ASME 2014 MAY 7–9, 2014 • LAS VEGAS, NEVADA

Verification and Validation Symposium

To Verify or not to Verify

L. Eça

with a "little help from my friends" of the CFD group of the Maritime Research Institute Netherlands (MARIN). M.Hoekstra, H.C.Raven, J. Windt, A. van der Ploeg, B. Starke, G. Vaz, C. Klaij, D. Rijpkema, S. Toxopeus, F.Pereira… and Patrick J. Roache

TÉCNICO LISBOA

MARIN

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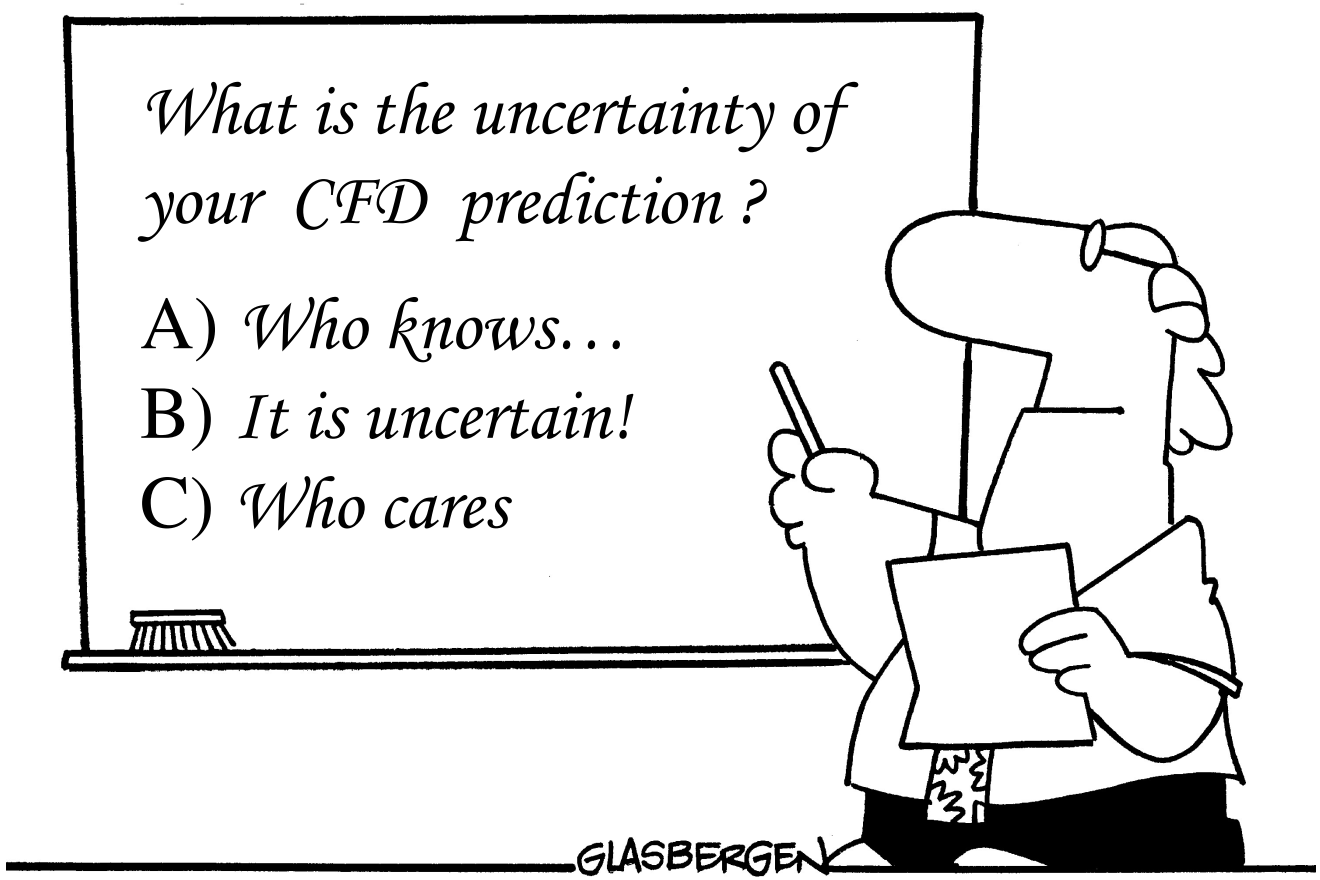
1. Motivation



1. Motivation

- CFD has evolved from a “demonstration of a capability” to a tool that is routinely used to take Engineering decisions.
- Can you rely on CFD?
- Do we have reliable mathematical models? (Validation)
- Can we trust our numerical solution? (Verification)

1. Motivation

- Why Solution Verification?
- Validation must be preceded by Verification.
- CFD solutions are often involved in optimization procedures requiring a large number of calculations where numerical accuracy may play an essential role
- Uncertainty quantification relies on thousands of solutions that may be insufficiently accurate to obtain reliable results

1. Motivation

- Last but not least, how accurate do we need to be to simulate directly turbulence? (DES,SAS,...,PANS,VMS,LES,DNS)
- Simulation of turbulence means unsteady flows
- What is the role of the numerical error (iterative and discretization errors) in these simulations?
- A first evaluation of these requirements may be performed for statistically periodic flows (URANS)

2. Solution Verification

- Solution Verification is the focus of this presentation.
- For any numerical solution of a quantity of interest ϕ, the goal of solution verification is to determine an interval (error bar) that should contain the (unknown) exact solution with "95% confidence"

$$\phi - U(\phi) \leq \phi_{exact} \leq \phi + U(\phi)$$

- There are several techniques proposed for the determination of $U(\phi)$

2. Solution Verification

- In this presentation, we will use grid/time refinement studies and power series expansions to obtain $U(\phi)$ (for well behaved data, the method becomes the GCI)

- The focus of this presentation is the so-called "practical applications"

- For the naval and offshore industry this means wall bounded flows at Reynolds numbers ranging from 10^5 to 10^9 (turbulent flows)

2. Solution Verification

- The main objective of the following examples is to illustrate the risks of "ignoring" Solution Verification
- What is the meaning of reading in papers "calculations were performed in a grid with 10^7 cells"?
- In complex geometries, what is the level of grid refinement required to obtain acceptable numerical uncertainties?

2. Solution Verification

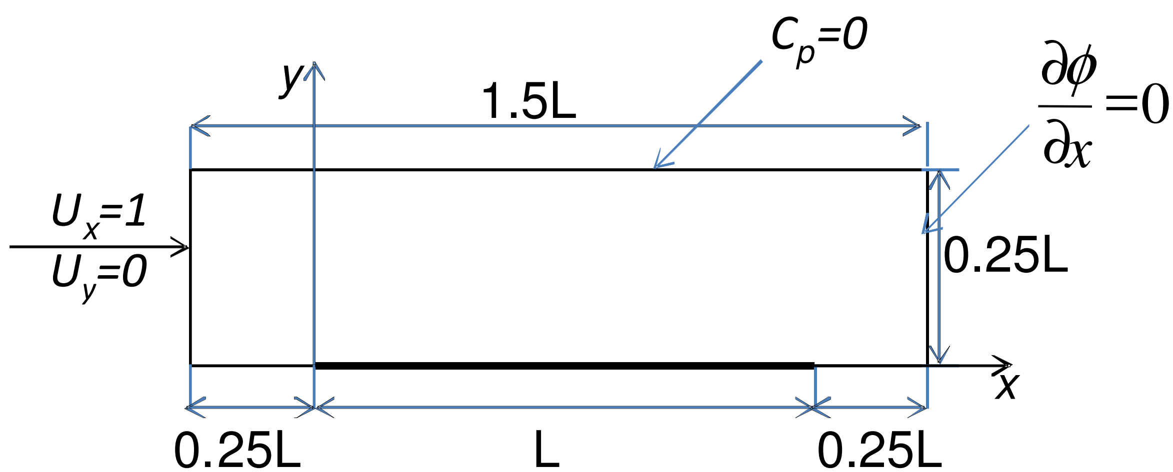
- In statistically periodic flows, what is the role of the iterative error?
- Is the iterative error negligible when we achieve a periodic solution?
- In complex flows, what is the level of grid and time refinement required to obtain acceptable numerical uncertainties?

3. Statistically Steady Flows

- Flow solver for all examples is ReFRESCO
- Reynolds-Averaged Navier-Stokes equations supplemented with a variety of turbulence models (eddy-viscosity and EARSM)
- Face based Finite Volume method for volumes of arbitrary shape using second-order accurate schemes
- Several Code Verification studies (including eddy-viscosity models) have been presented (as for example, in the first two-editions of these Conferences)

3. Statistically Steady Flows

- Flow over a flat plate at Reynolds number 10^7



- Time-averaged Navier-Stokes equations supplemented with eddy-viscosity models

3. Statistically Steady Flows

- Flow over a flat plate at Reynolds number 10^7
- Three eddy-viscosity turbulence models
  1. SST k-ω two-equation model (SST)
  2. k-$\sqrt{k}$L two-equation model (KSKL)
  3. Spalart & Allmaras one-equation model (SPAL)
- Quantity of interest:
  Friction resistance coefficient of the plate

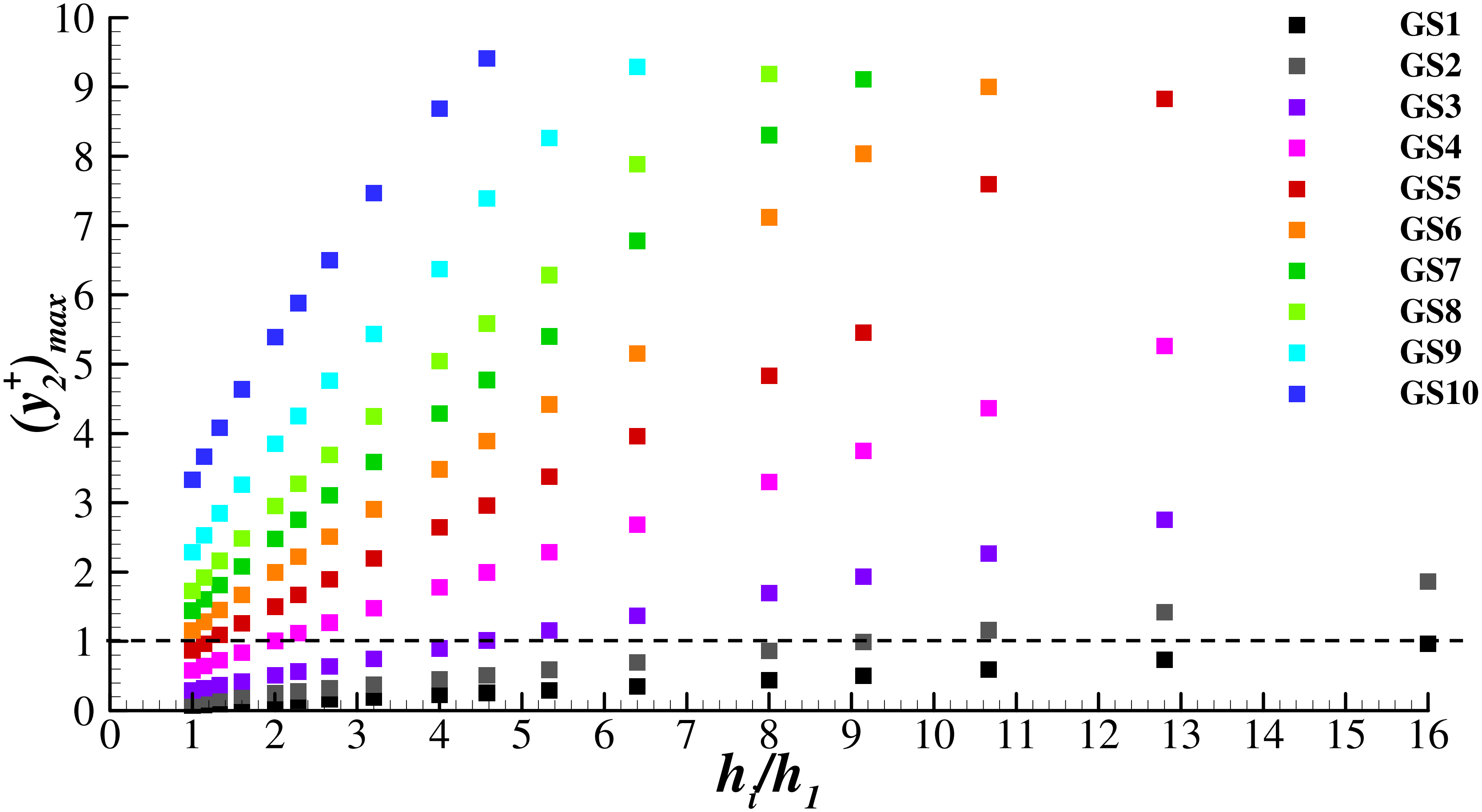
$$C_F = \frac{\int_0^L \tau_w dx}{\frac{1}{2}\rho U_\infty^2 L} = \frac{\int_0^L \mu \left(\frac{\partial U_x}{\partial y}\right)_{y=0} dx}{\frac{1}{2}\rho U_\infty^2 L}$$

3. Statistically Steady Flows

- Flow over a flat plate at Reynolds number 10^7
- 10 sets of 17 geometrically similar orthogonal grids with clustering of grid nodes at the leading and trailing edges and at the wall
- Same number of cells (1152 to 294912, $1 \leq h_i/h_1 \leq 16$) and horizontal grid line spacing for all sets
- Different stretching parameters for the definition of the size of the near-wall cells
- Negligible iterative and round-off errors

3. Statistically Steady Flows

Flow over a flat plate at Reynolds number 10^7



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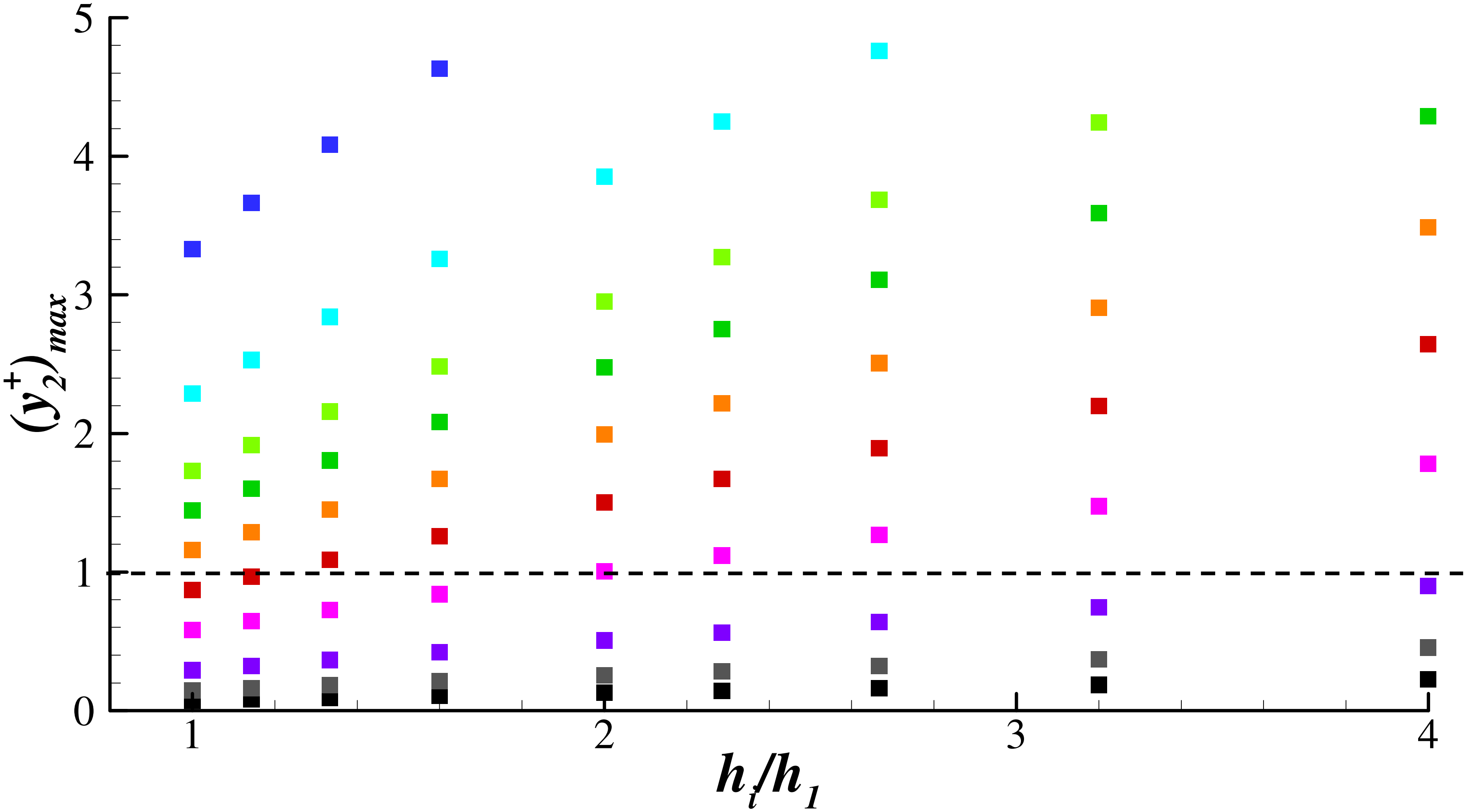
Flow over a flat plate at Reynolds number 10^7



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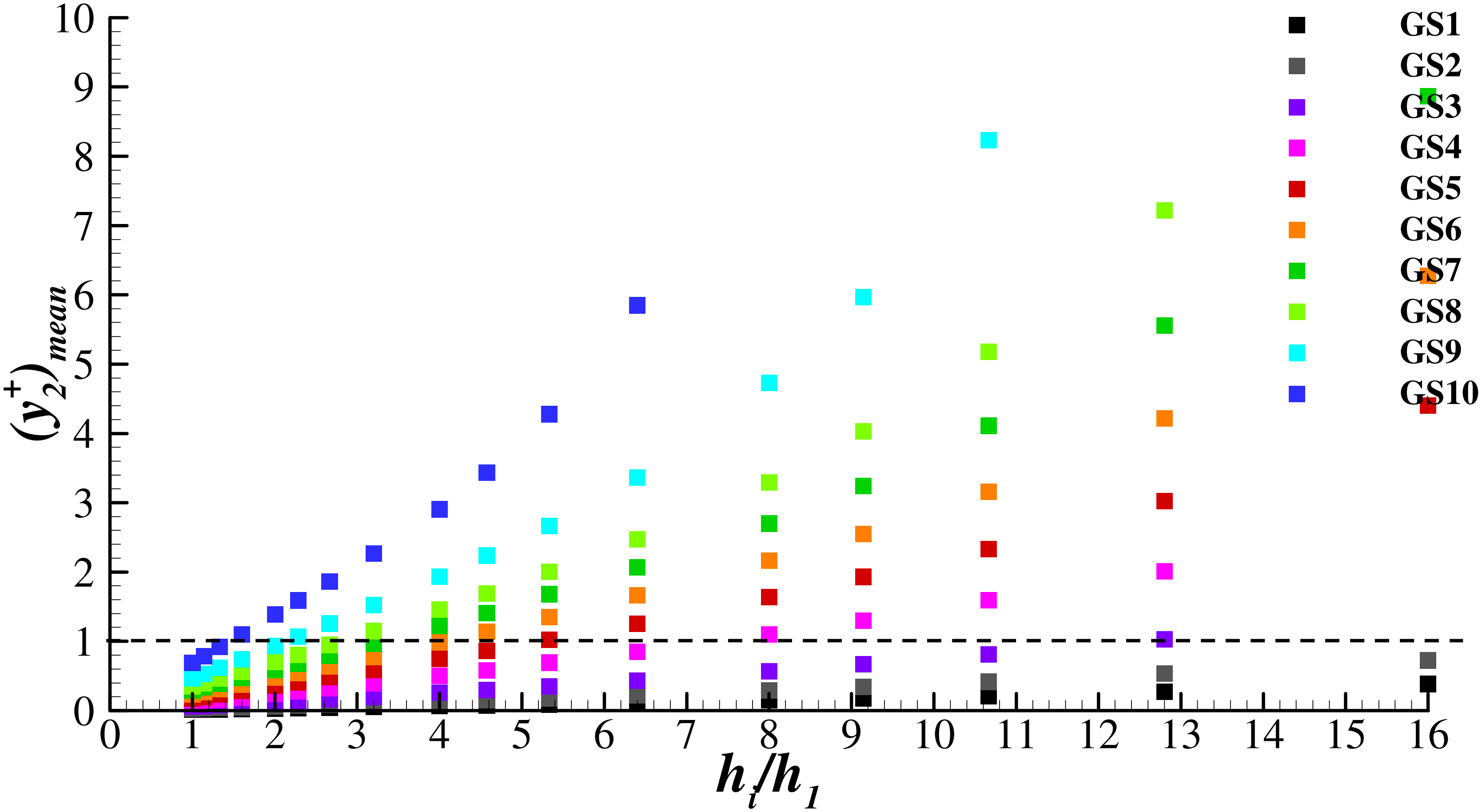

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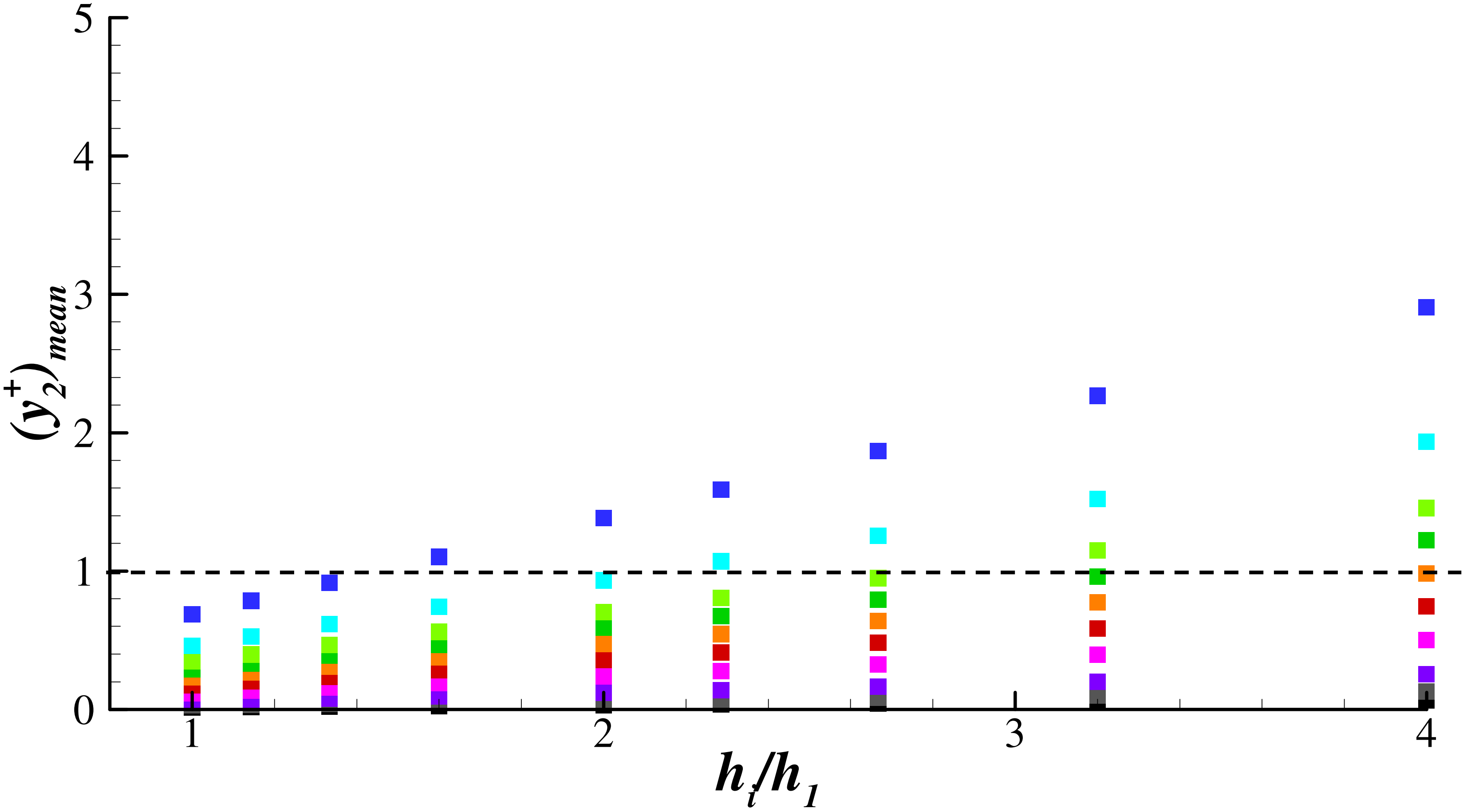

