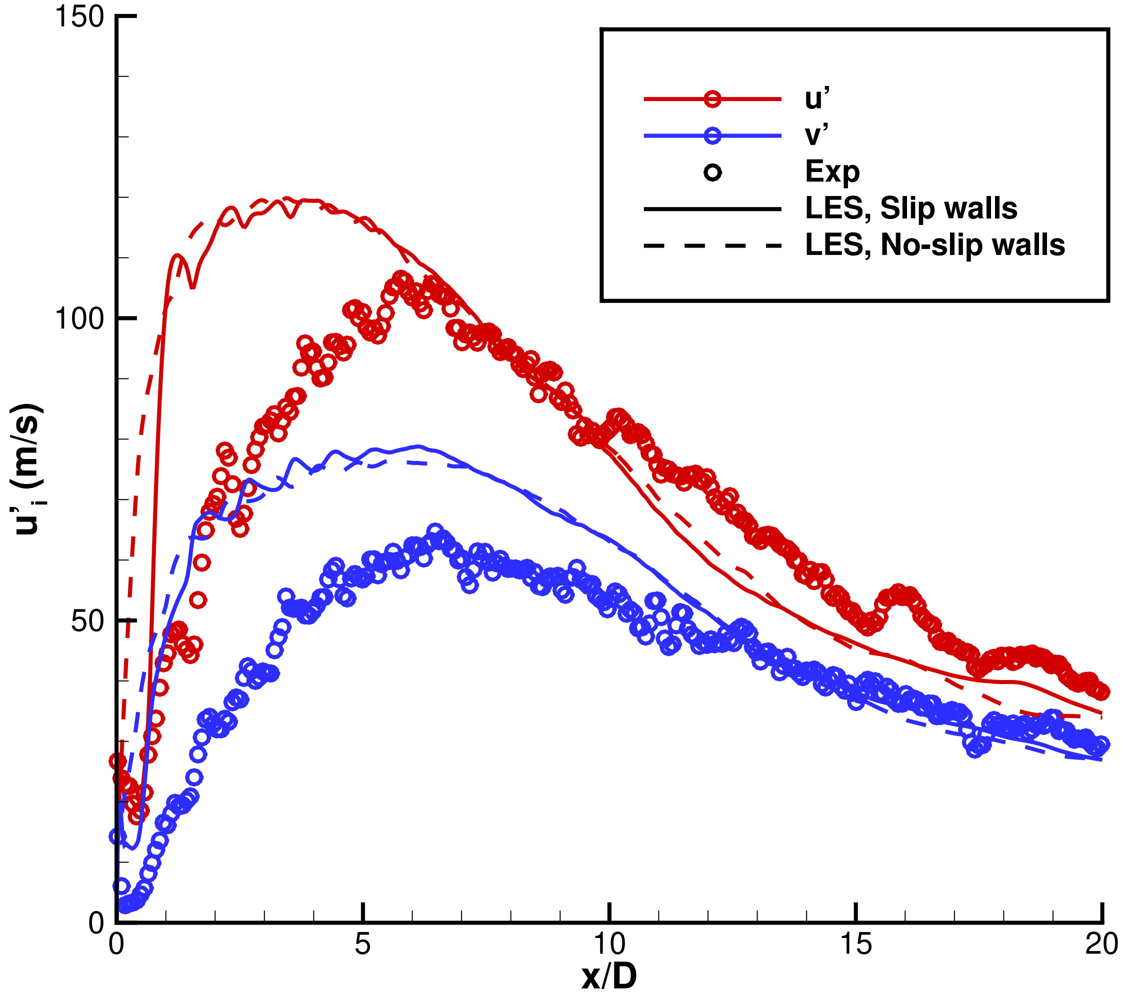
Case 4 – Turbulence Intensities



Centerline



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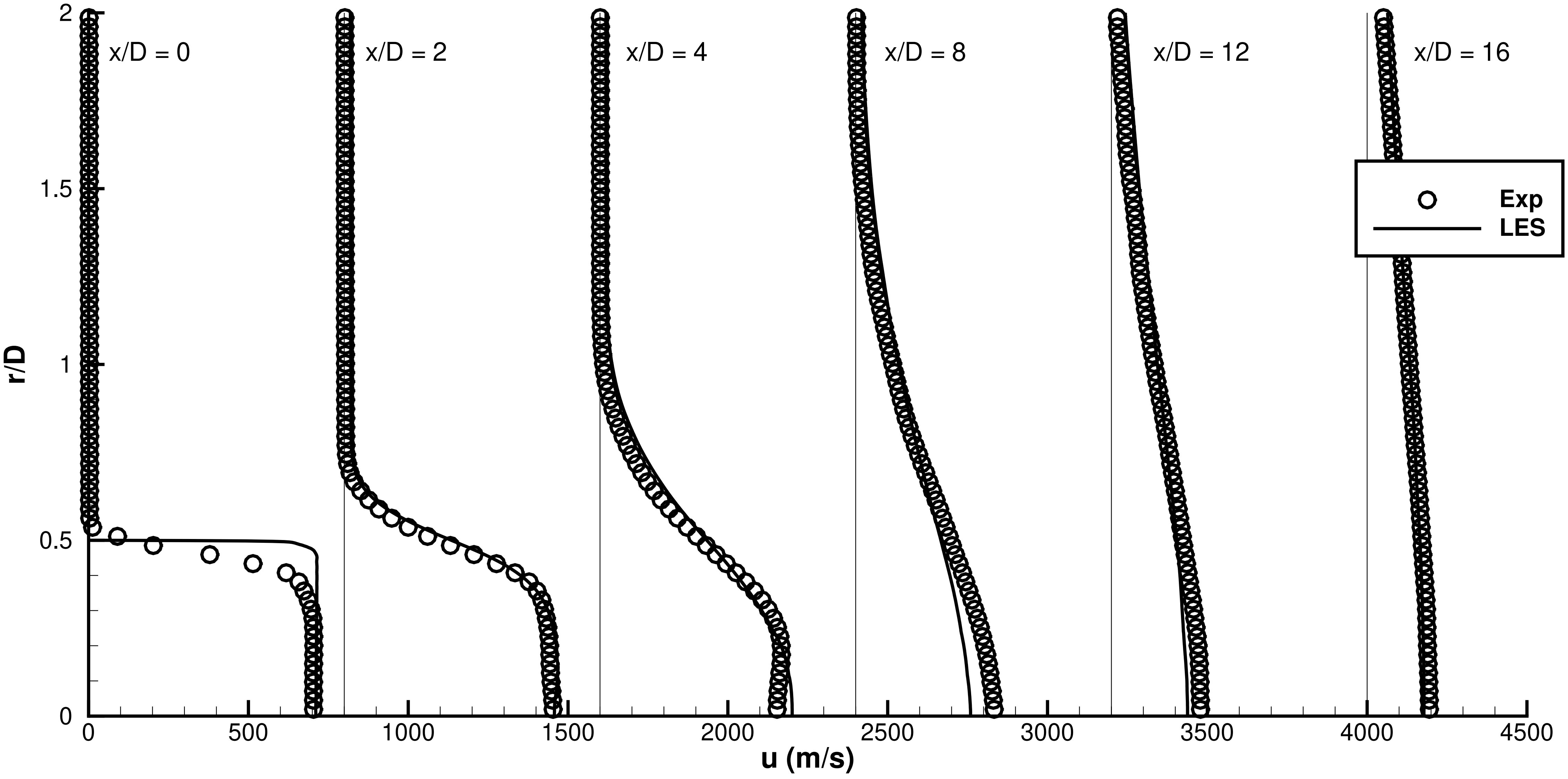
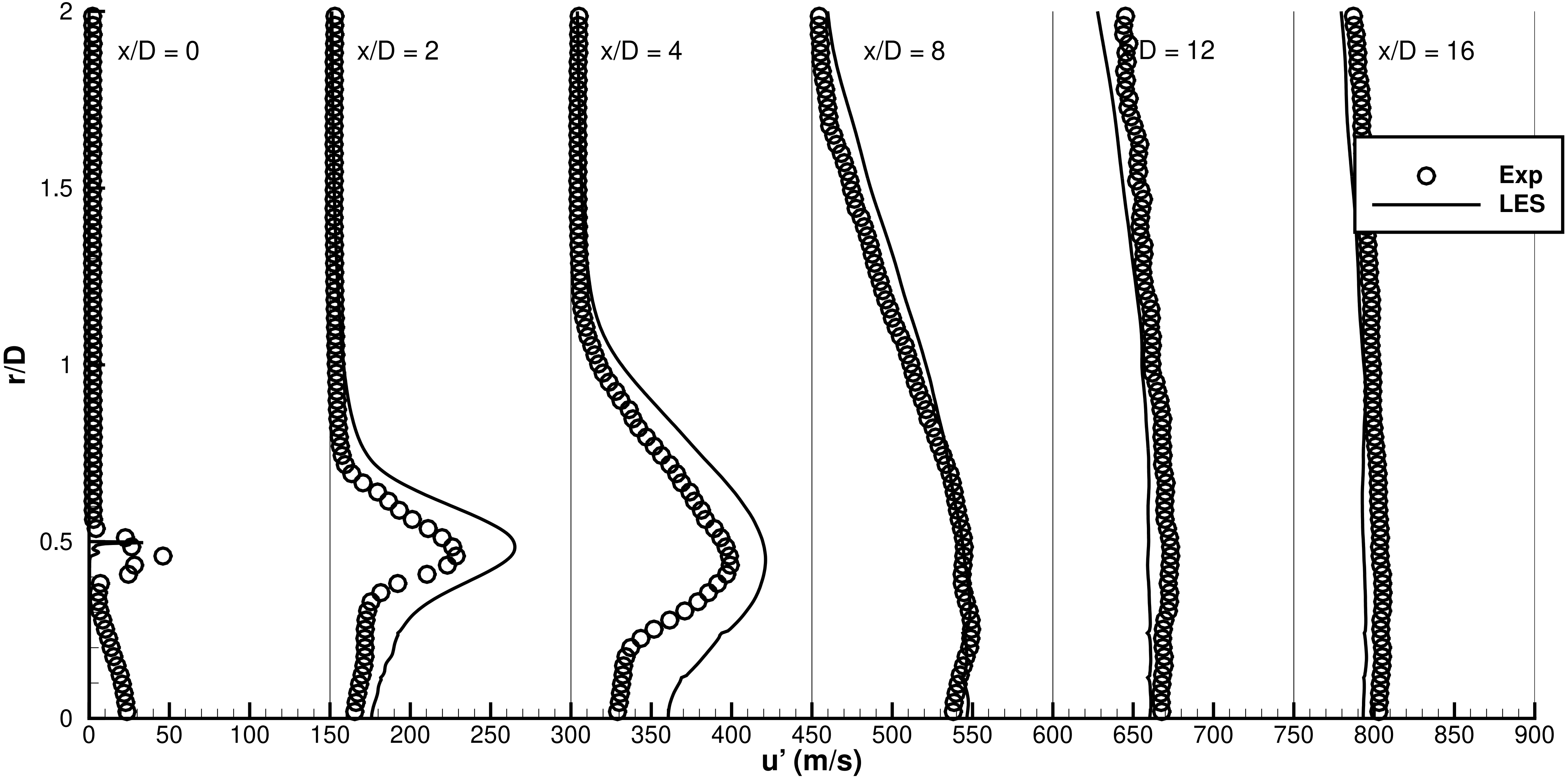
Case 4 – Radial Profiles of Streamwise Velocity



Slip wall case

subsequent profiles shifted by 800 (m/s)

Case 4 – Radial Profiles of Streamwise Turb. Int.



Slip wall case

subsequent profiles shifted by 150 (m/s)

Summary

- Both simulation cases exhibit shorter potential cores than the experiment
  - Indicative of under-resolved simulations
  - Possibly an effect of the shock capturing filter damping turbulent structures
  - Perfectly expanded case is worse than the over-expanded case
- The simulations' laminar nozzle boundary layer caused an unphysical separation in the over-expanded nozzle
  - The resulting shock structure was not correct
  - Indicates that the experimental boundary layer was turbulent
  - A slip wall boundary condition provided better results with the correct shock structure
- The grid blocking structure that reduced azimuthal grid spacing near the centerline created artifacts in the turbulence intensity profiles

Potential Future Work

- Explore grid refinement
- Implement a synthetic eddy method turbulent inflow to simulate the turbulent nozzle boundary layer
- Explore improvements to the grid blocking scheme near the centerline
- Compare these finite difference results to Flux Reconstruction results using the GFR code