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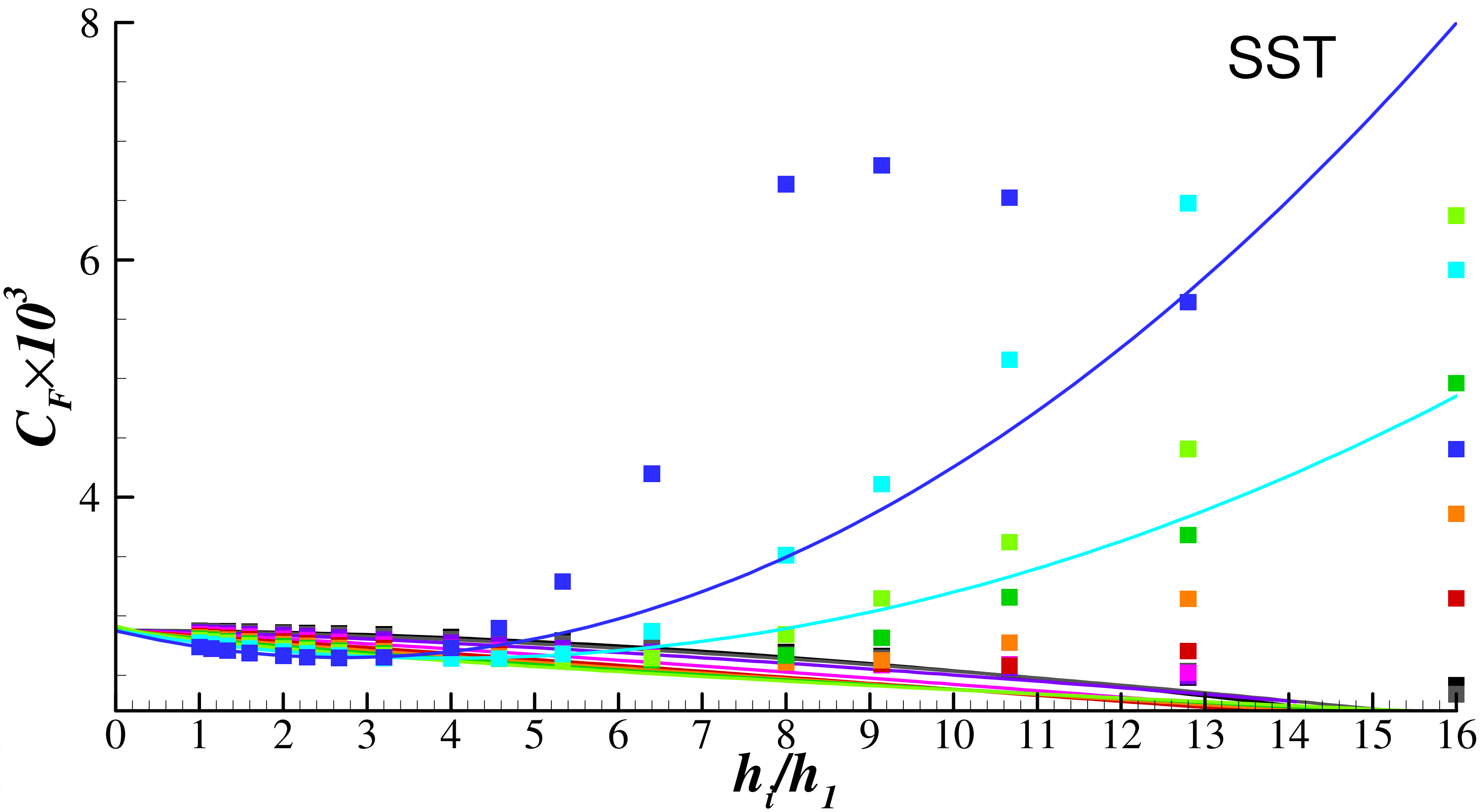

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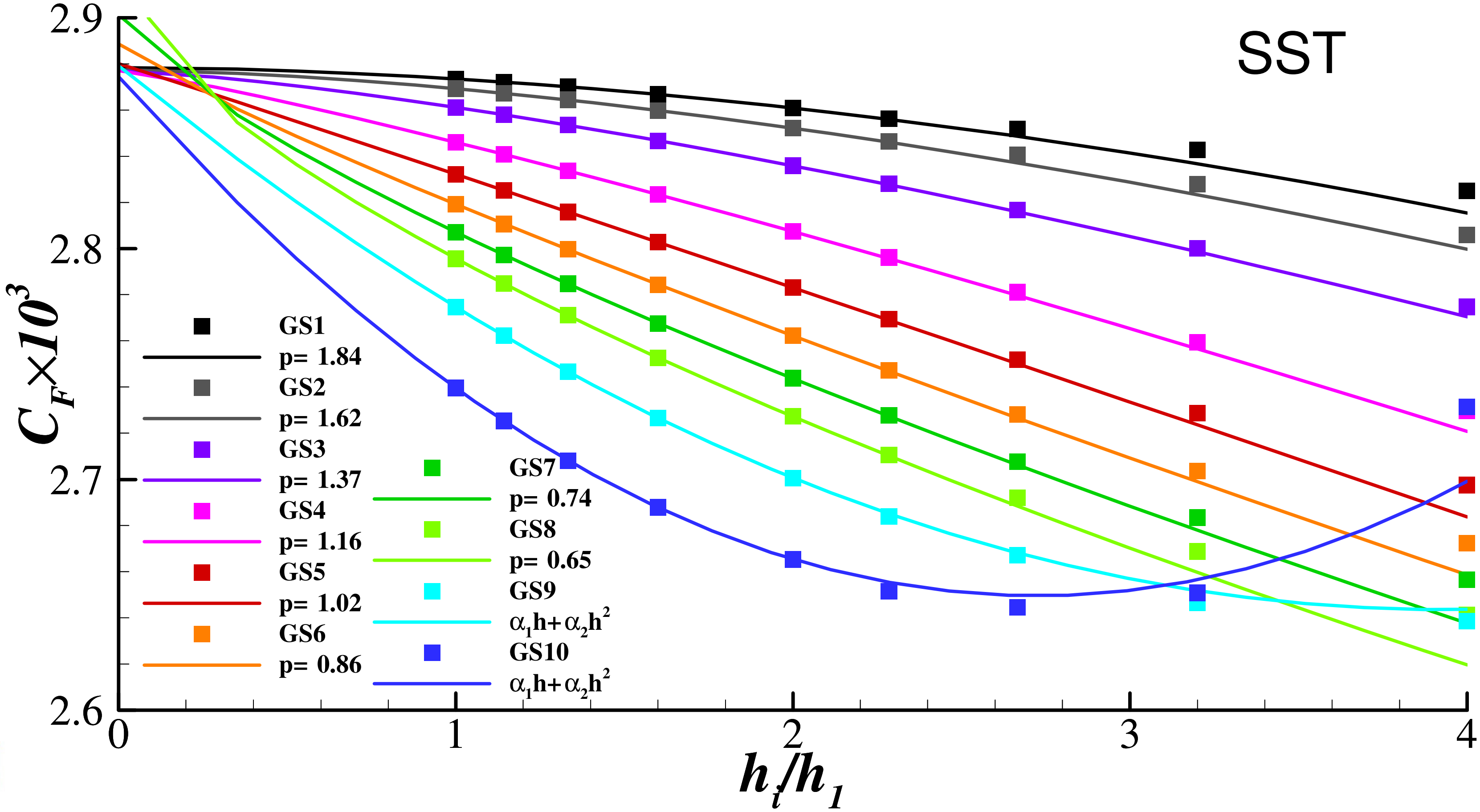

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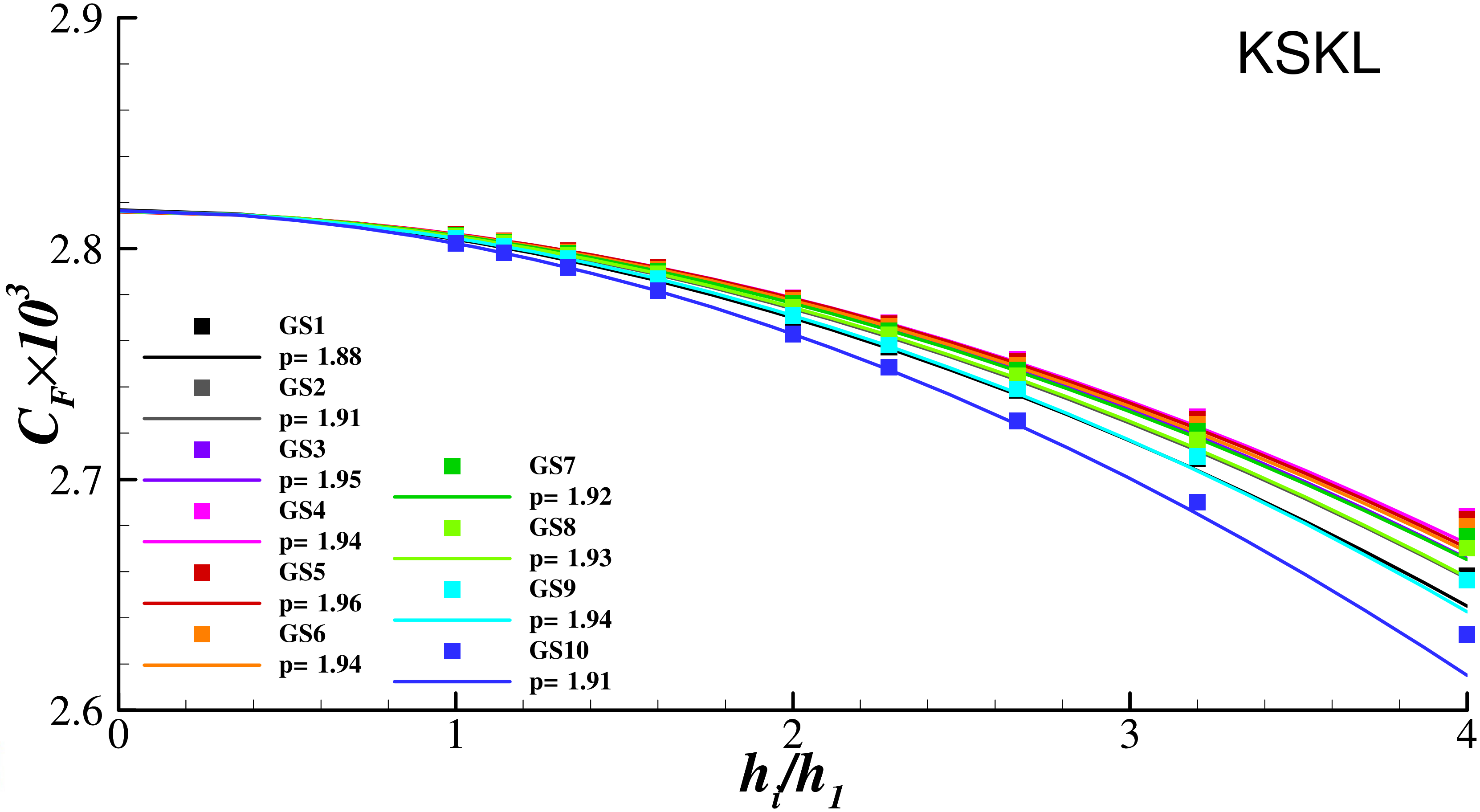

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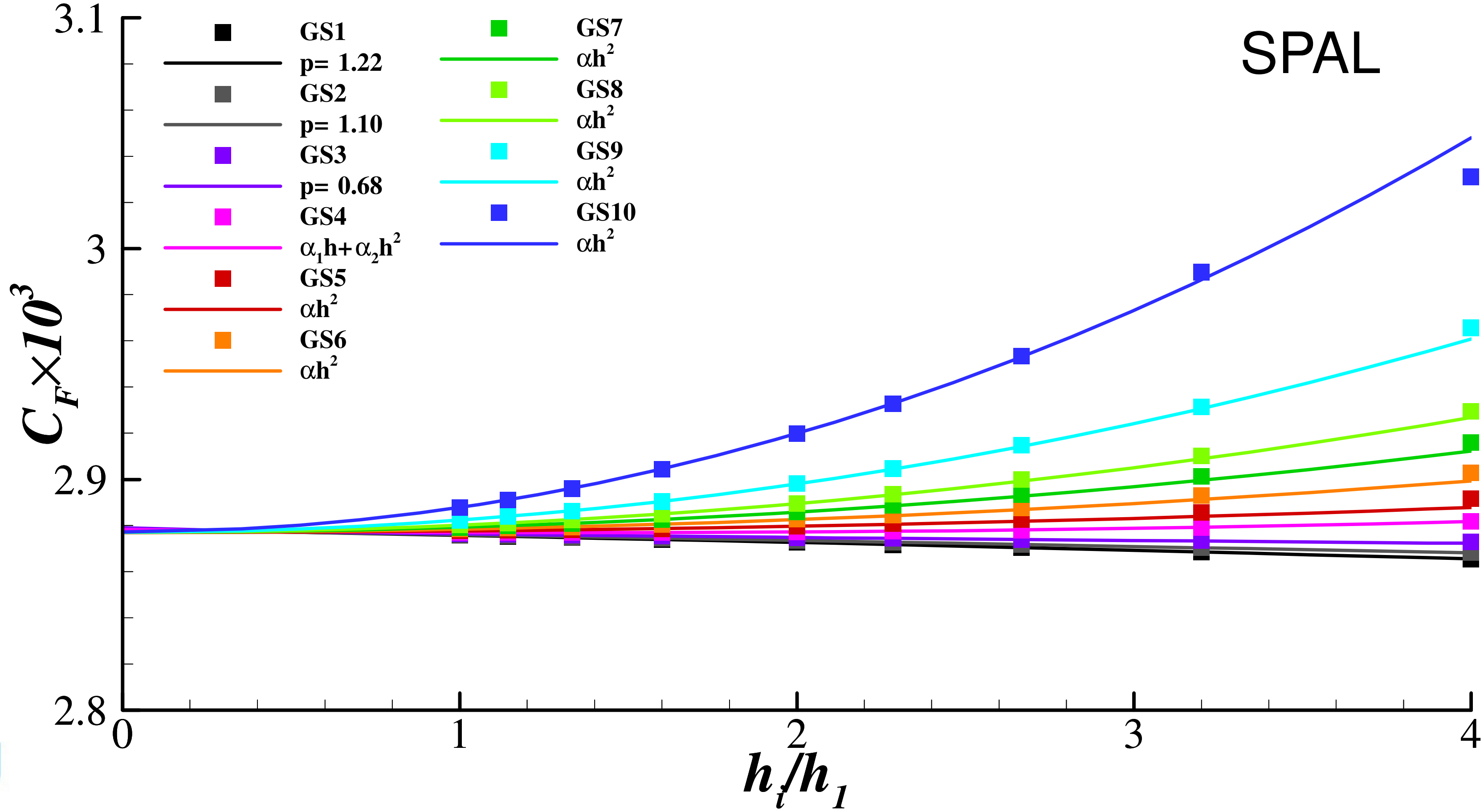
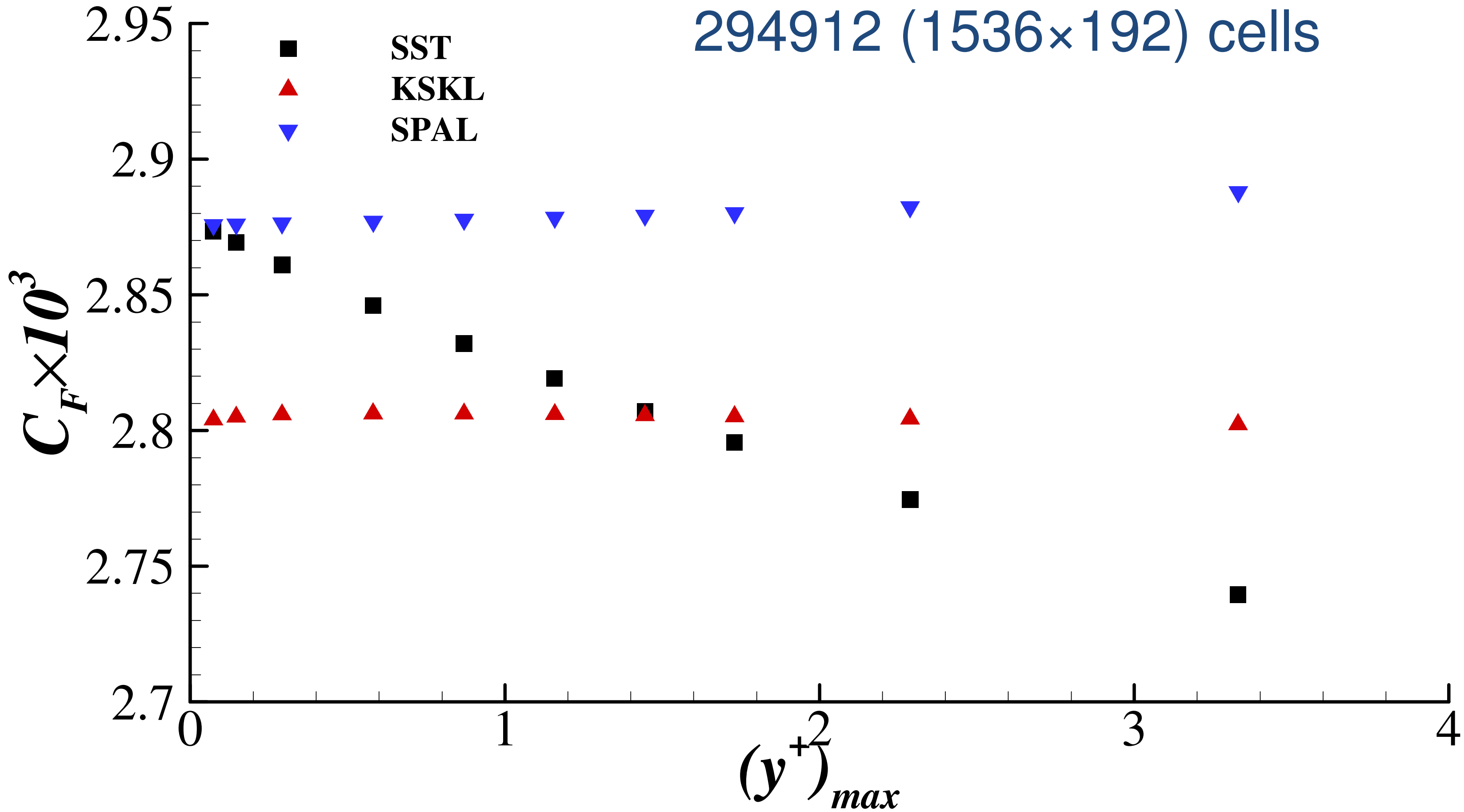


3. Statistically Steady Flows

Flow over a flat plate at Reynolds number 10^7

294912 (1536×192) cells



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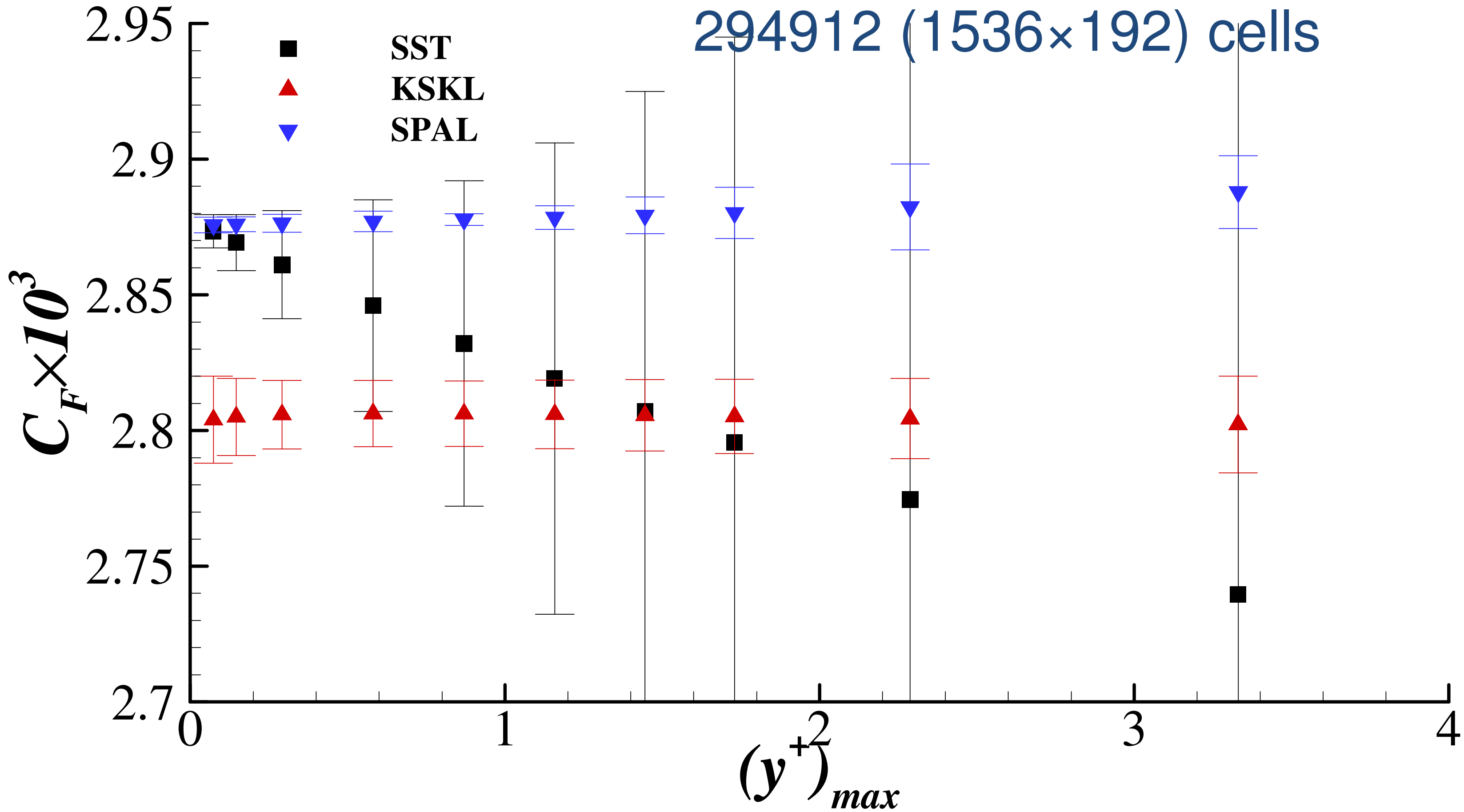
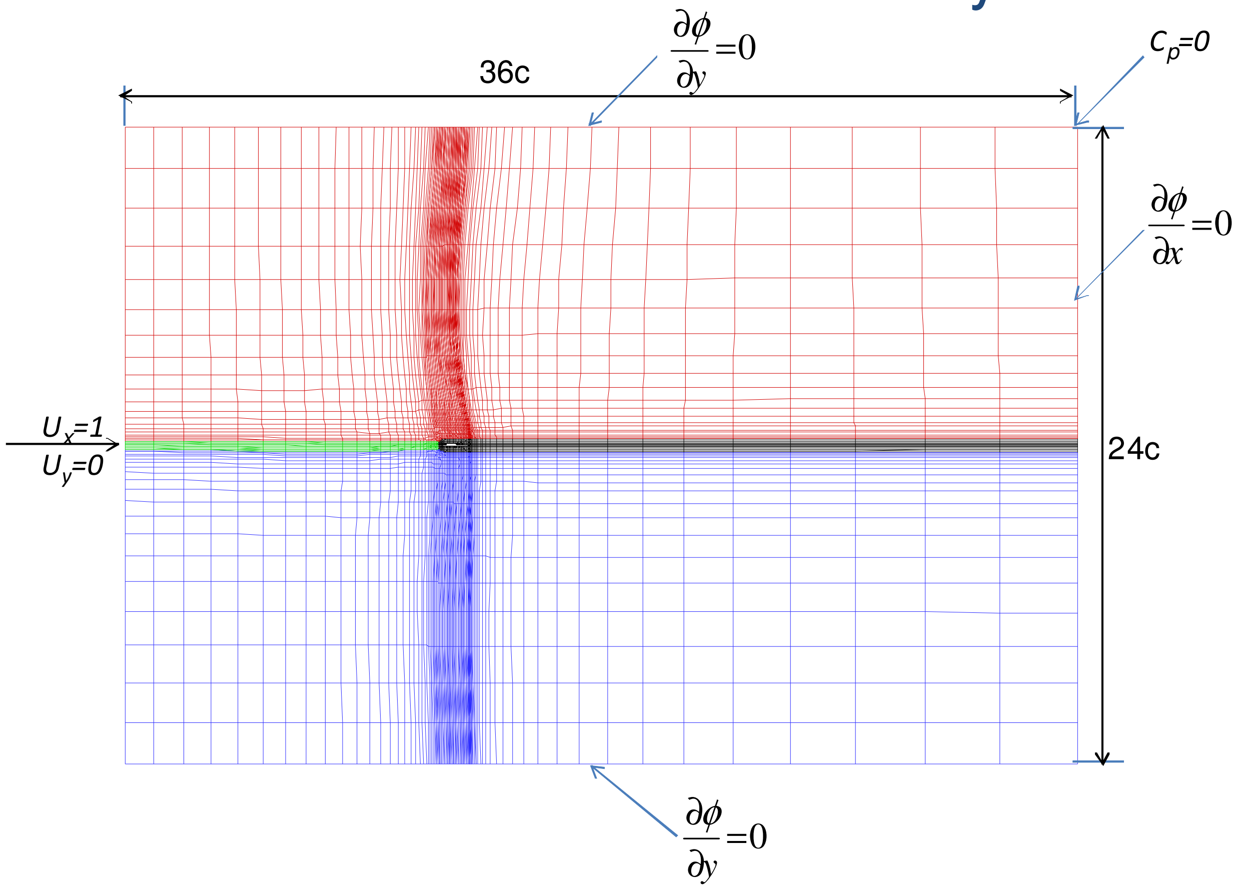


3. Statistically Steady Flows

- Flow around a NACA 0012 airfoil at Reynolds number 6×10^6

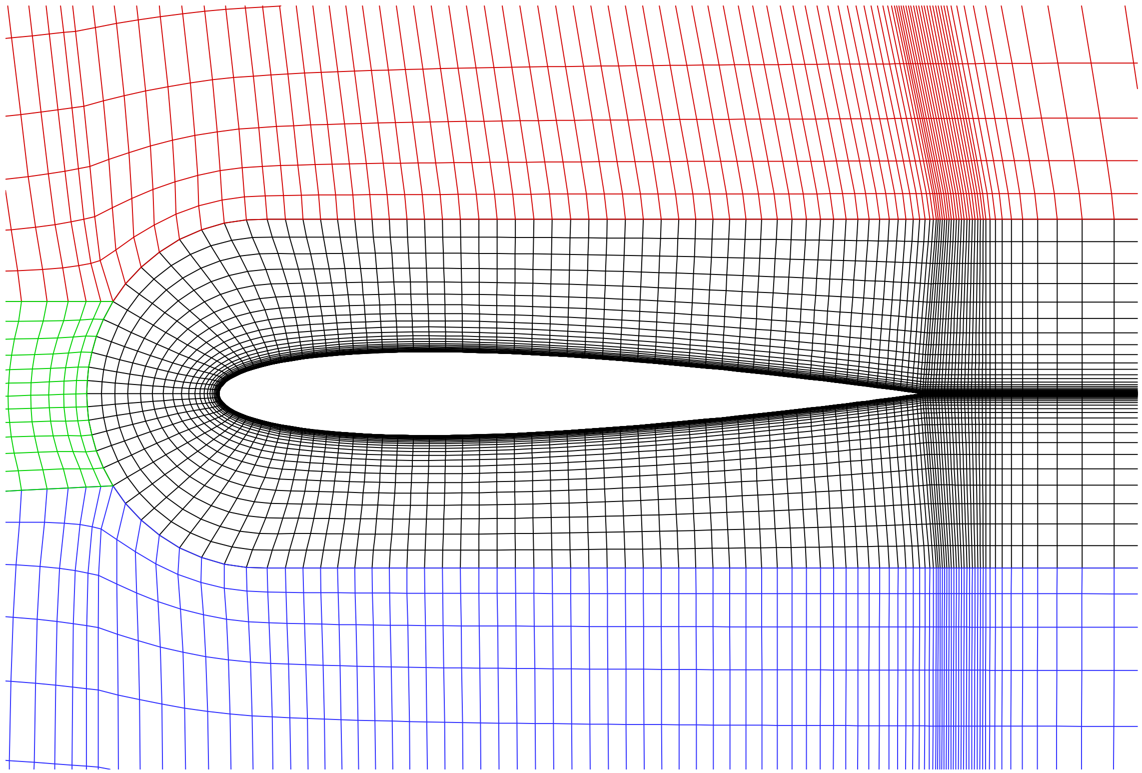


3. Statistically Steady Flows

- Flow around a NACA 0012 airfoil at Reynolds number 6×10^6, α=0º and α=5º
- Three eddy-viscosity turbulence models
  1. SST k-ω two-equation model (SST)
  2. k-$\sqrt{k}$L two-equation model (KSKL)
  3. Spalart & Allmaras one-equation model (SPAL)
- Quantities of interest:
  - Lift coefficient, $C_L = (C_L)_{friction} + (C_L)_{pressure}$
  - Drag coefficient, $C_D = (C_D)_{friction} + (C_D)_{pressure}$

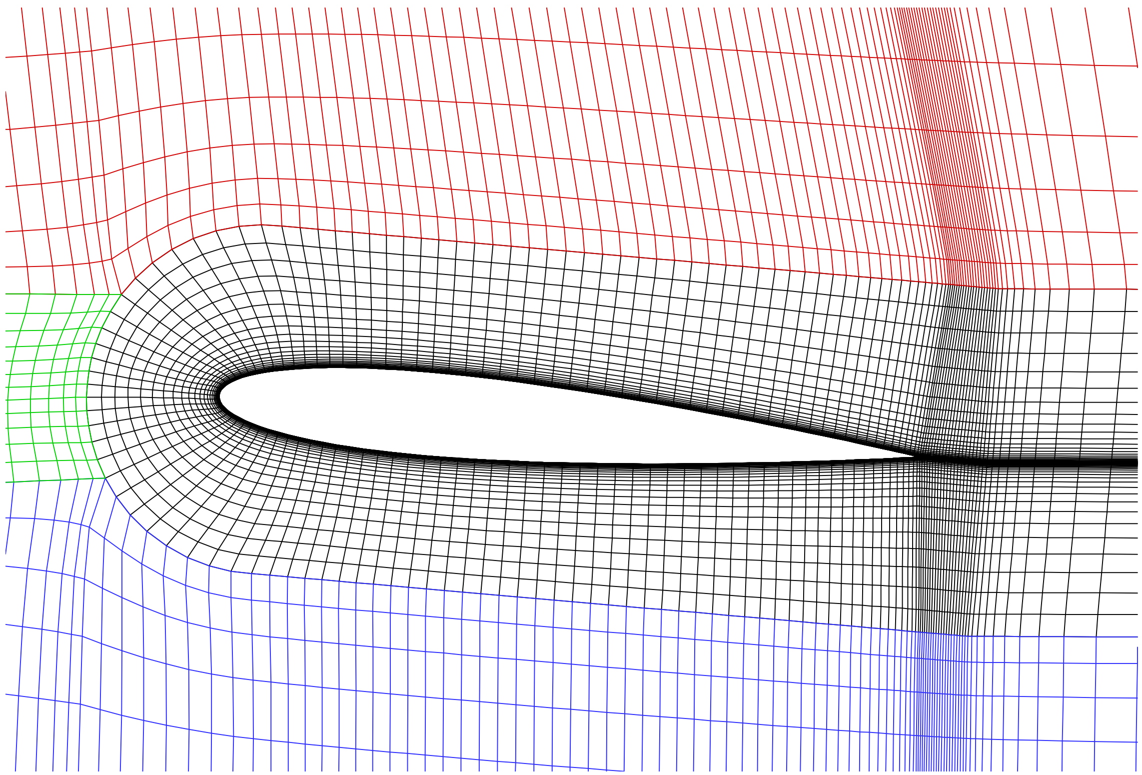
3. Statistically Steady Flows

Flow around a NACA 0012, $Re=6\times10^6$ and $\alpha=0º$



3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10^6 and α=5º

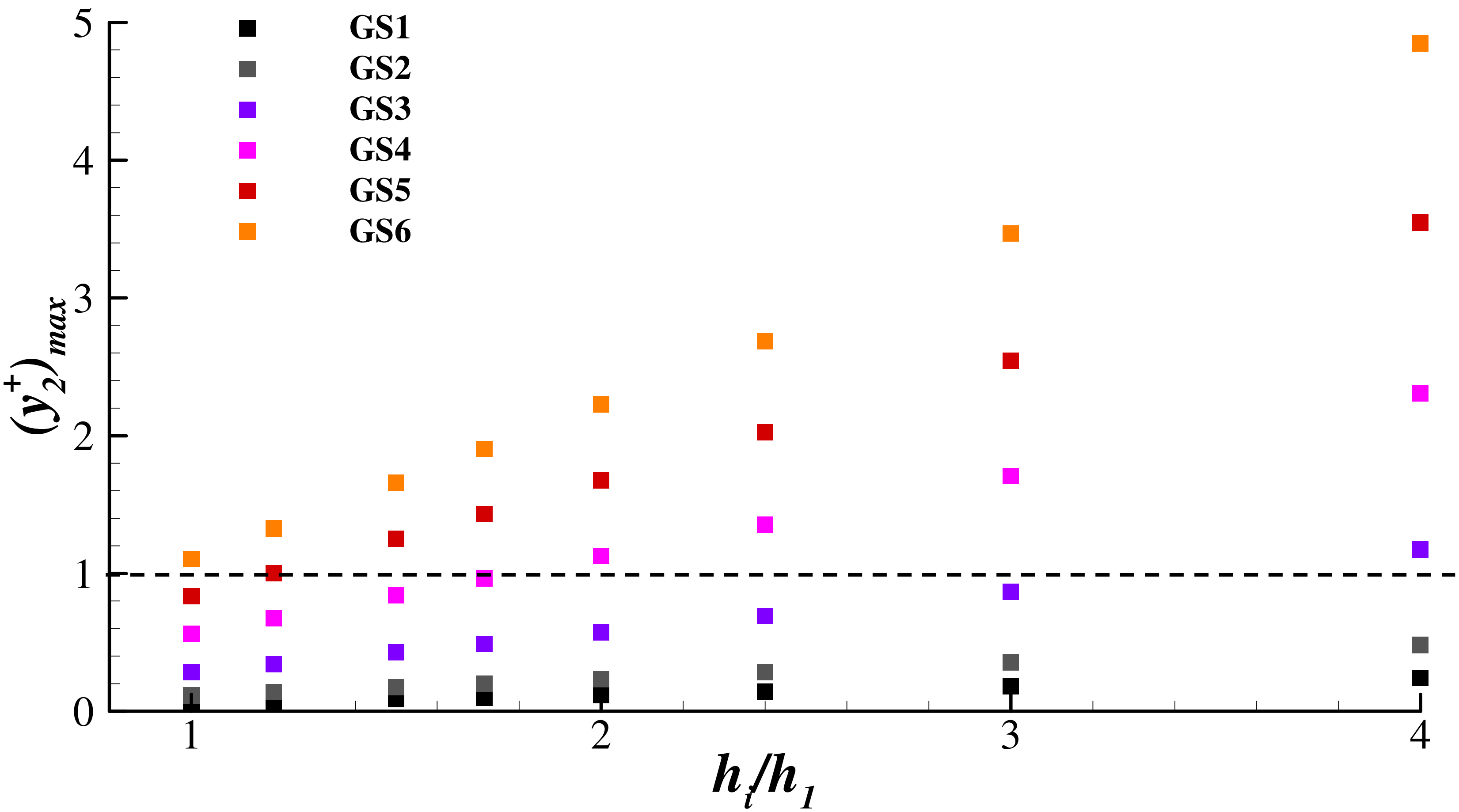


3. Statistically Steady Flows

- Flow around a NACA 0012 airfoil at Reynolds number 6×10^6, α=0º and α=5º
- 6 sets of 9 geometrically similar multiblock grids with clustering of grid nodes at the leading and trailing edges and at the wall
- Same number of cells (32670 to 522720, $1 \leq h_i/h_1 \leq 4$) for all sets
- Different stretching parameters for the definition of the size of the near-wall cells
- Negligible iterative and round-off errors, but...

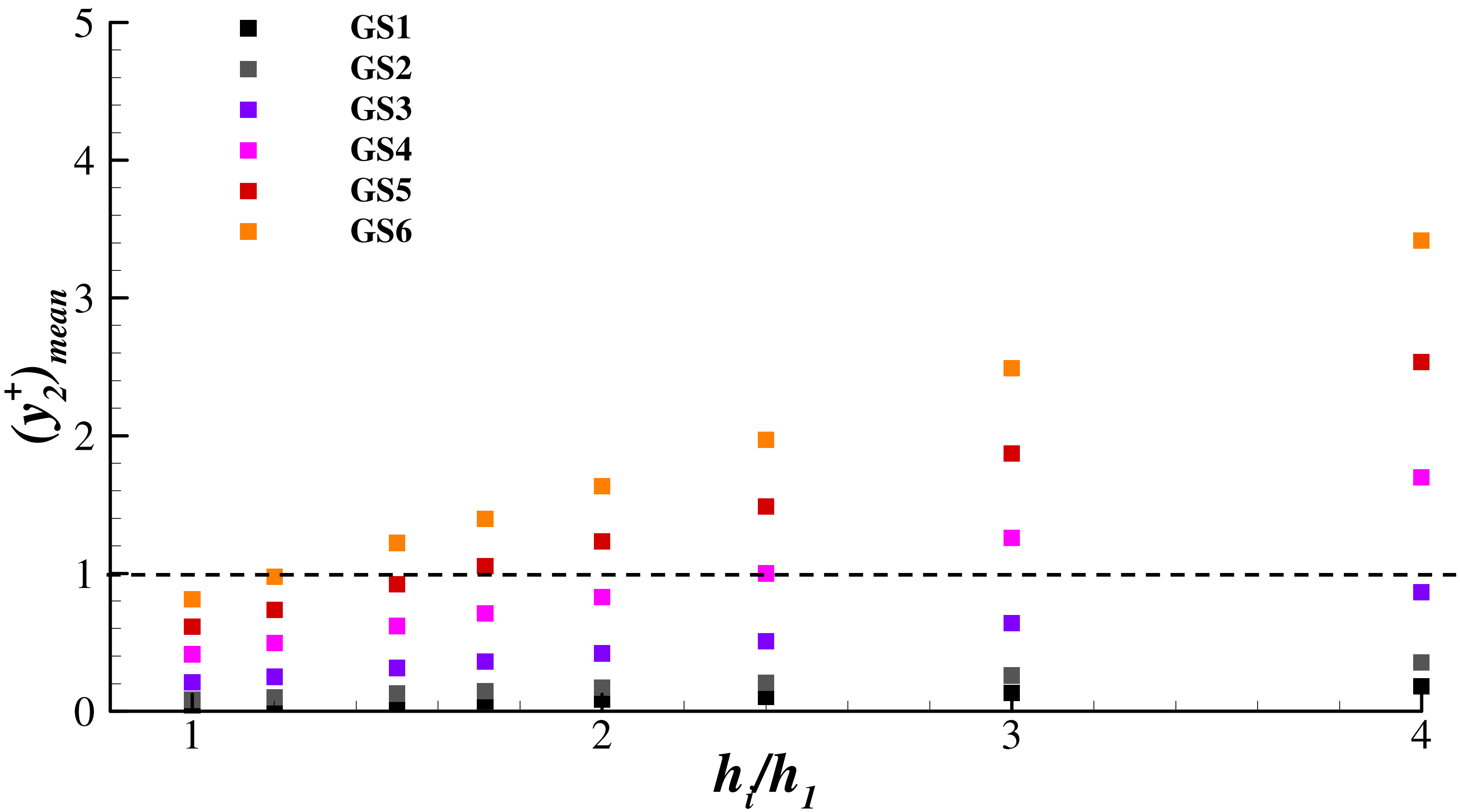
3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10^6 and α=0º



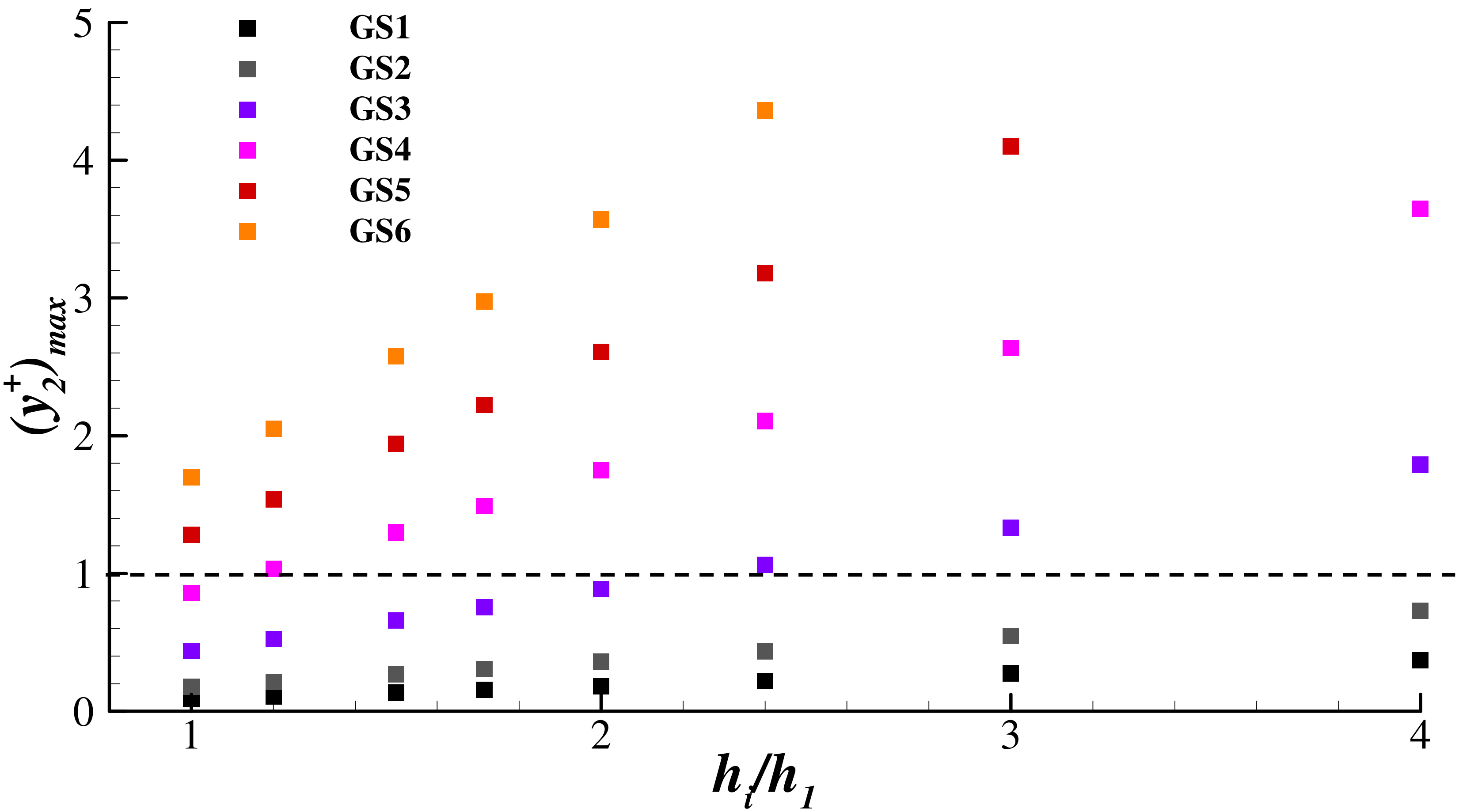
3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10^6 and α=0º



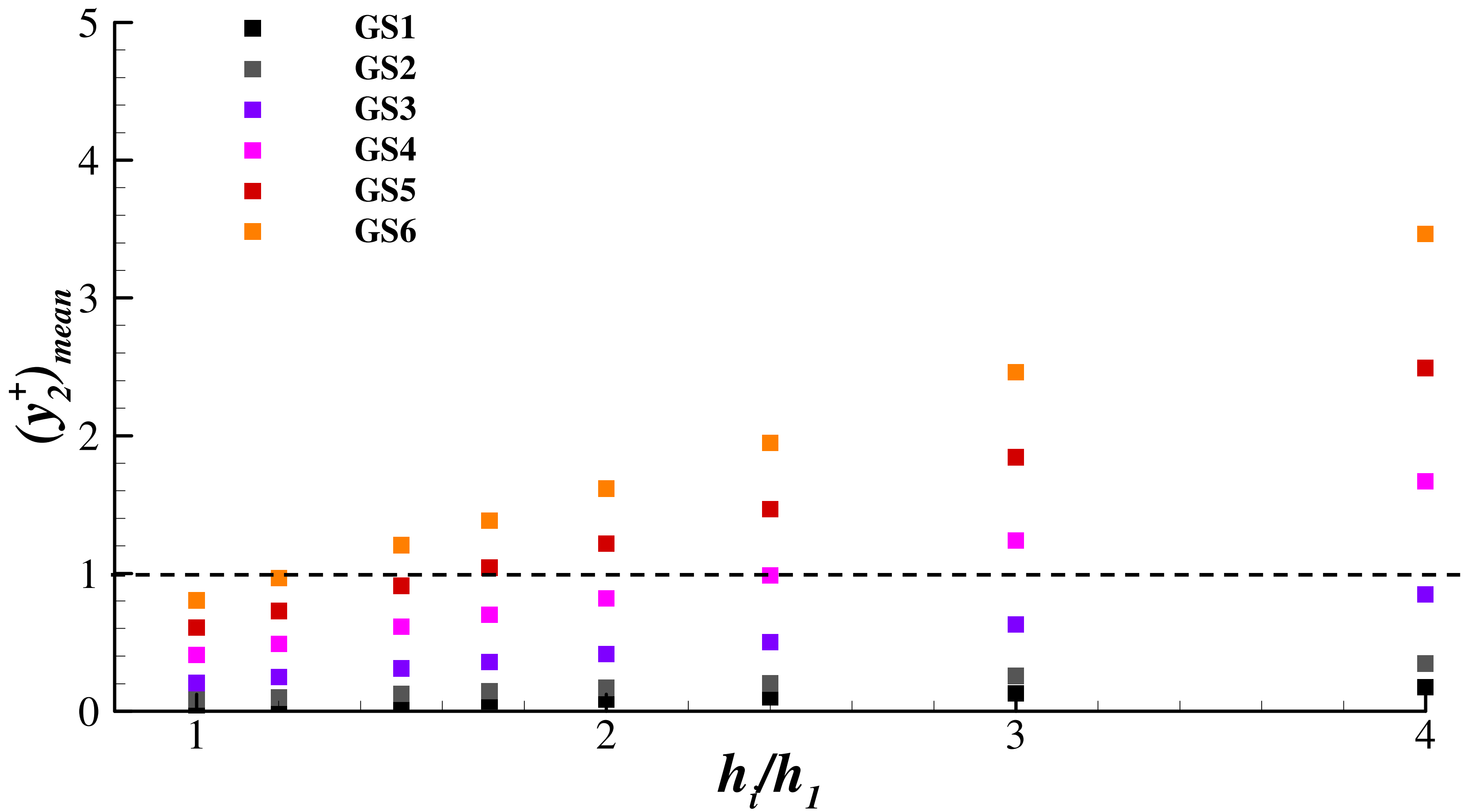
3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10^6 and α=5º



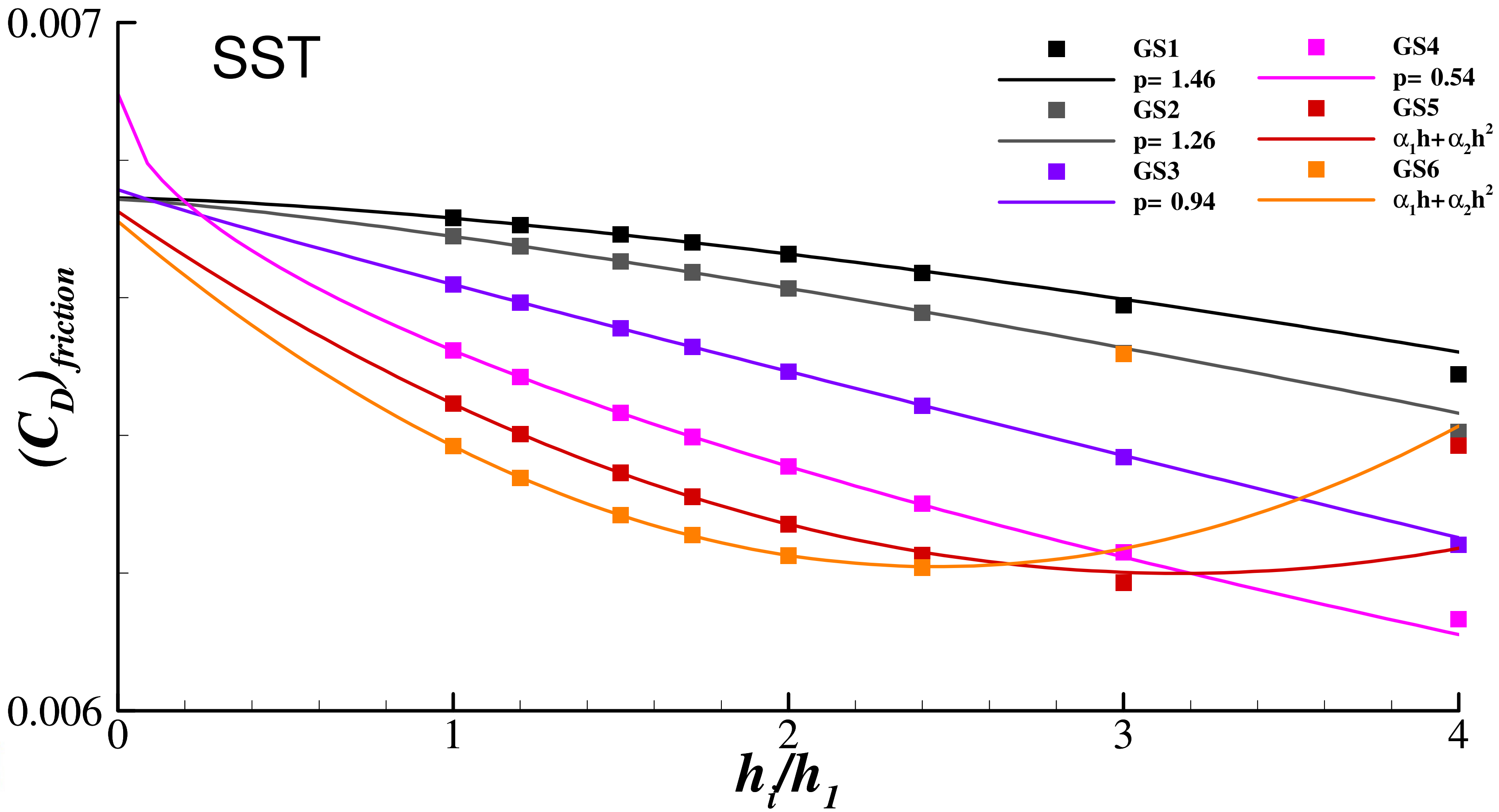
3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10^6 and α=5º



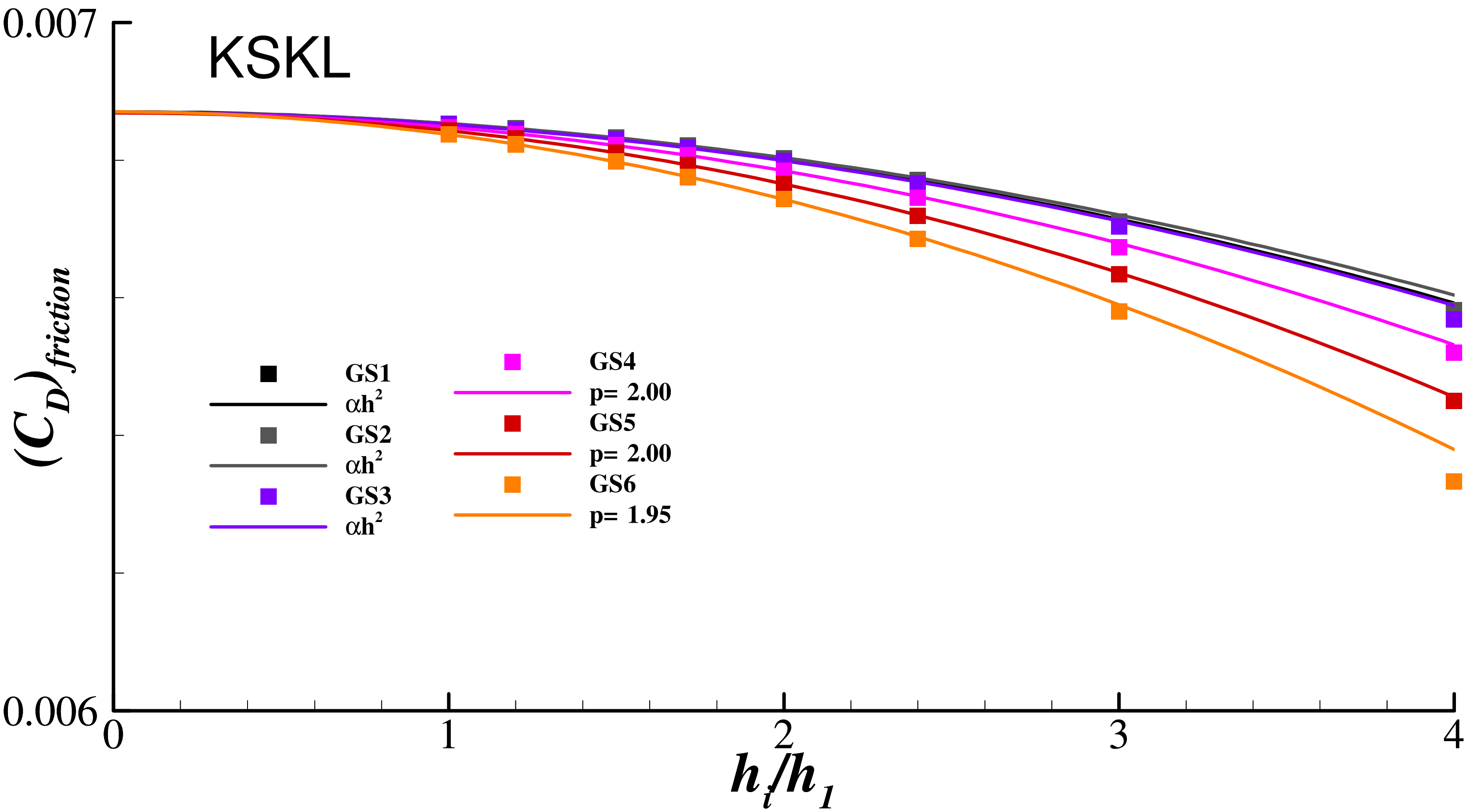
3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10⁶ and α=5º



3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10^6 and α=5º



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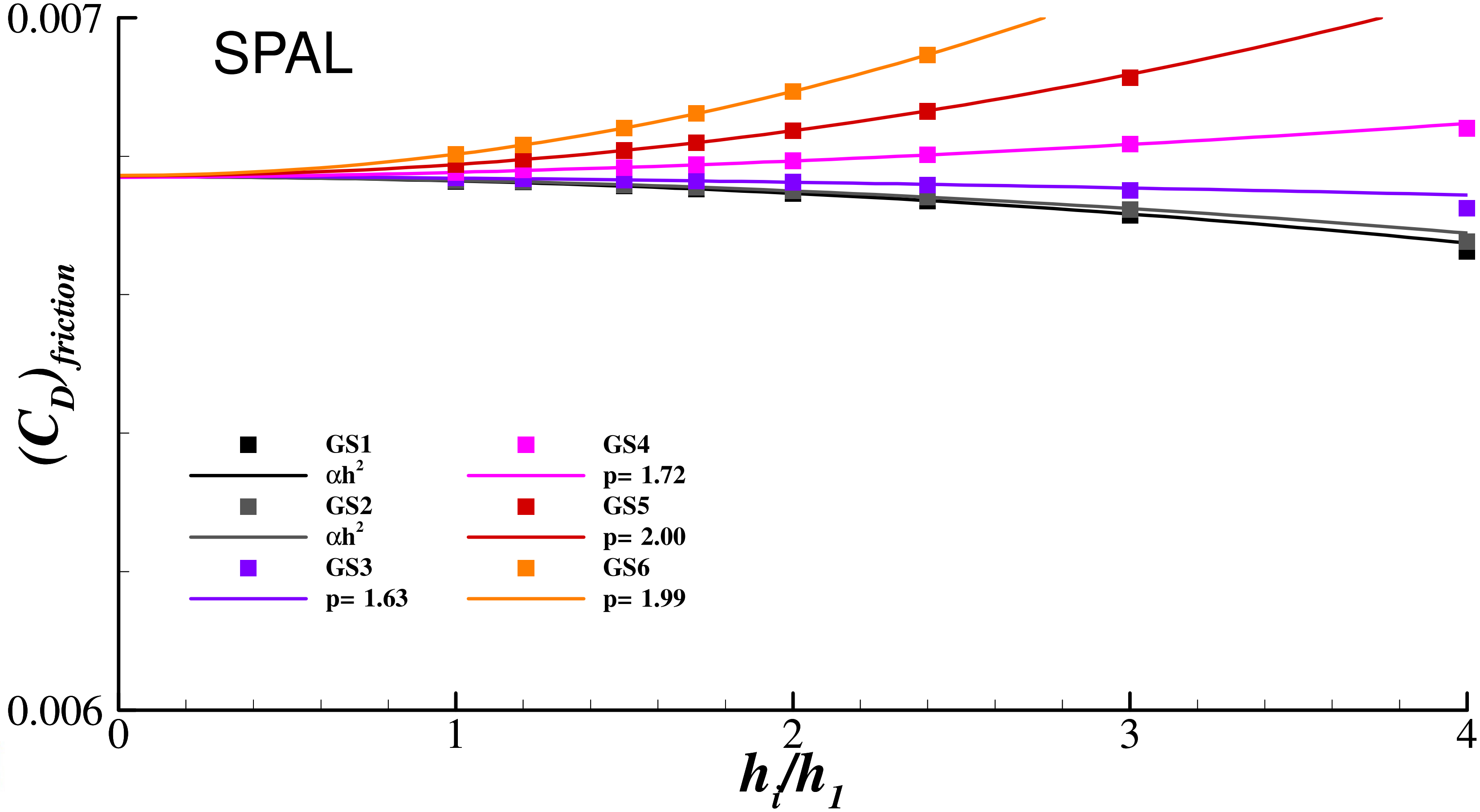
Flow around a NACA 0012, Re=6×10^6 and α=5º



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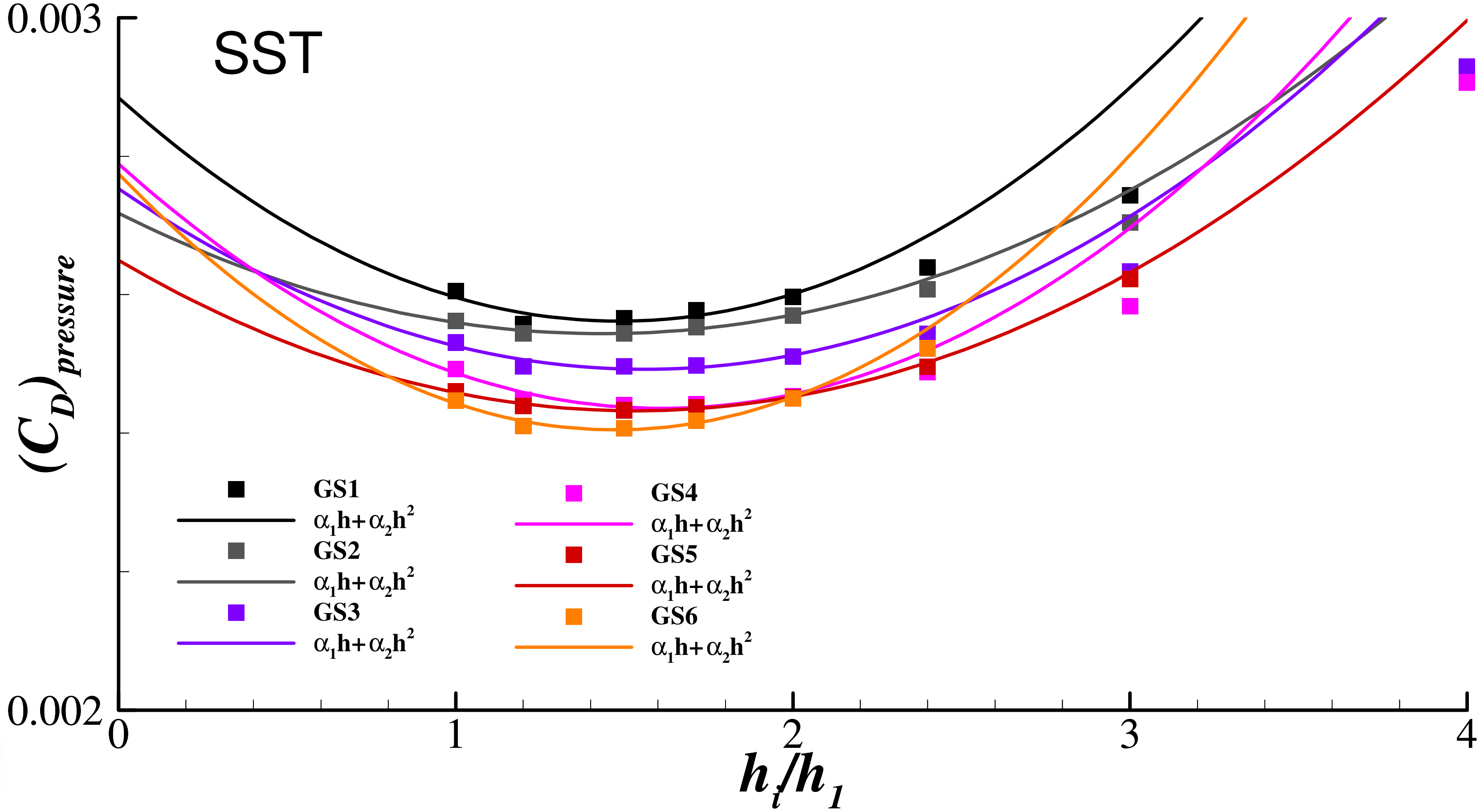
Flow around a NACA 0012, Re=6×10^6 and α=5º



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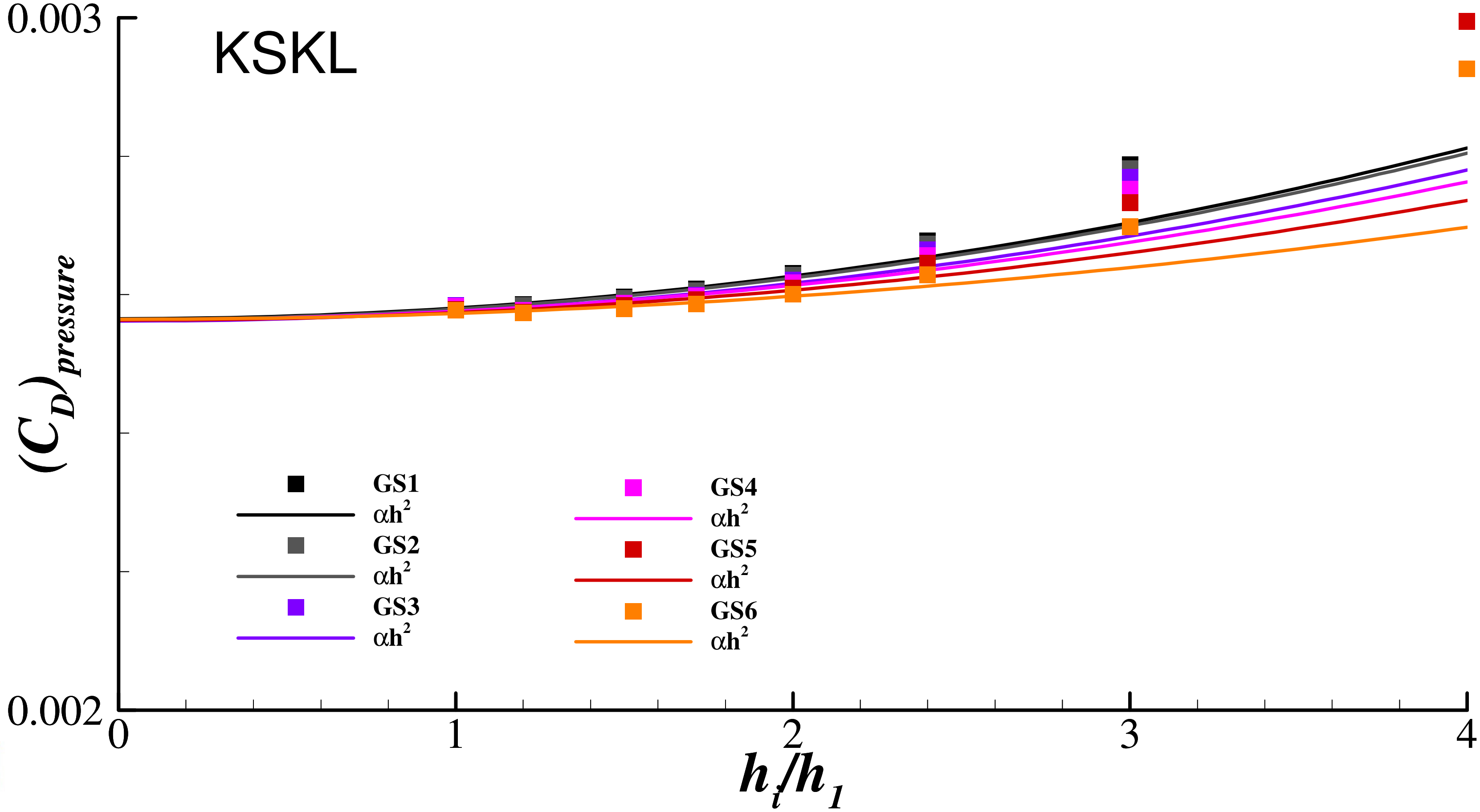
Flow around a NACA 0012, Re=6×10^6 and α=5º



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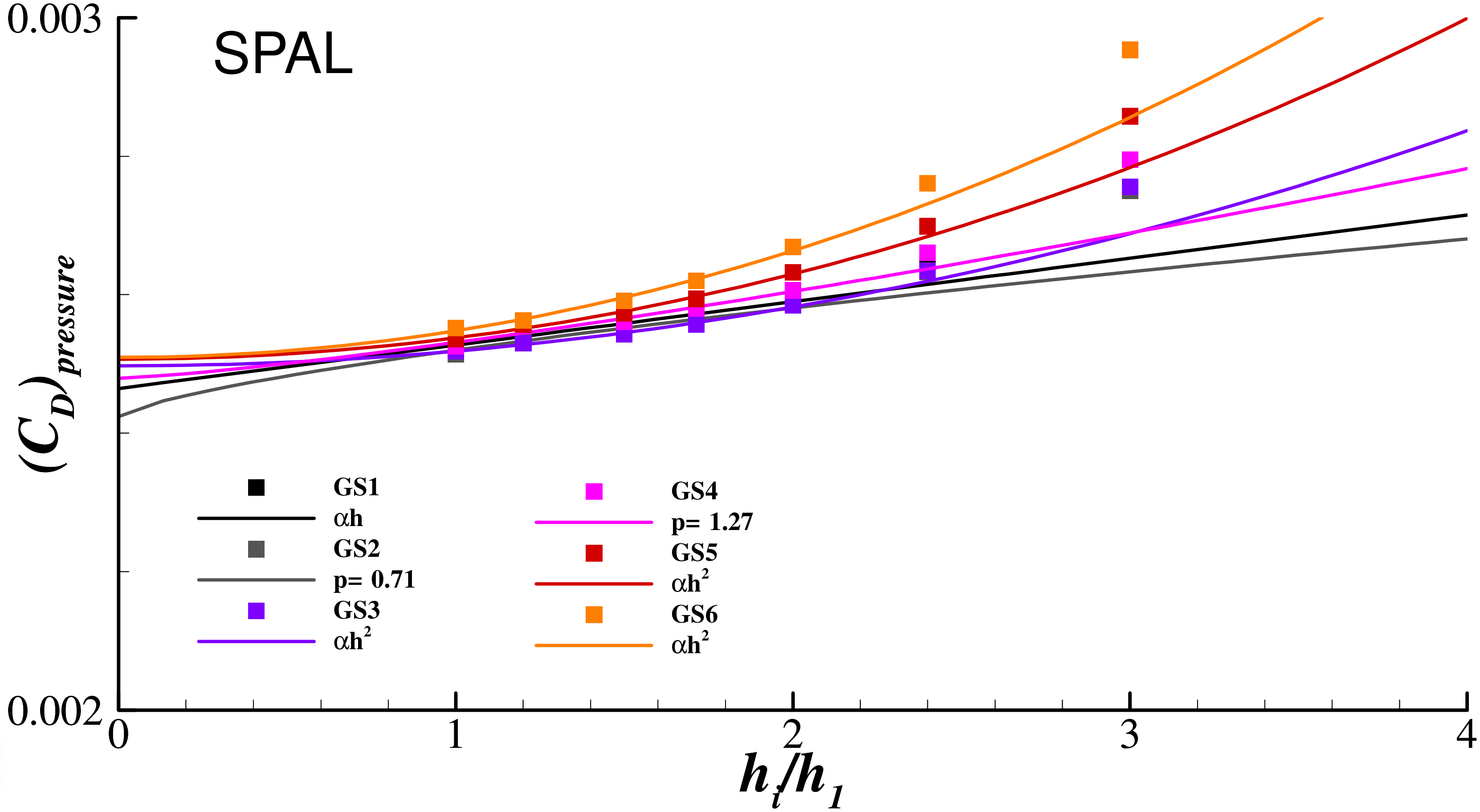
Flow around a NACA 0012, Re=6×10^6 and α=5º



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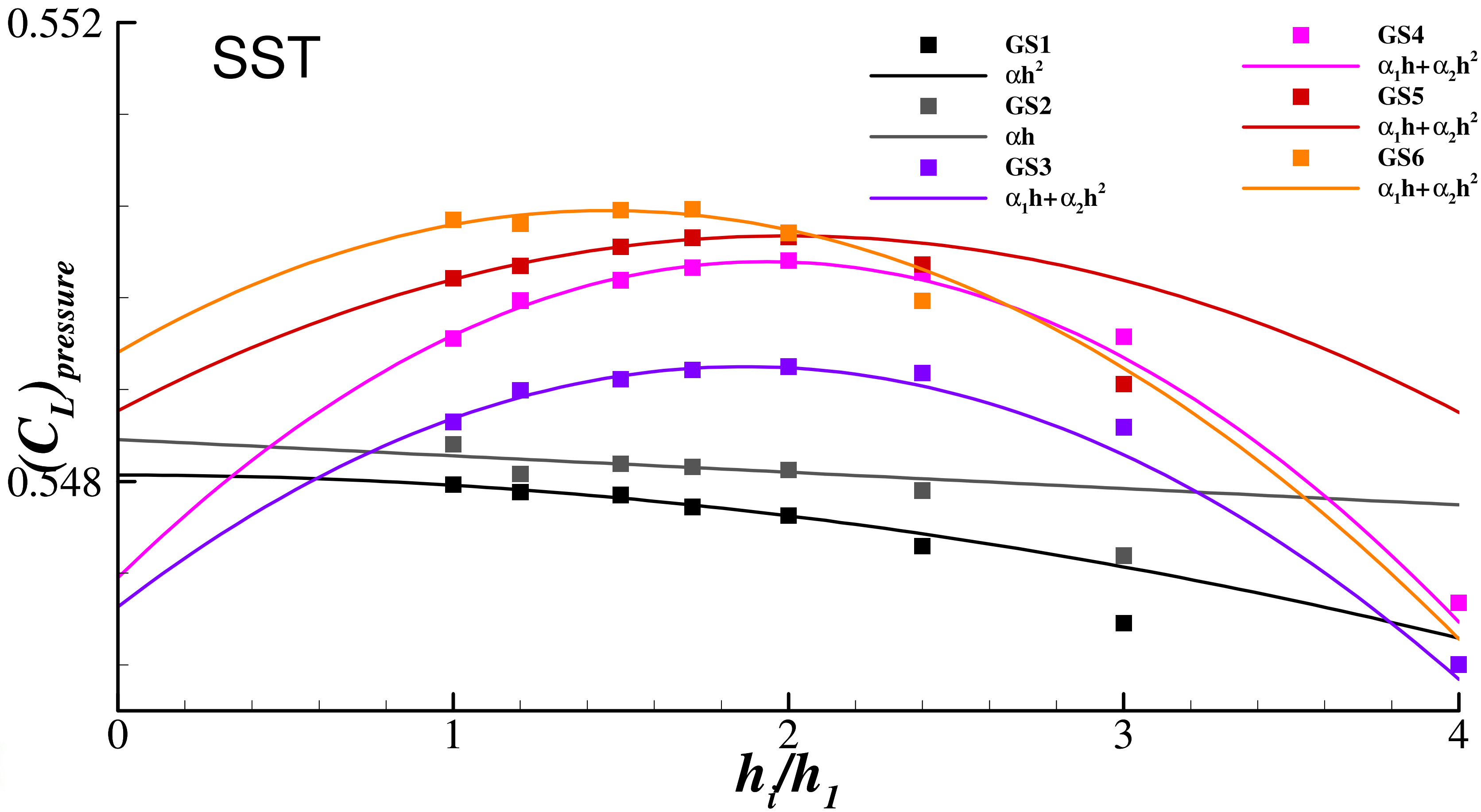
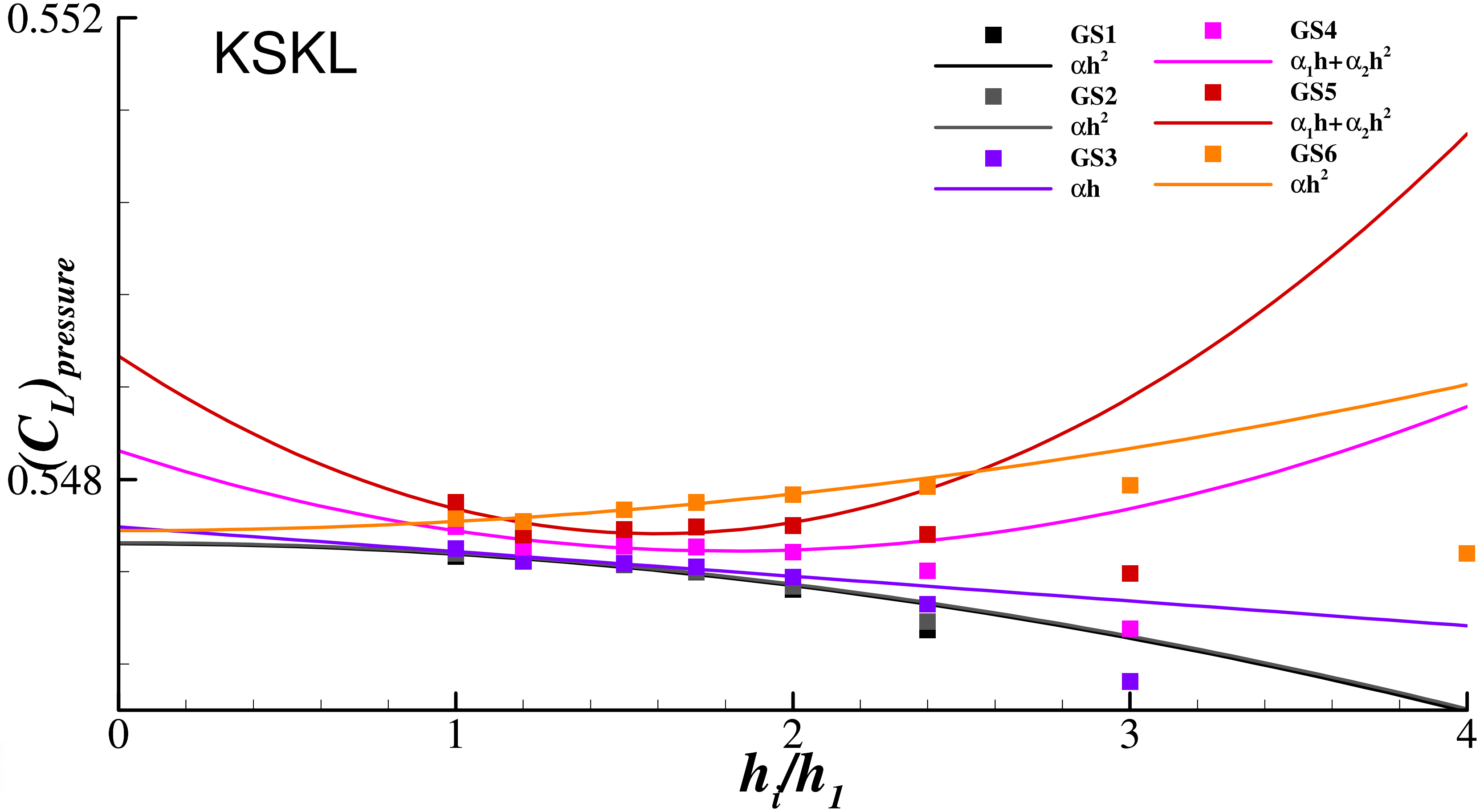
Flow around a NACA 0012, Re=6×10^6 and α=5º



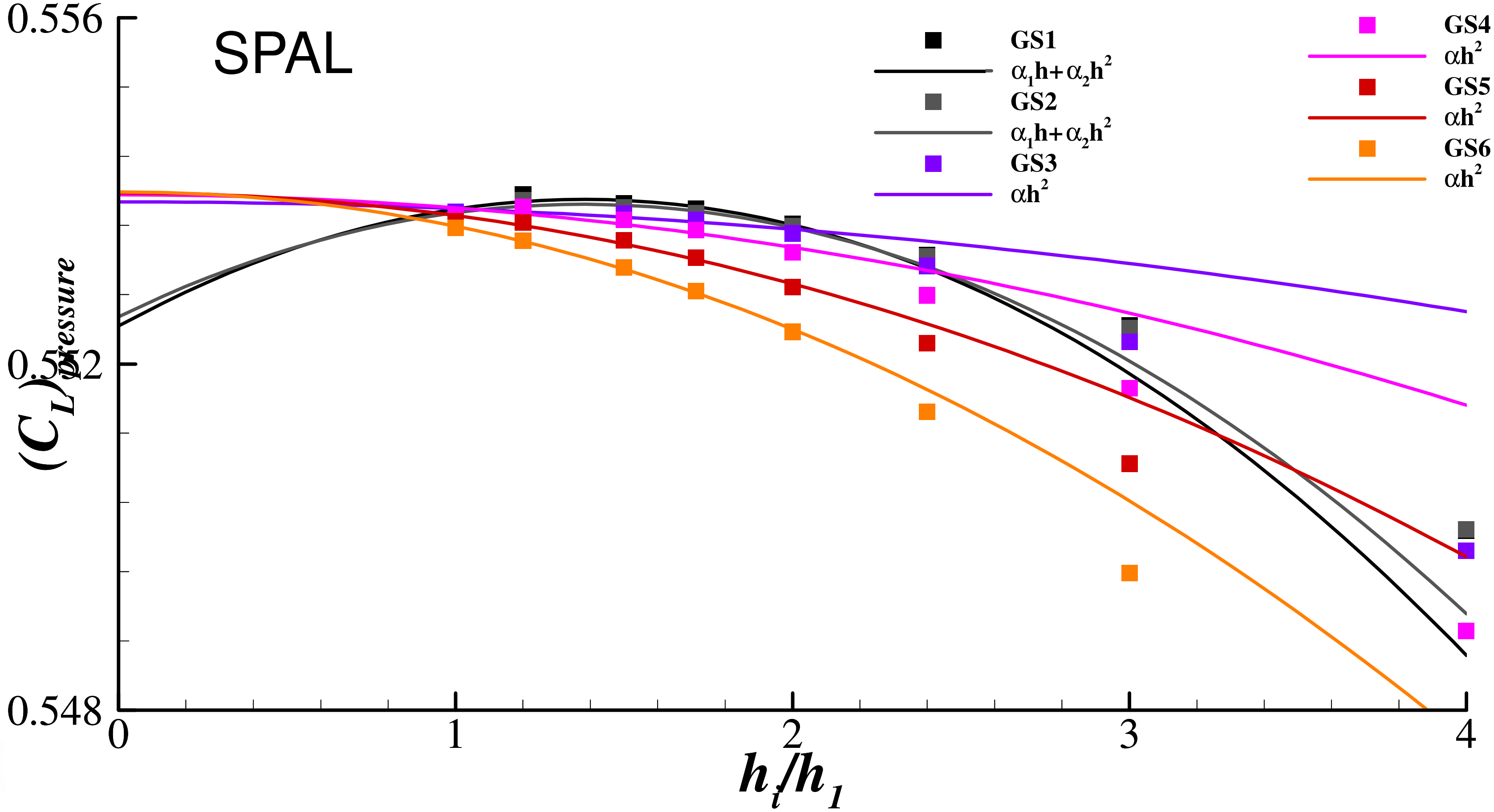
3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10⁶ and *α*=5º



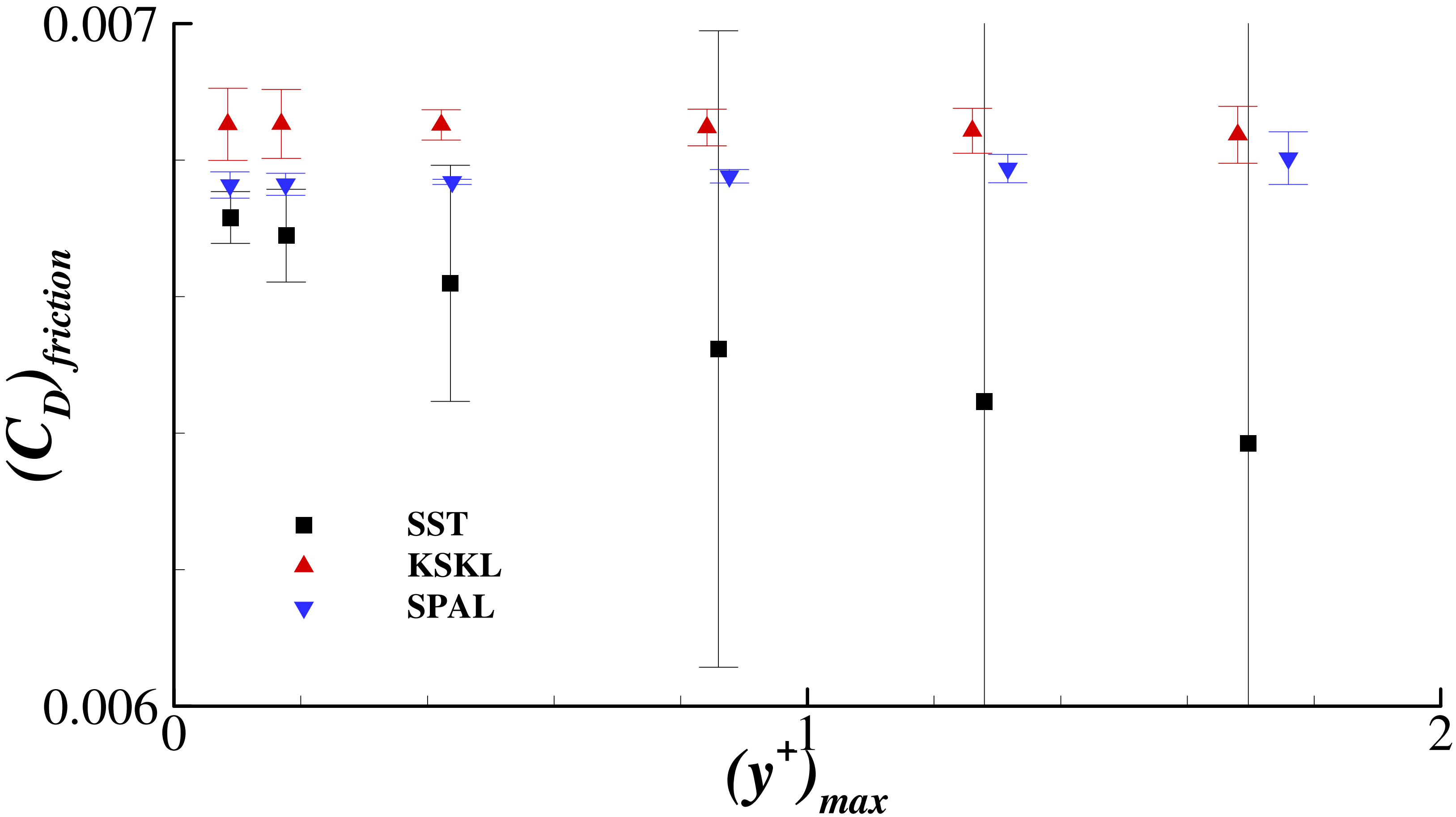
3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10⁶ and α=5º



3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10^6 and α=5º



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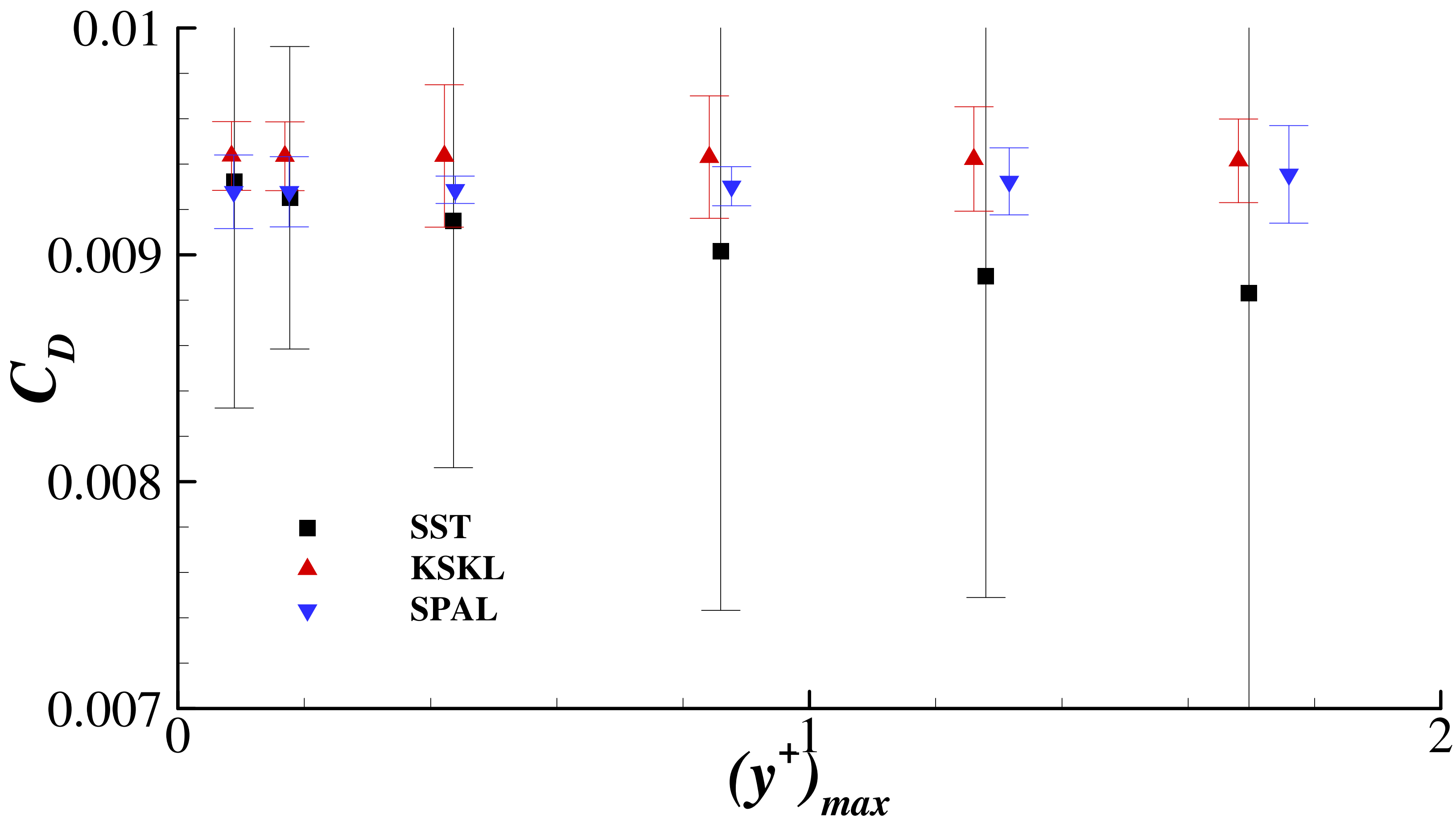
Flow around a NACA 0012, Re=6×10^6 and α=5º



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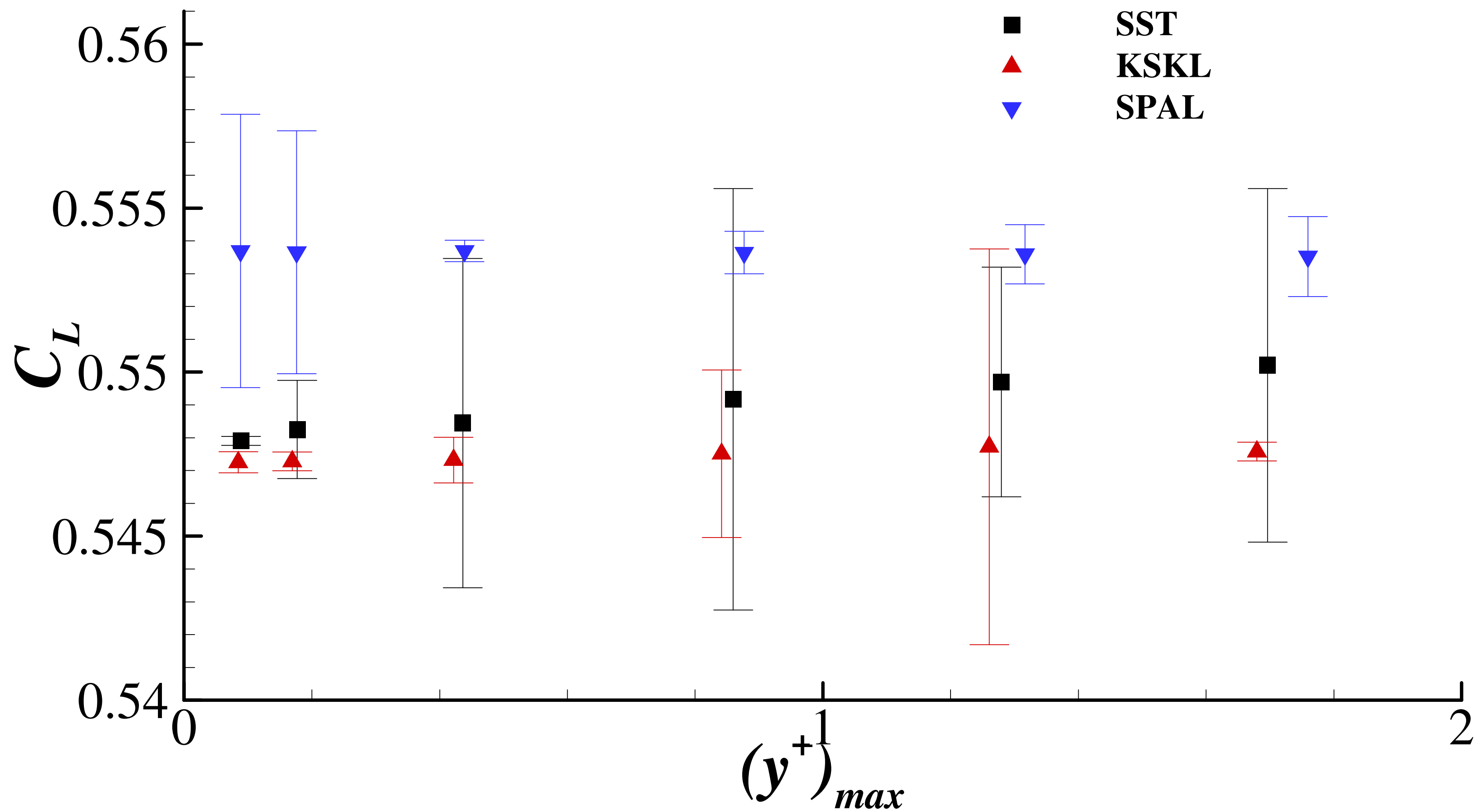
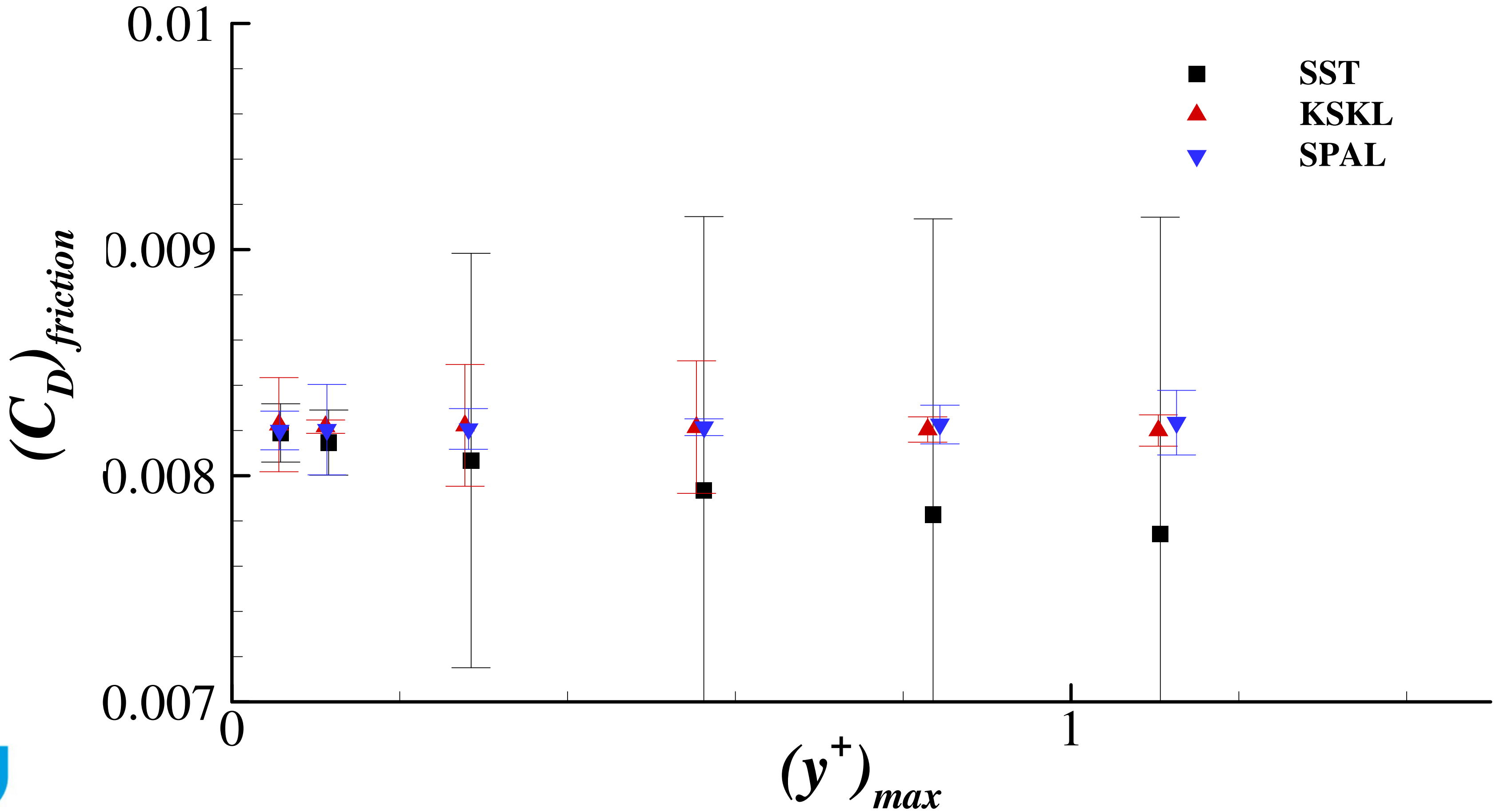
Flow around a NACA 0012, Re=6×10^6 and α=5º



3. Statistically Steady Flows

Flow around a NACA 0012, Re=6×10^6 and α=0º



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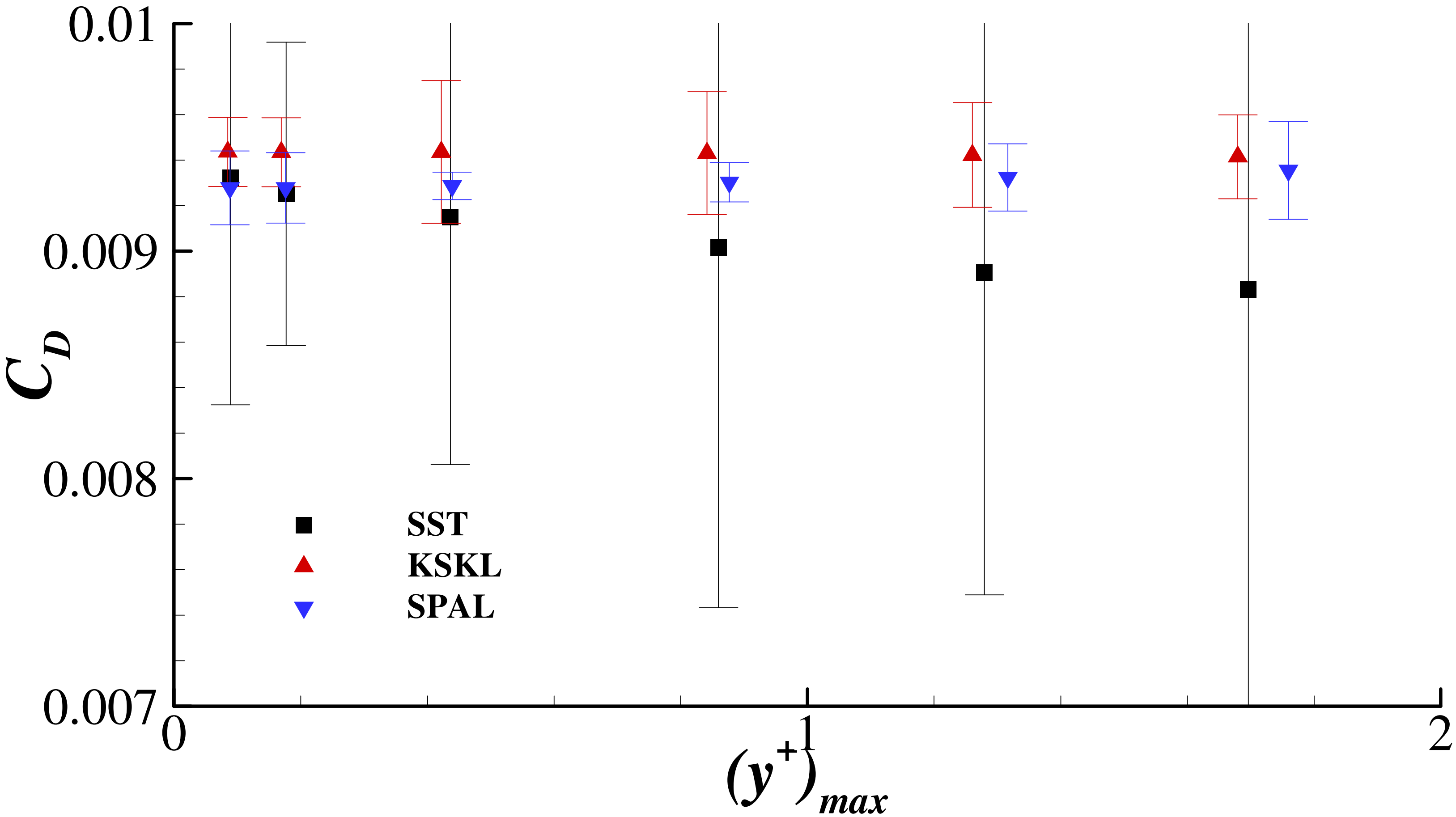
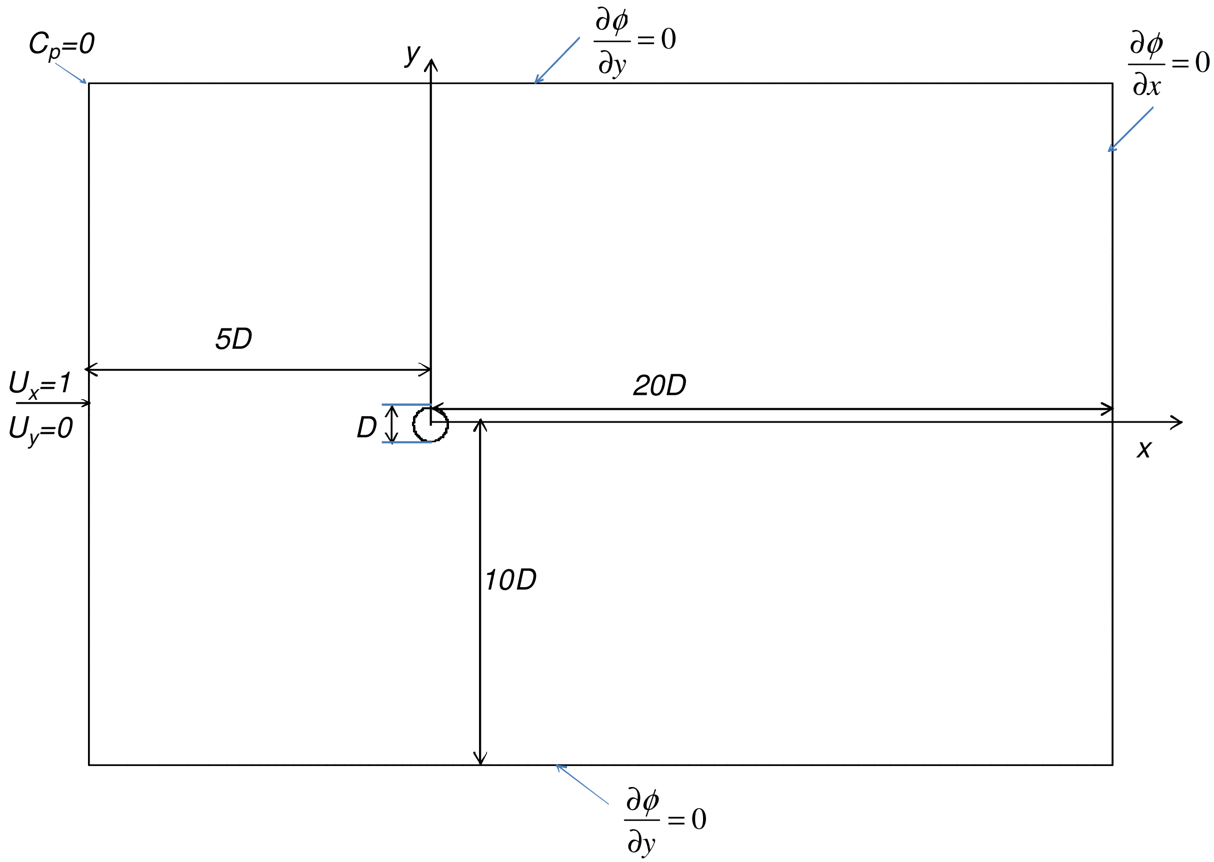
Flow around a NACA 0012, Re=6×10^6 and α=0º



4. Statistically Unsteady Flows

- Flow around a circular cylinder at Reynolds number 6.31×10^4



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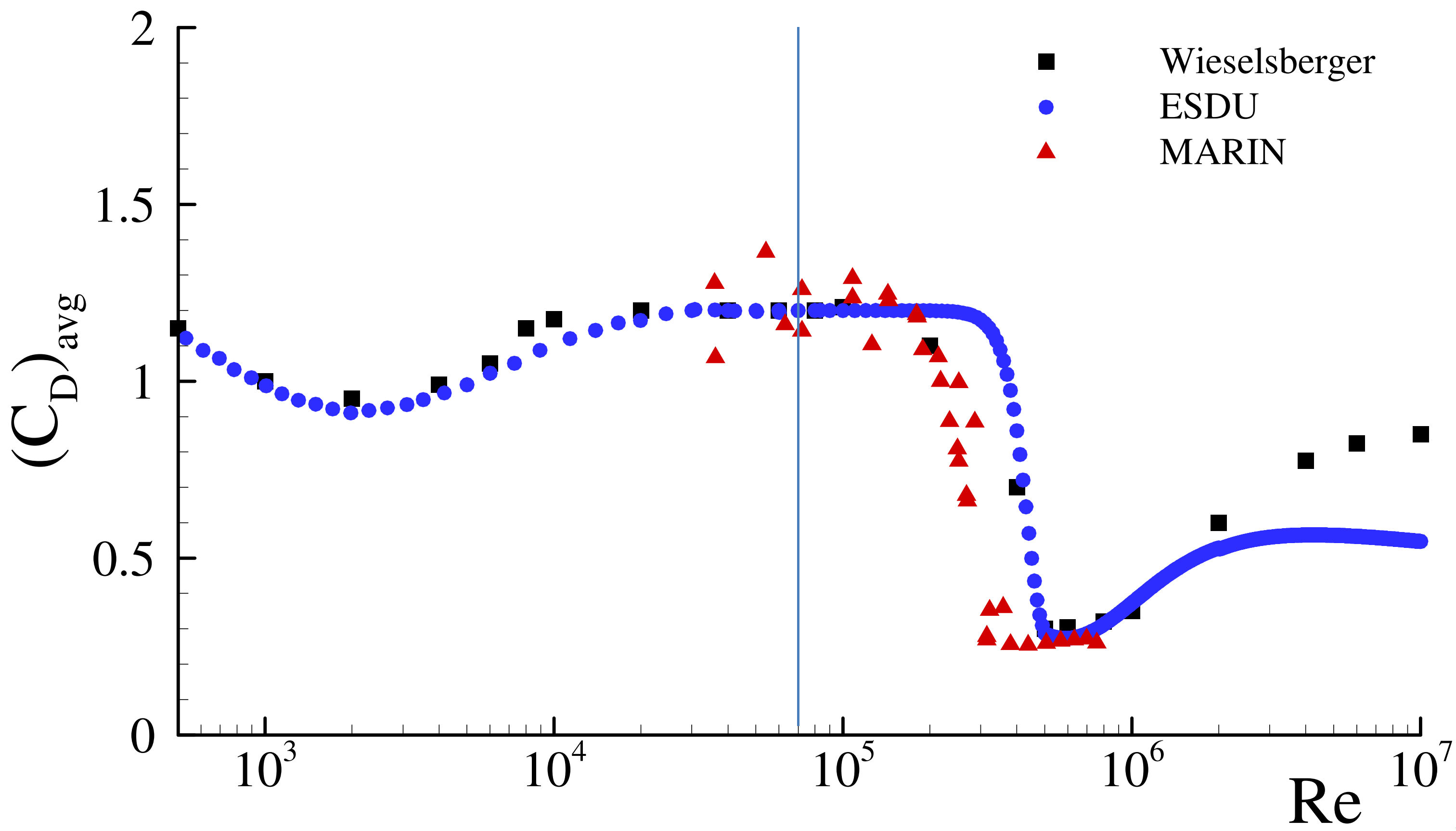

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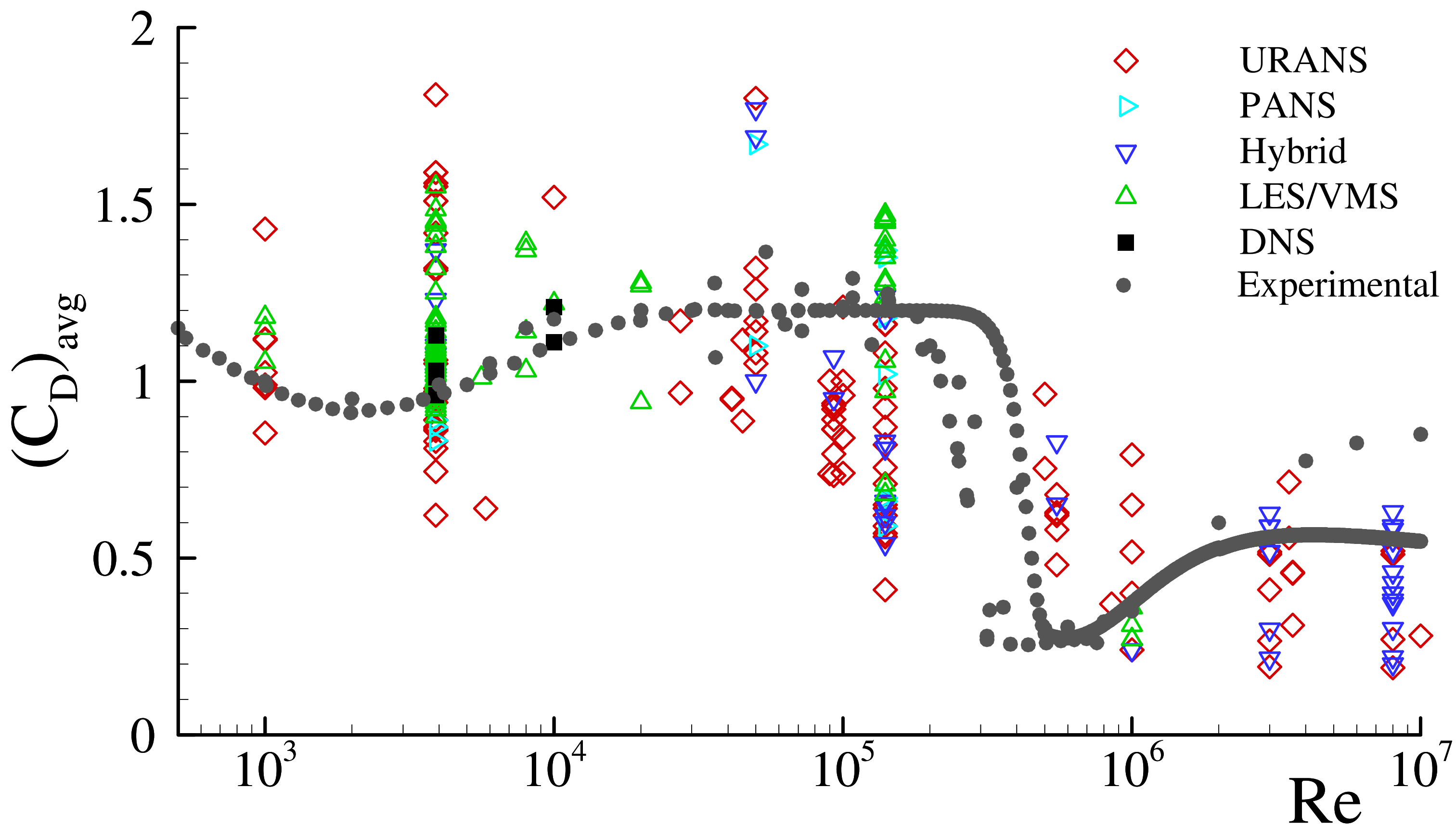


4. Statistically Unsteady Flows

- Flow around a circular cylinder at Reynolds number 6.31×10^4
- SST k-ω two-equation model (SST)
- Quantities of interest:
  - Average and maximum drag coefficient, $(C_D)_{avg}$, $(C_D)_{max}$
  - Maximum lift coefficient, $(C_L)_{max}$
- Simultaneous grid and time refinement $r_i = h_i/h_1 = \tau_i/\tau_1 = \lambda_i/\lambda_1$

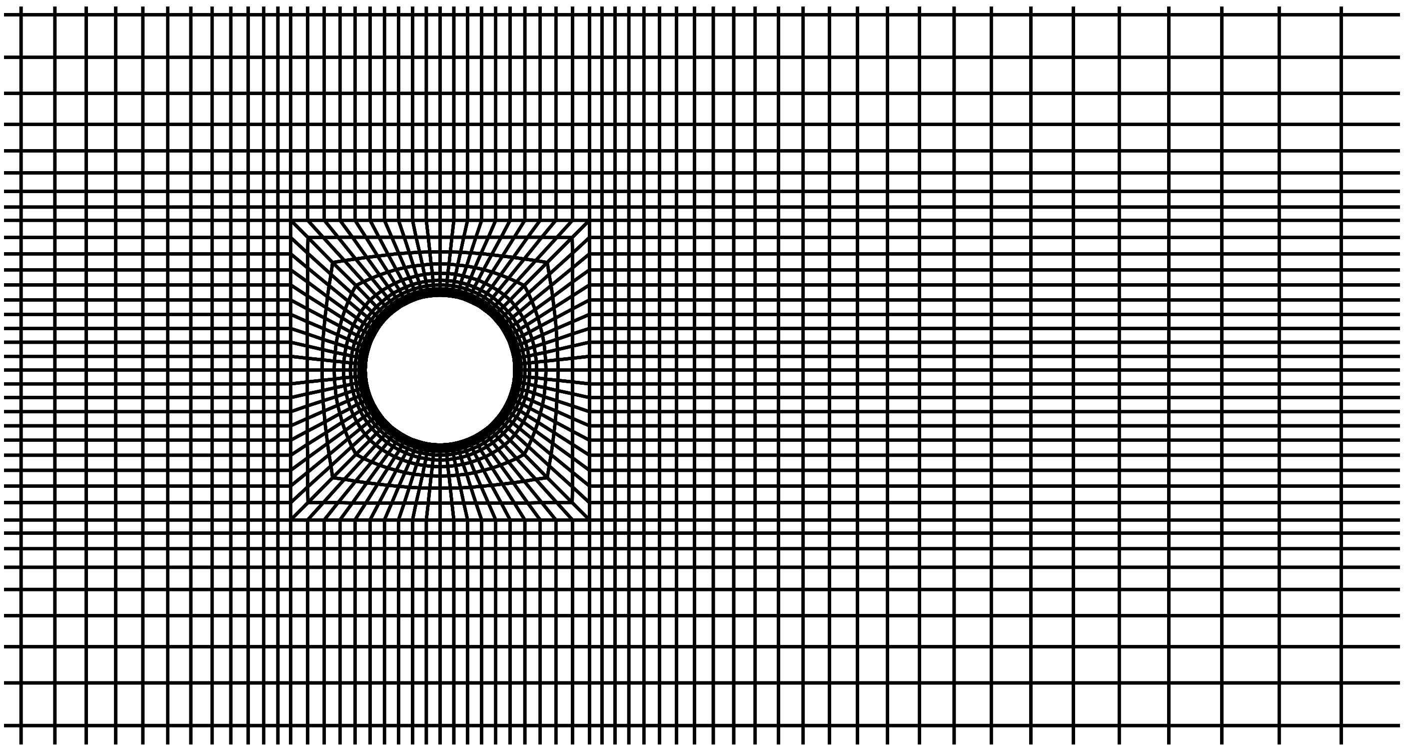
4. Statistically Unsteady Flows

- Flow around a circular cylinder at Reynolds number 6.31×10^4
- Two sets of multiblock geometrically similar grids
  - Set A, 16 grids, 5600 to 358400 cells, $1 \leq h_i/h_1 \leq 8$
    Finest - $(y_2^+)_{max}<0.1$, Coarsest - $(y_2^+)_{max}<1$
    Maximum Courant number 8.8
    Average Courant number 1.5
  - Set B, 16 grids, 8016 to 288576 cells, $1 \leq h_i/h_1 \leq 6$
    Finest - $(y_2^+)_{max}<0.1$, Coarsest - $(y_2^+)_{max}<0.7$

	B1	B2	B3
Maximum Courant number	7.0,	17,	33
Average Courant number	1.7,	4.1,	8.4

4. Statistically Unsteady Flows

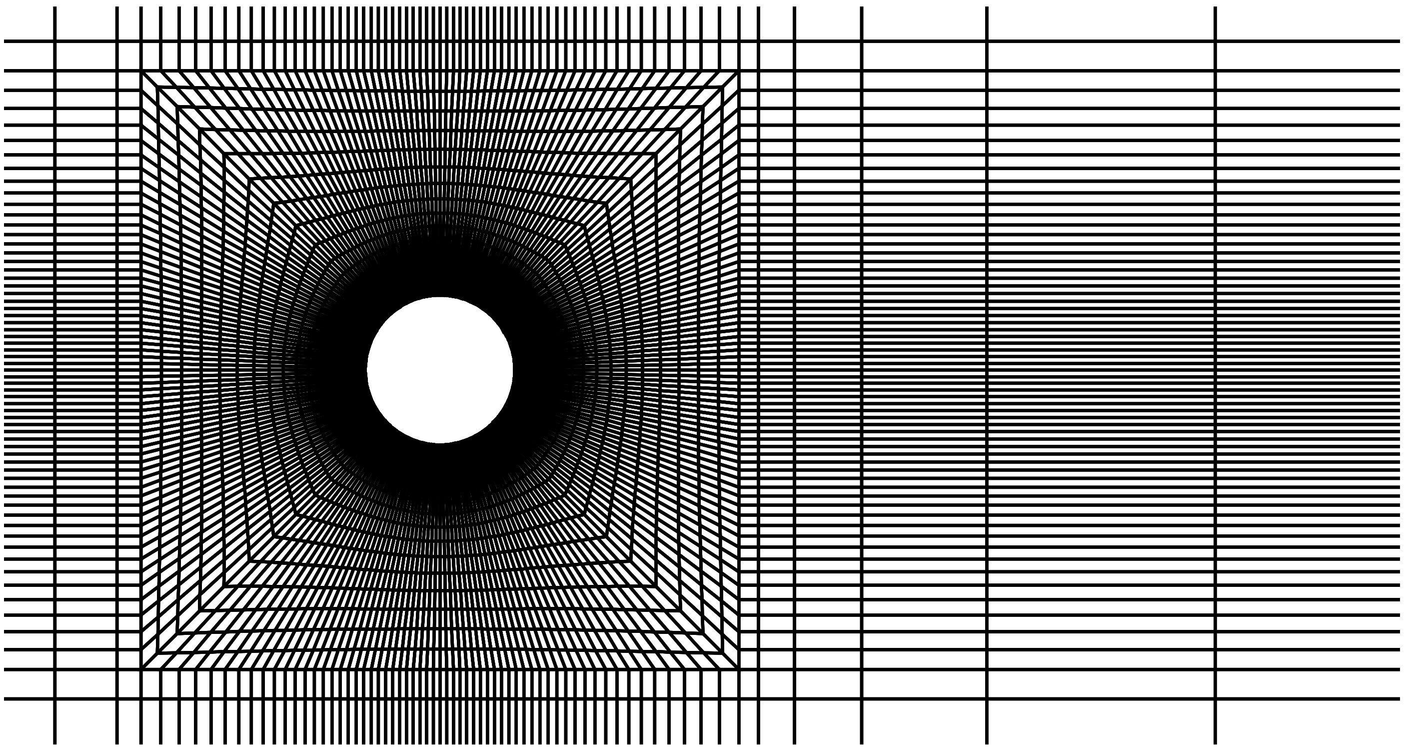
- Flow around a circular cylinder at Reynolds number 6.31×10^4



Set A

4. Statistically Unsteady Flows

- Flow around a circular cylinder at Reynolds number 6.31×10^{4}



Set B

4. Statistically Unsteady Flows

- Iterative error has two components:
  1. Solution must become periodic
     (Negligible influence of initial condition)
     Convergence criteria defines how much flow time needs to be calculated

  2. Each time step of an implicit method requires the solution of a non-linear system of equations
     (Equivalent to a statistically steady flow)
     Convergence criteria (tol_{it}) defines how accurate is the solution of each time step

4. Statistically Unsteady Flows

- Present solutions were obtained with the following strategy:
  1. Calculate 200 non-dimensional time units (45 cycles) with $(tol_{it})=10^{-2}$
  2. For $(tol_{it})=10^{-3}$, $(tol_{it})=10^{-4}$, $(tol_{it})=10^{-5}$ and $(tol_{it})=10^{-6}$, calculate 120 non-dimensional time units using the solution obtained with the previous value of (tol_{it}) as the starting condition
  3. Check periodicity of the solution

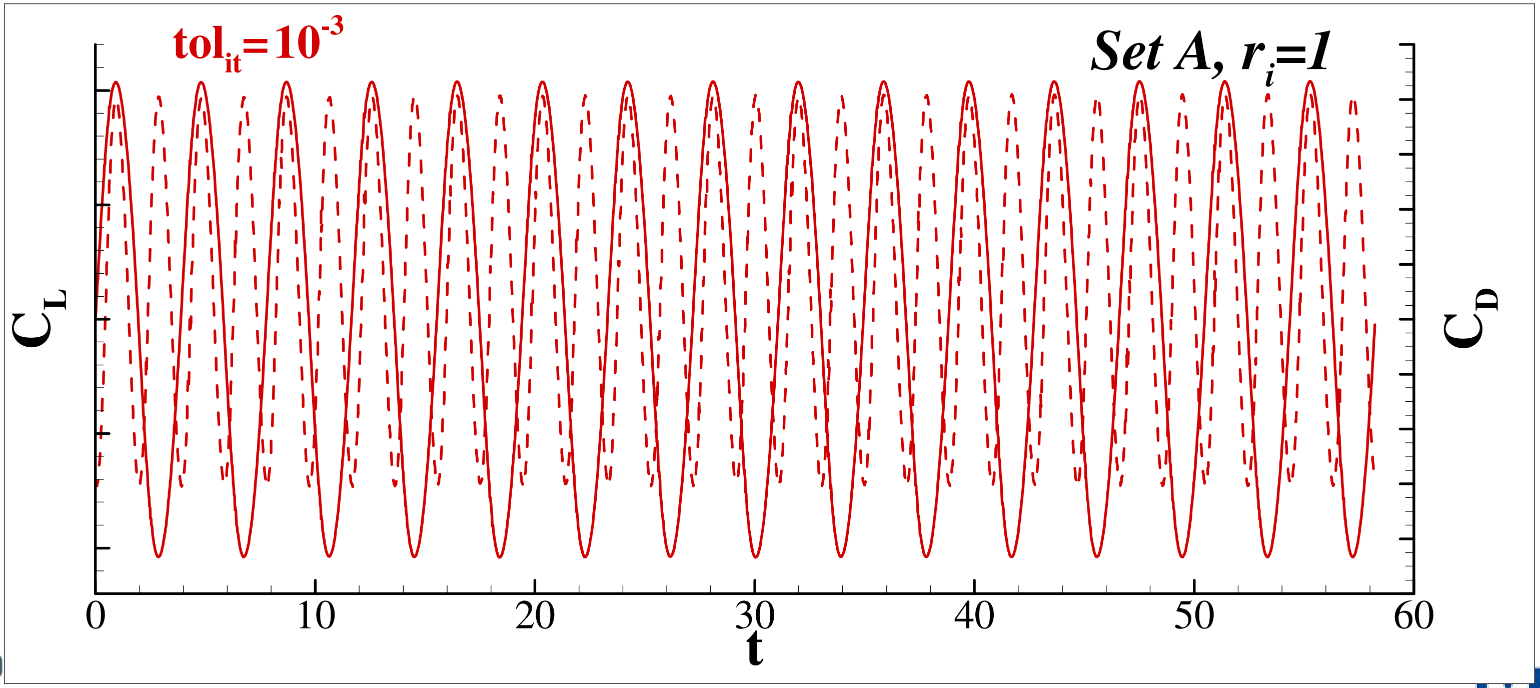
4. Statistically Unsteady Flows

- Convergence criteria at each time step is based on the L_∞ norm of the normalized residual of all equations solved (including transport equations of turbulence quantities)

- Main diagonal is used for the normalization, i.e. the residuals are equivalent to the changes for a Jacobi iteration

4. Statistically Unsteady Flows

- Flow around a circular cylinder at Reynolds number 6.31×10^4
- Calculated time sufficient to achieve periodic flow for most cases with all values of (tol_{it}) tested



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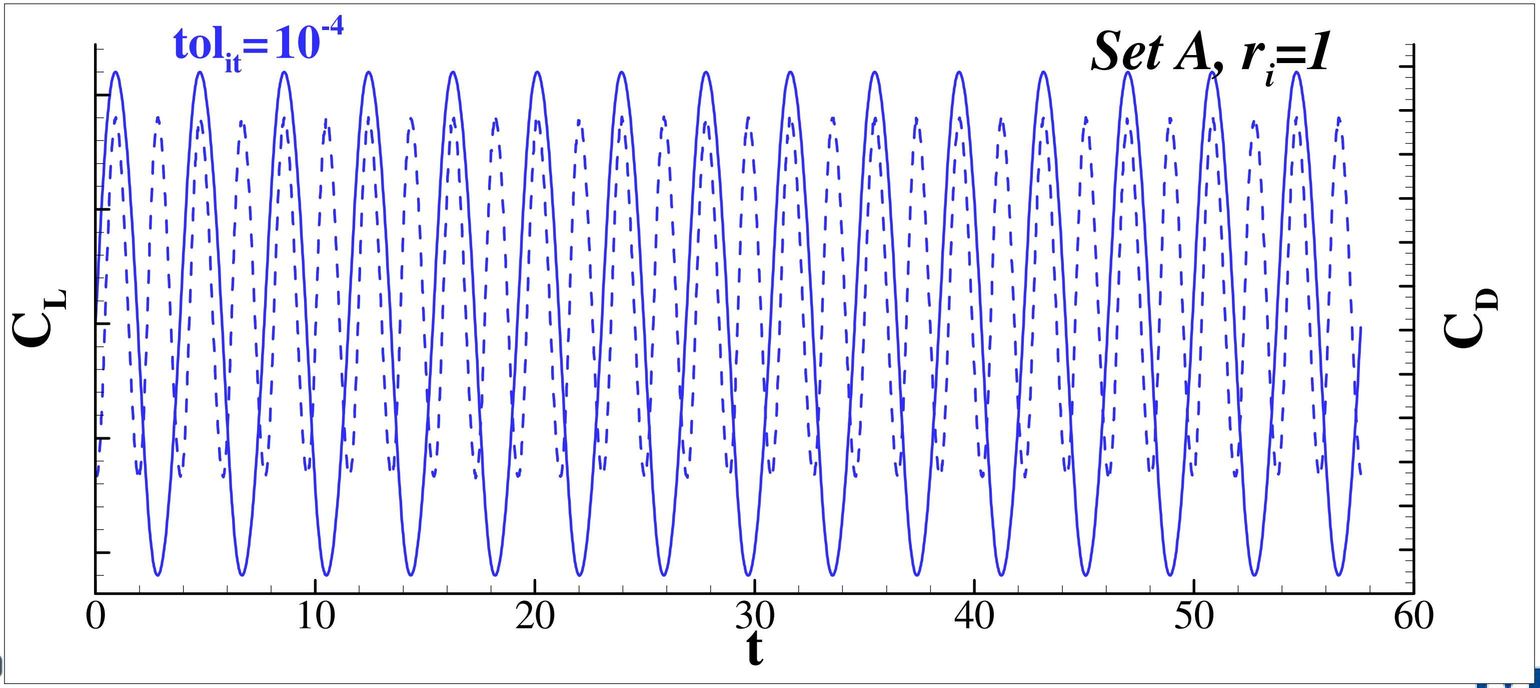

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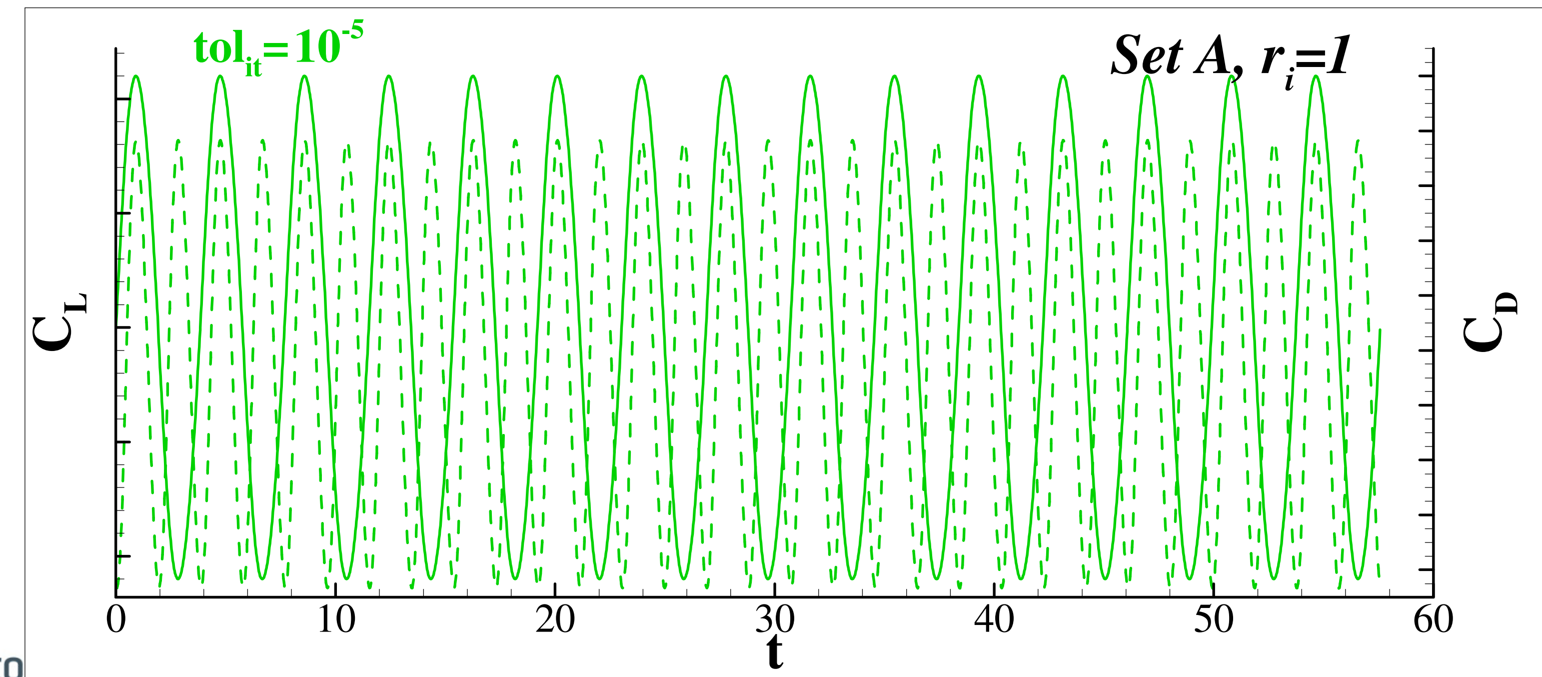

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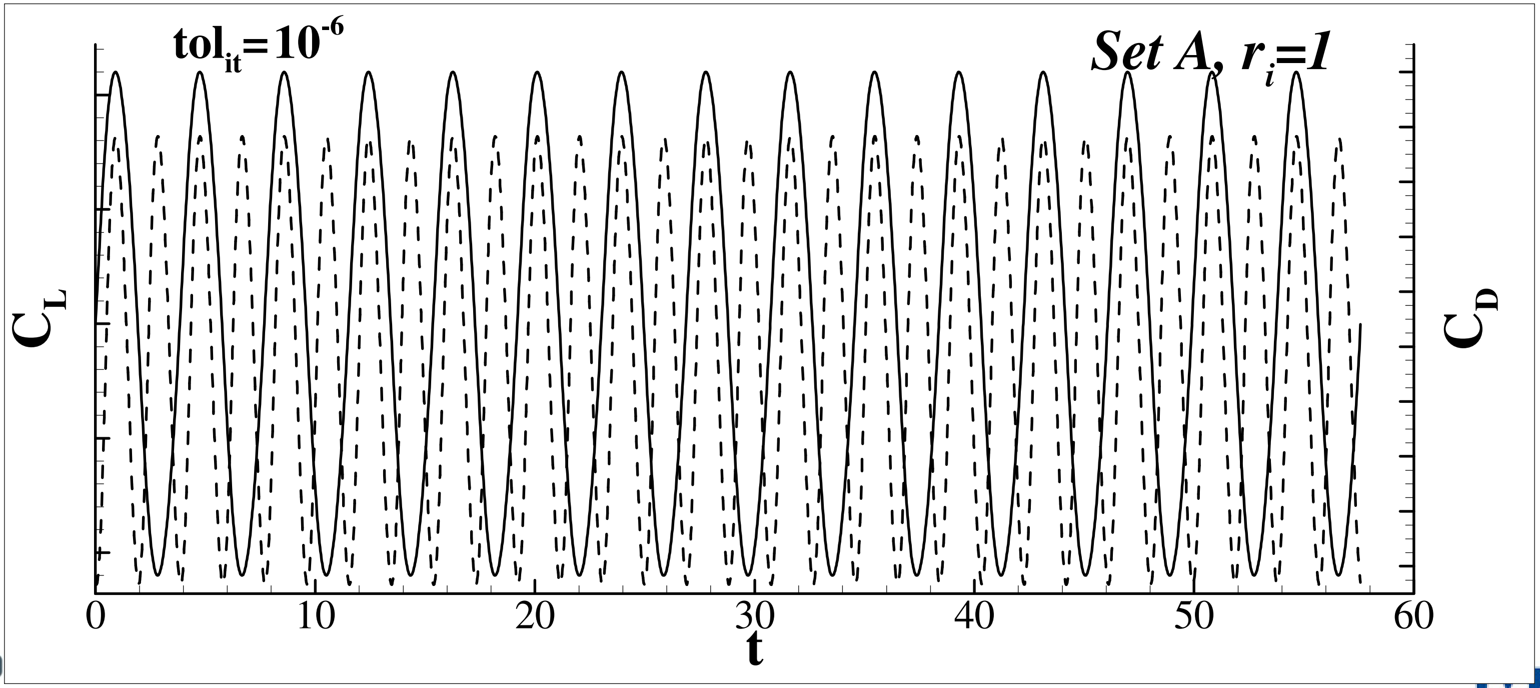

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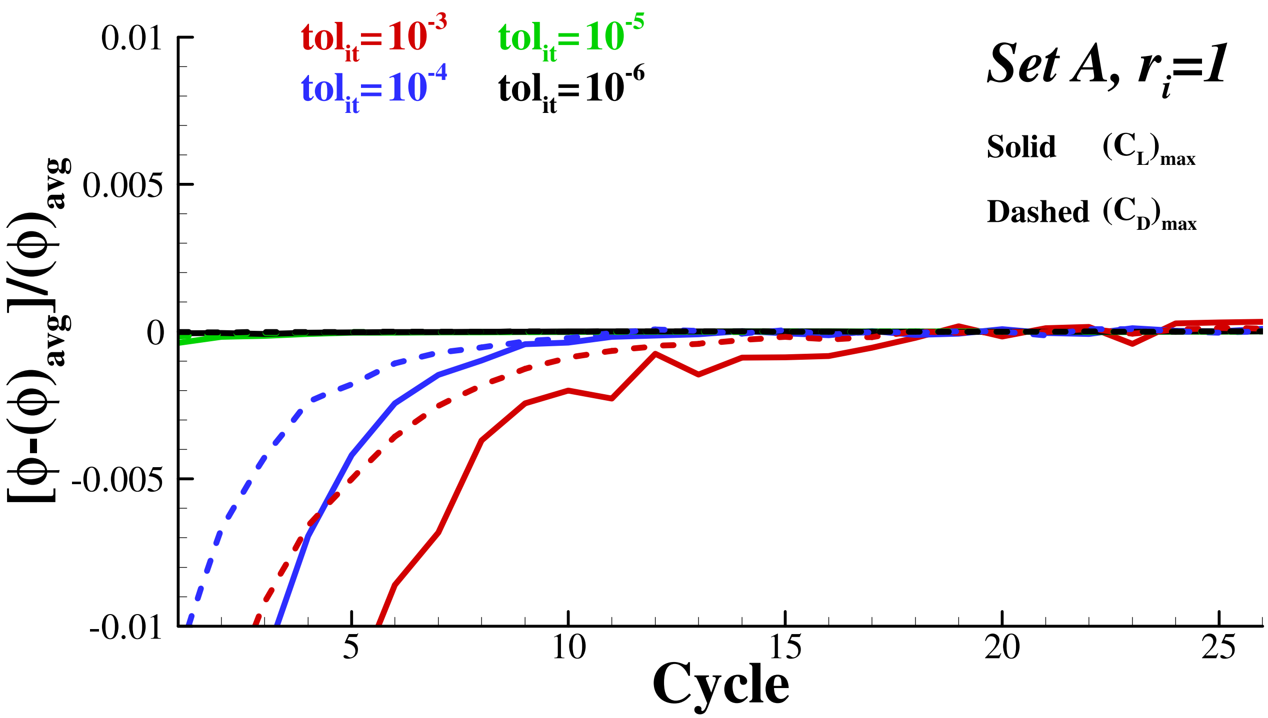

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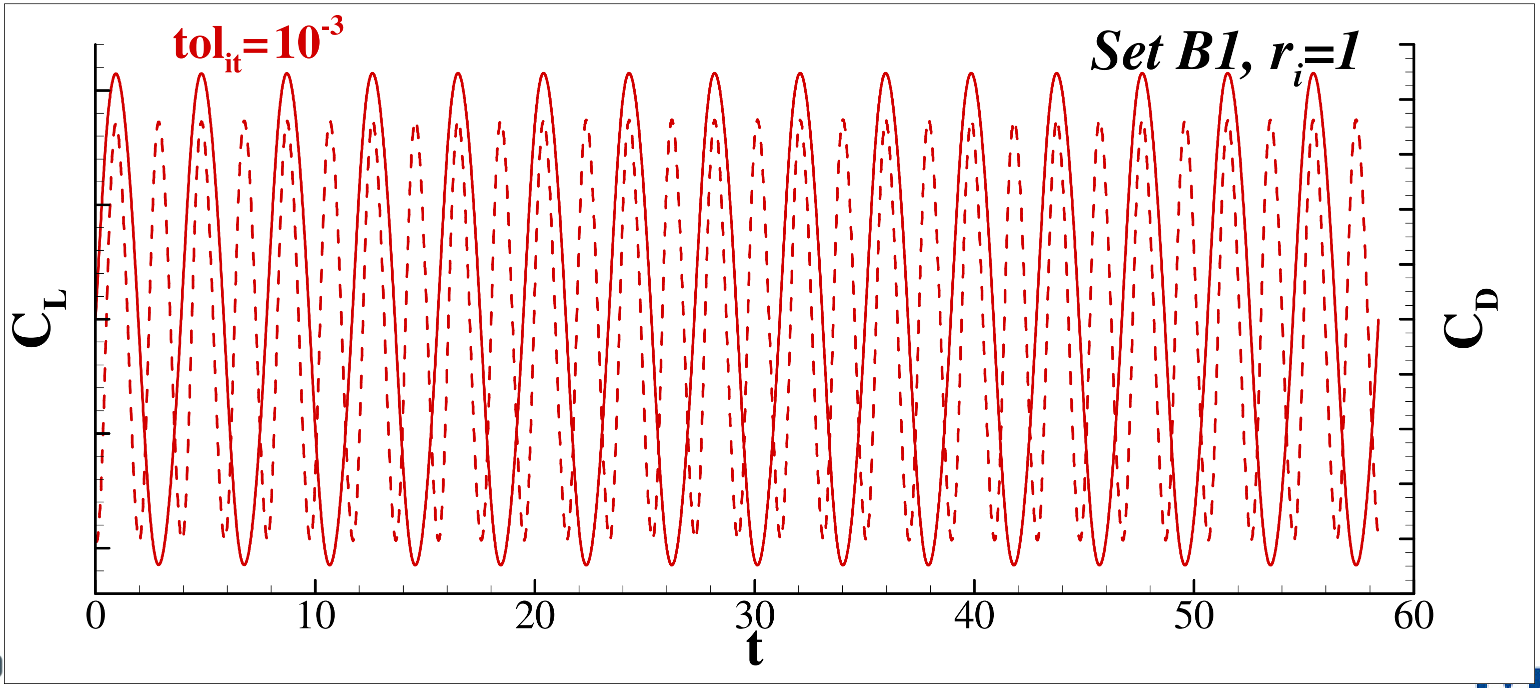

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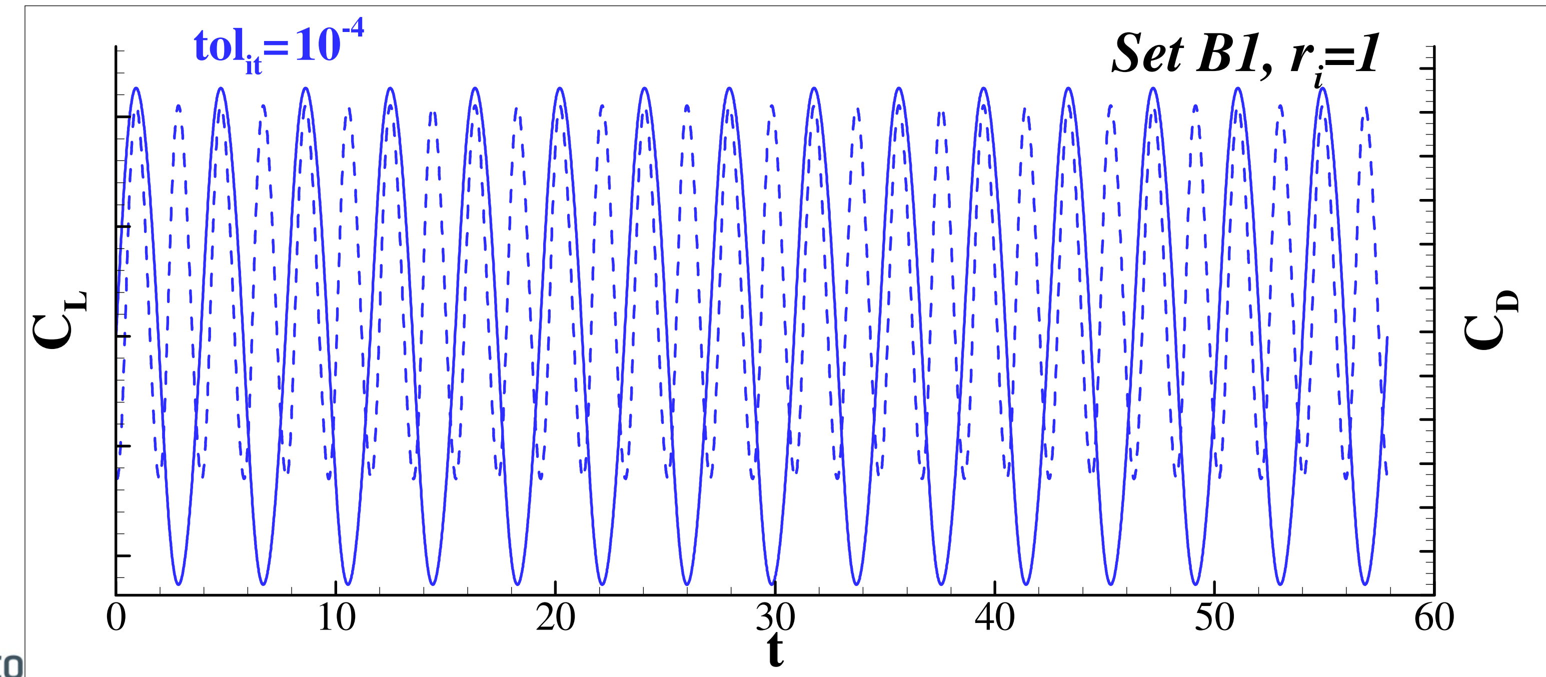

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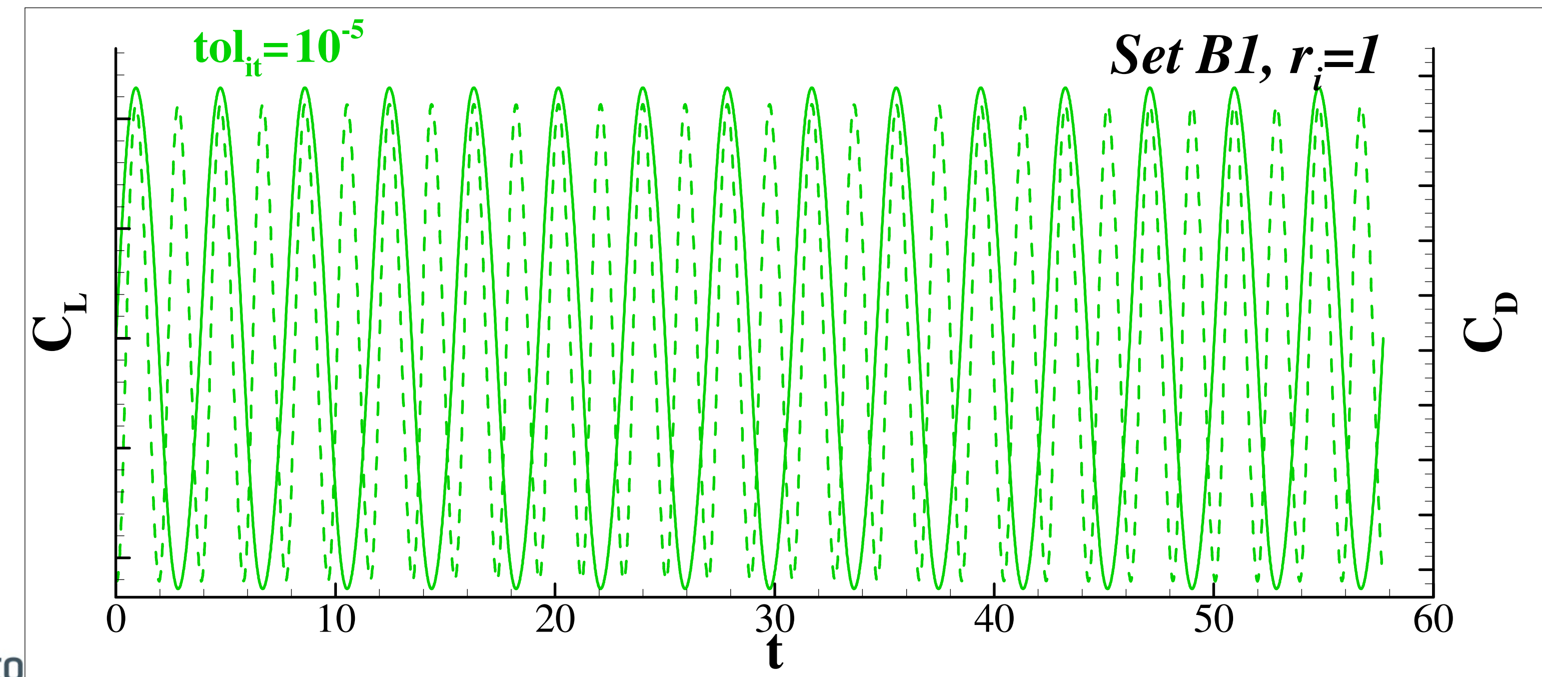

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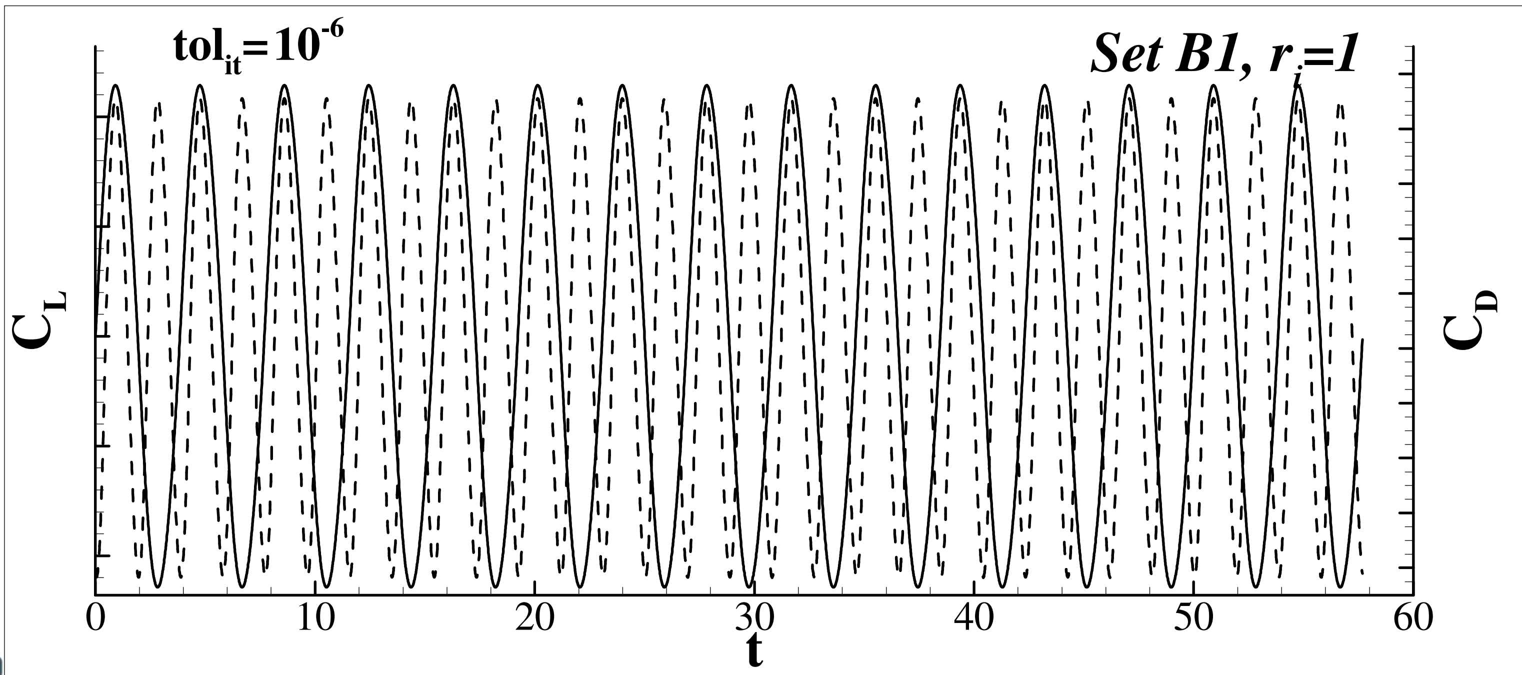

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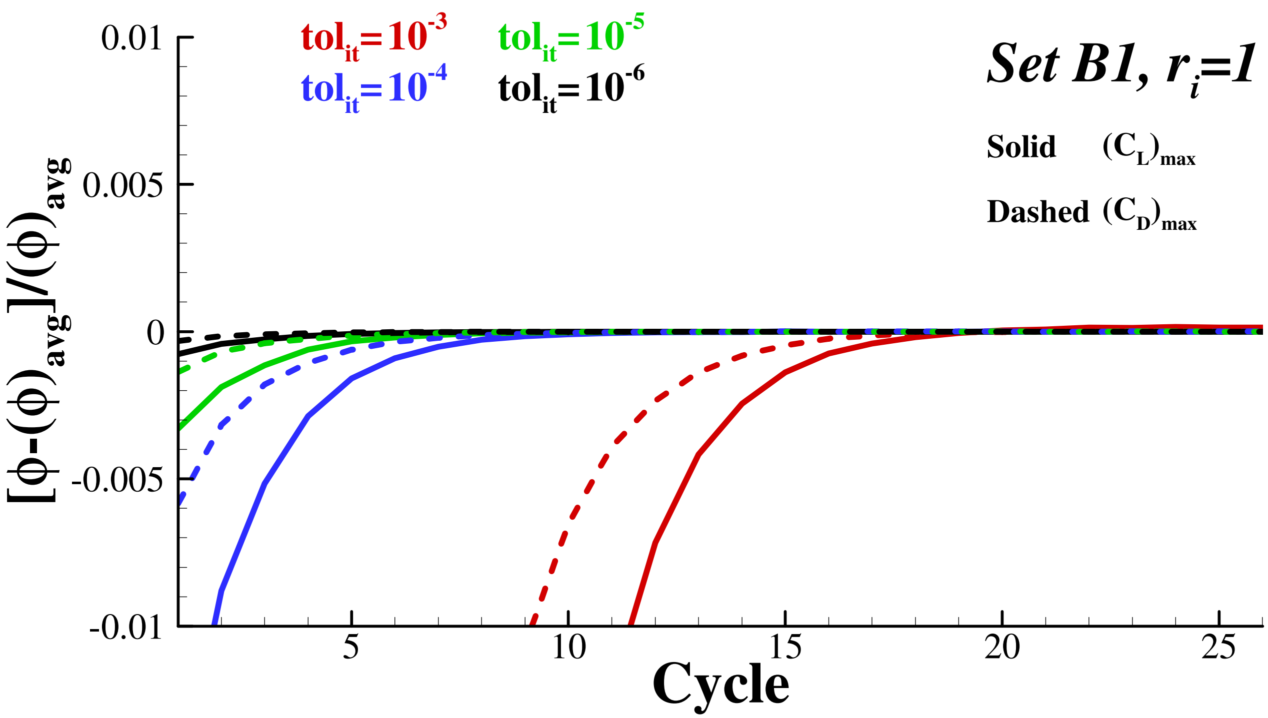

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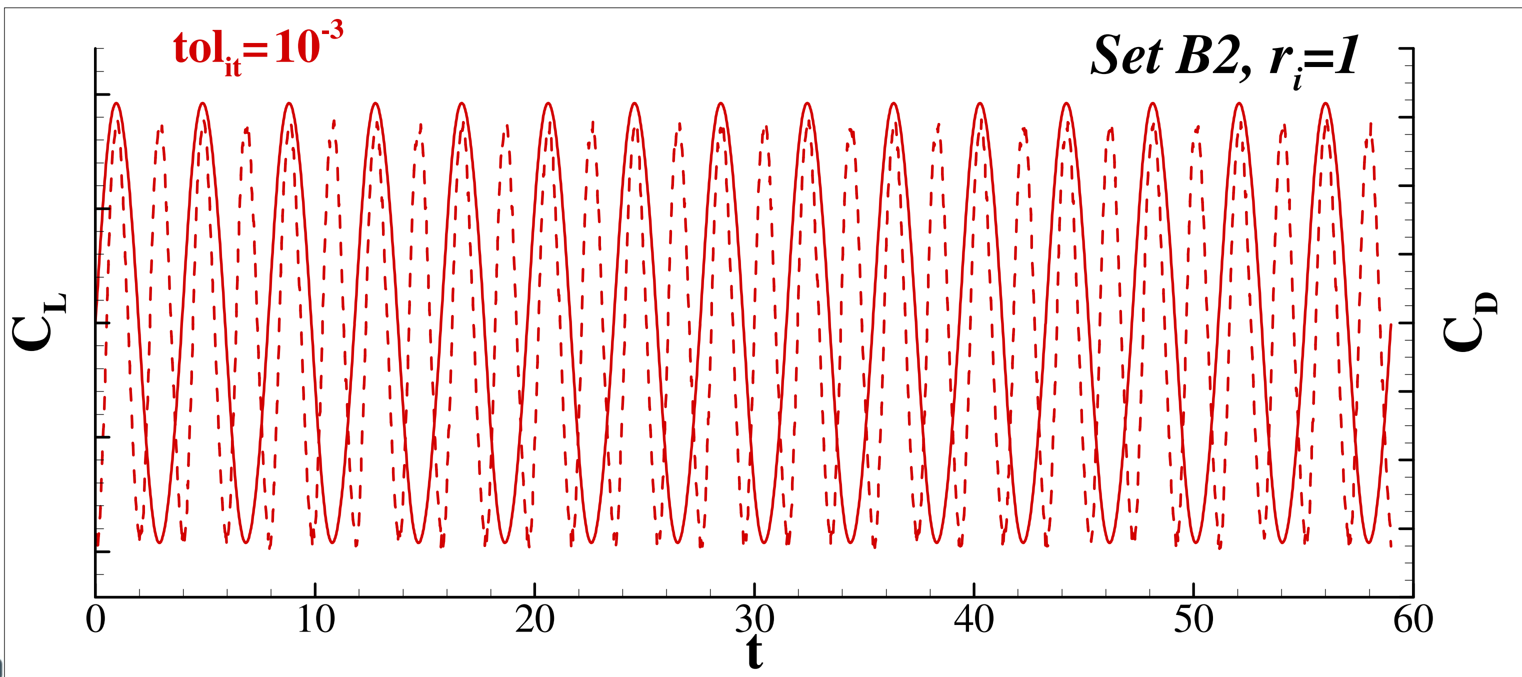

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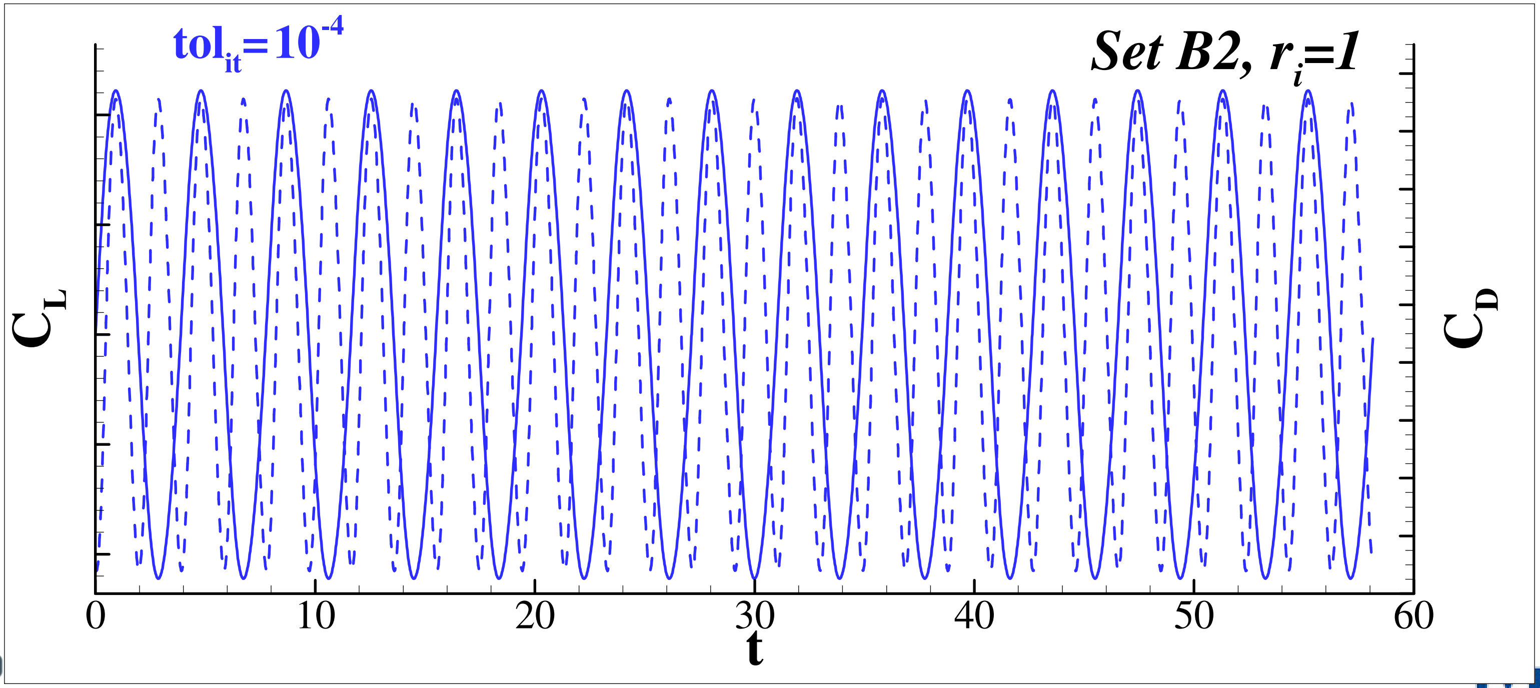

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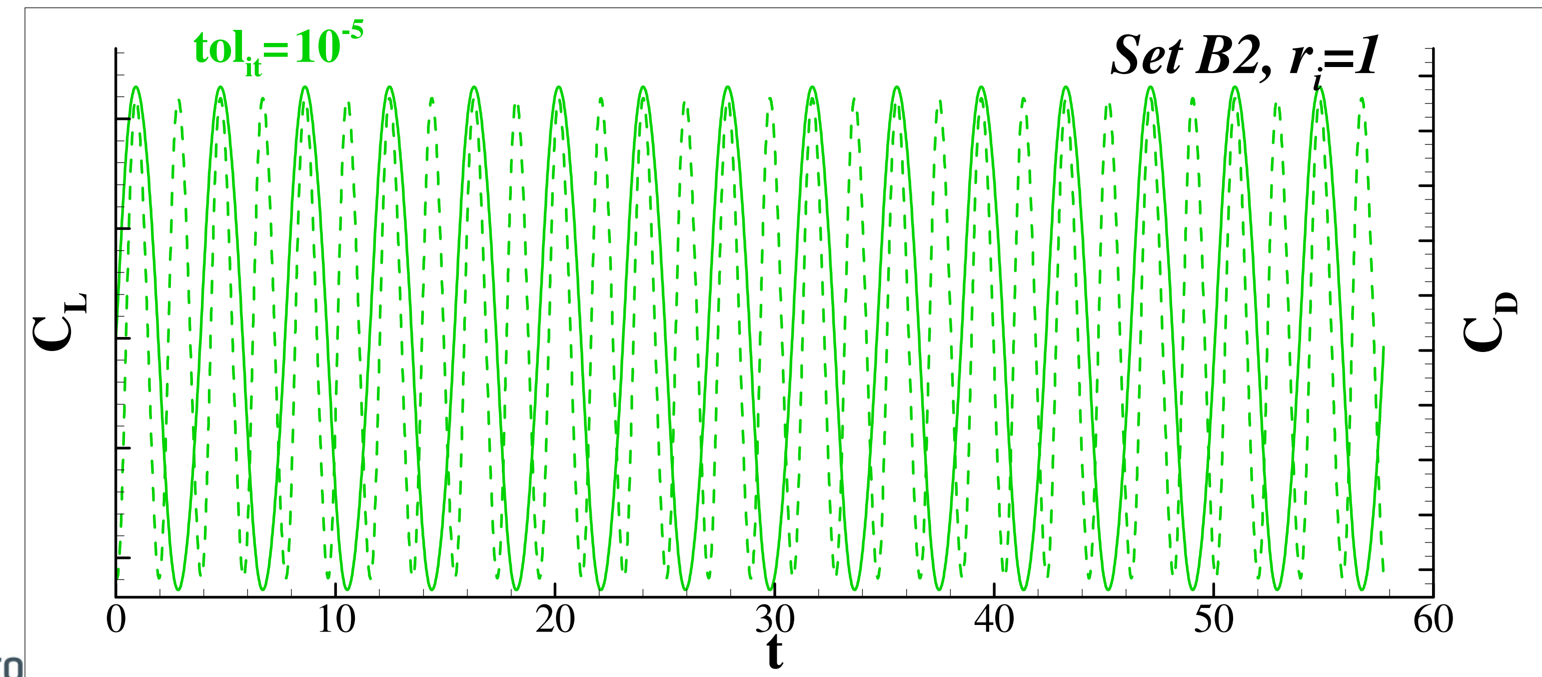

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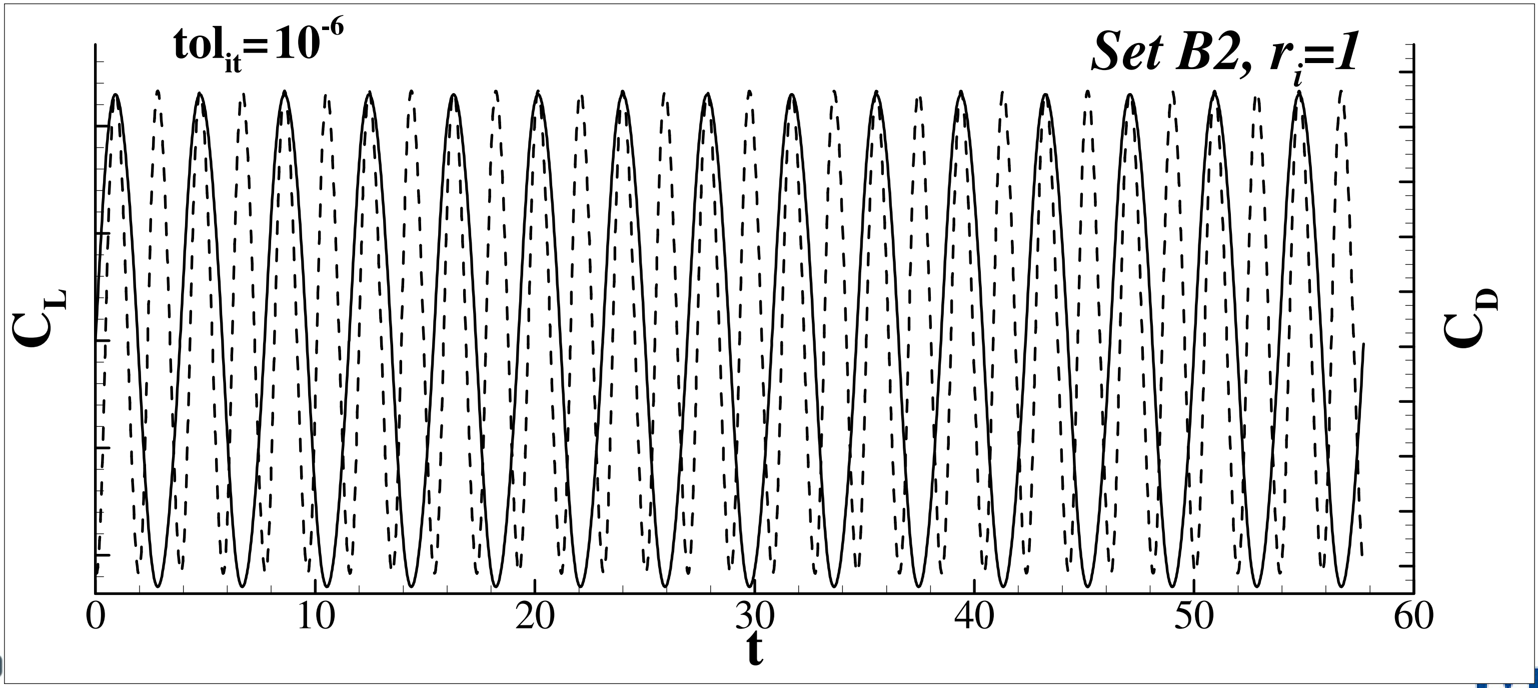

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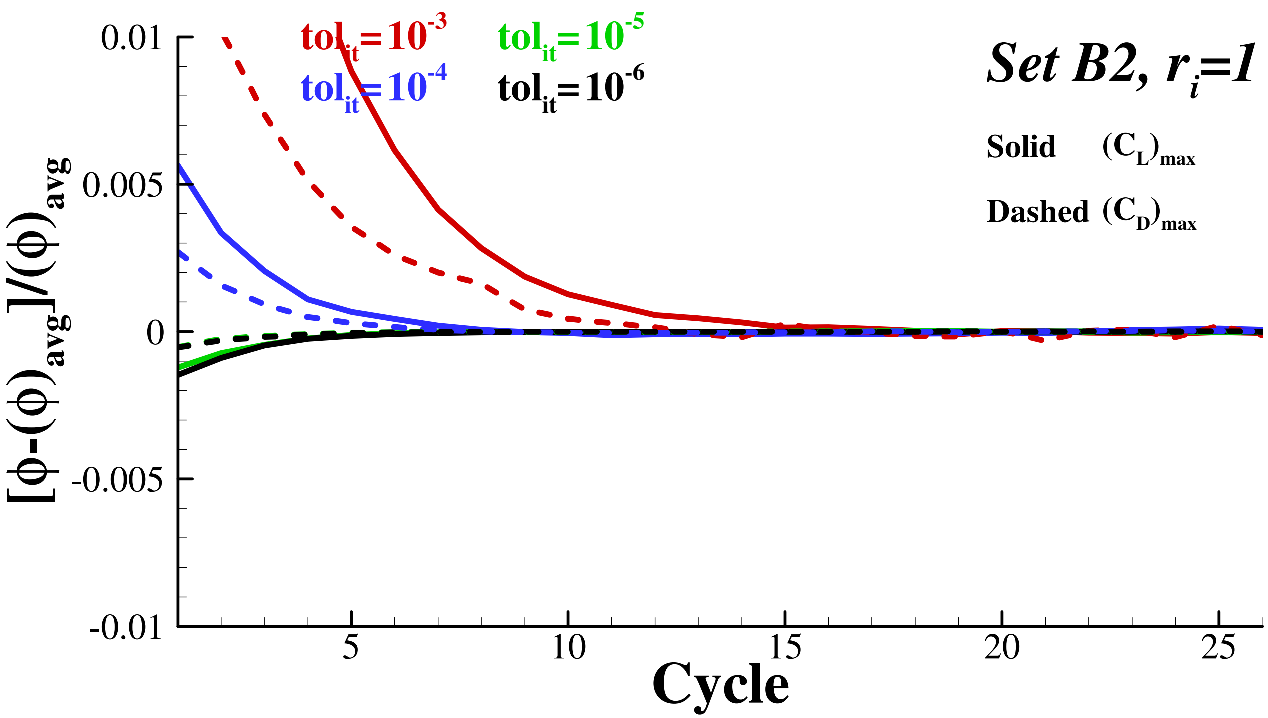

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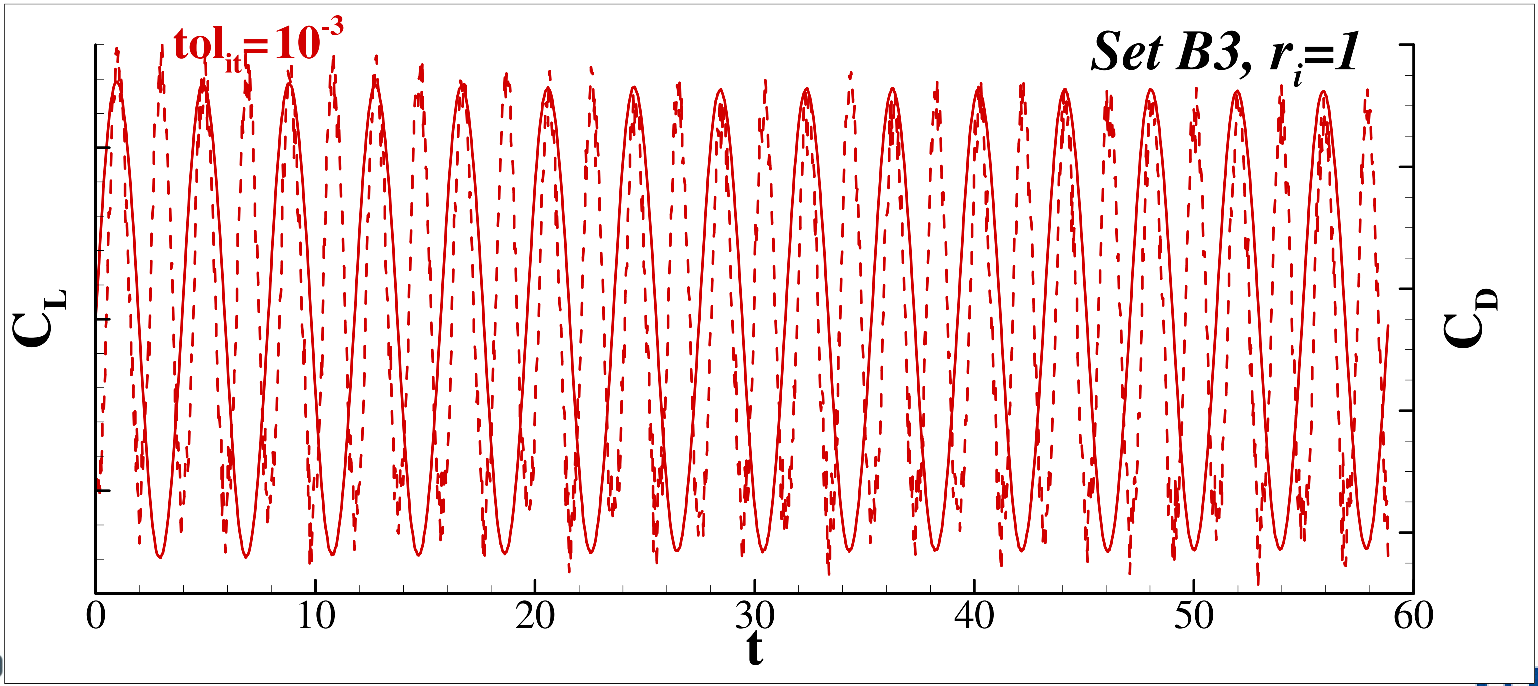

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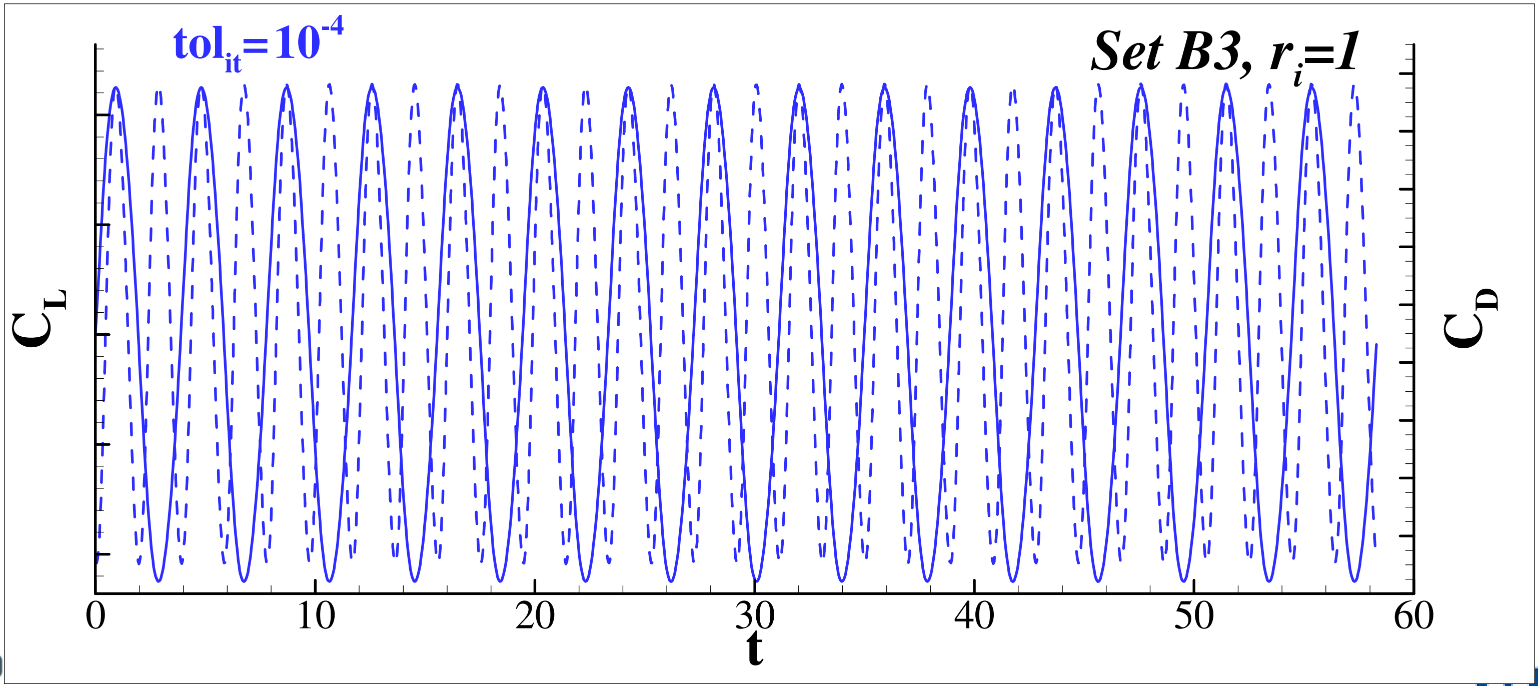

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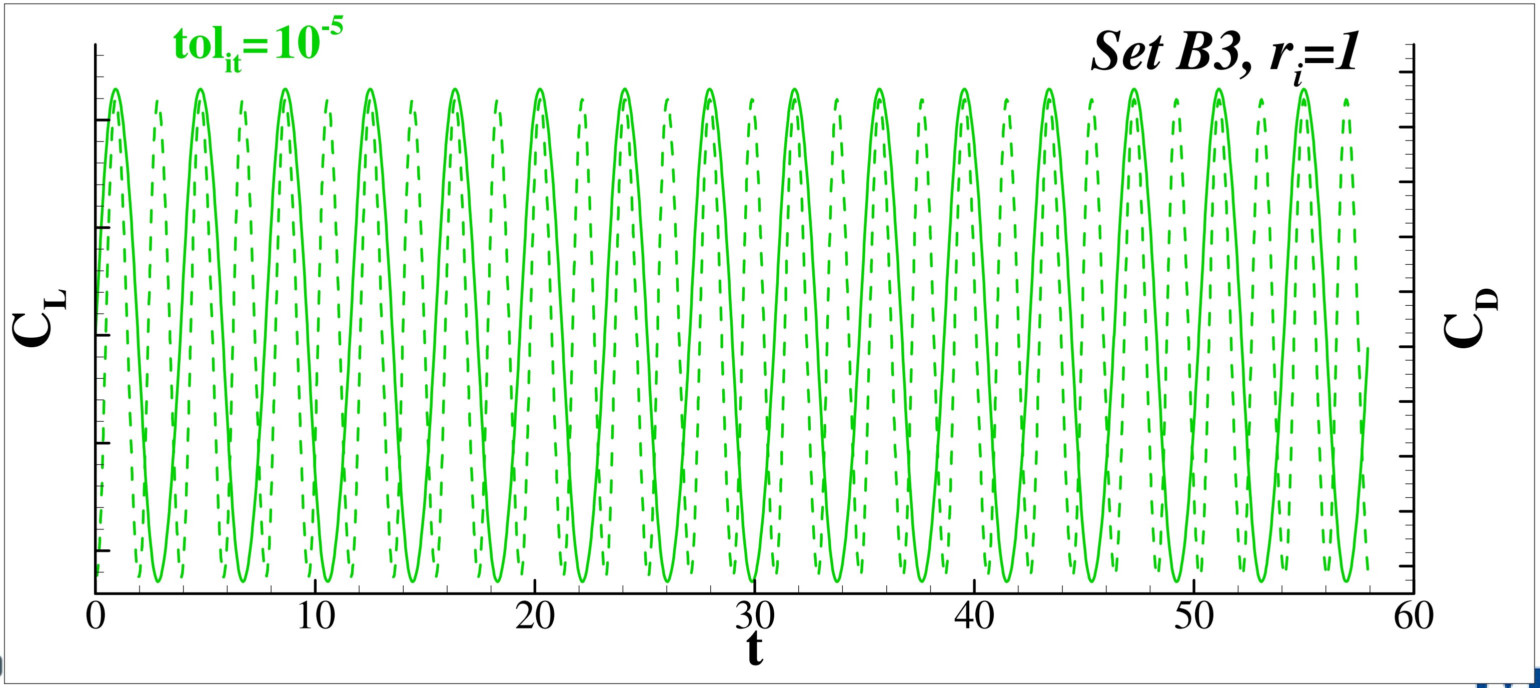

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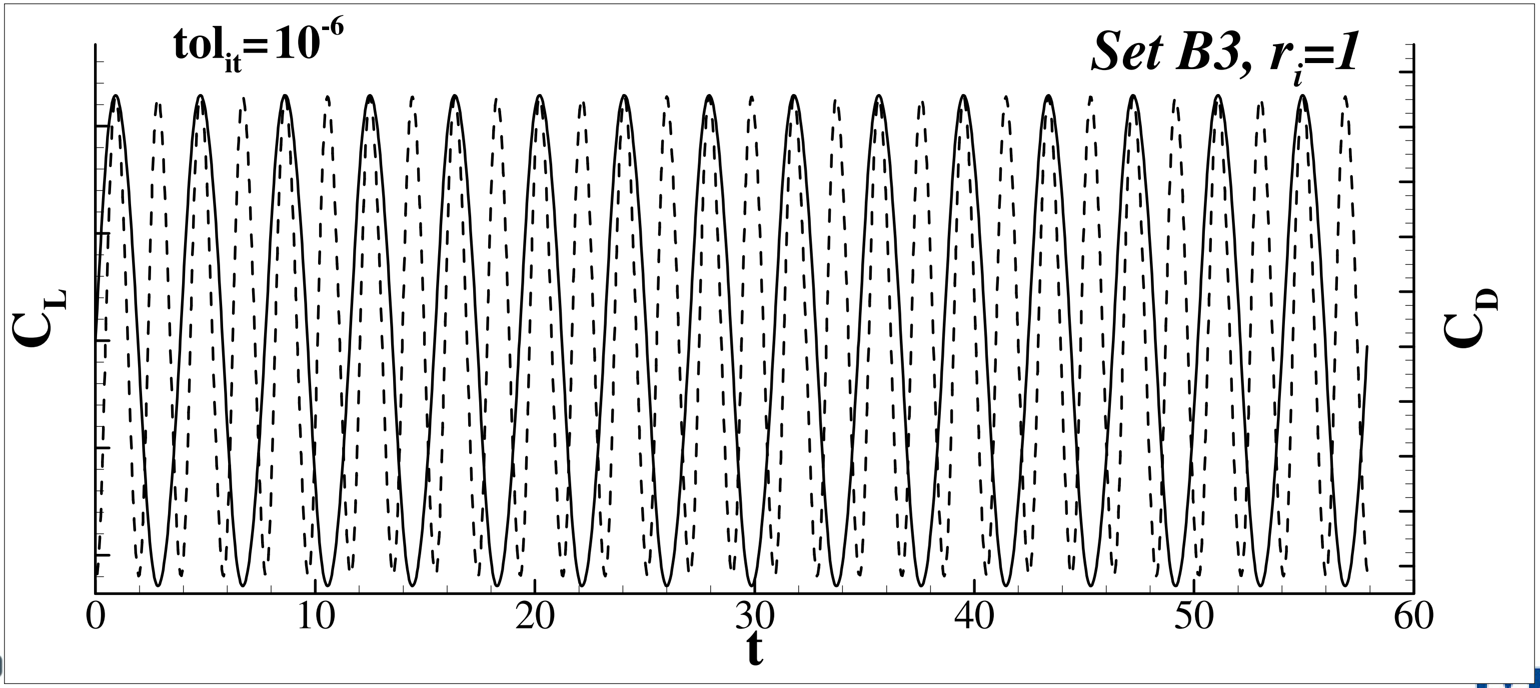

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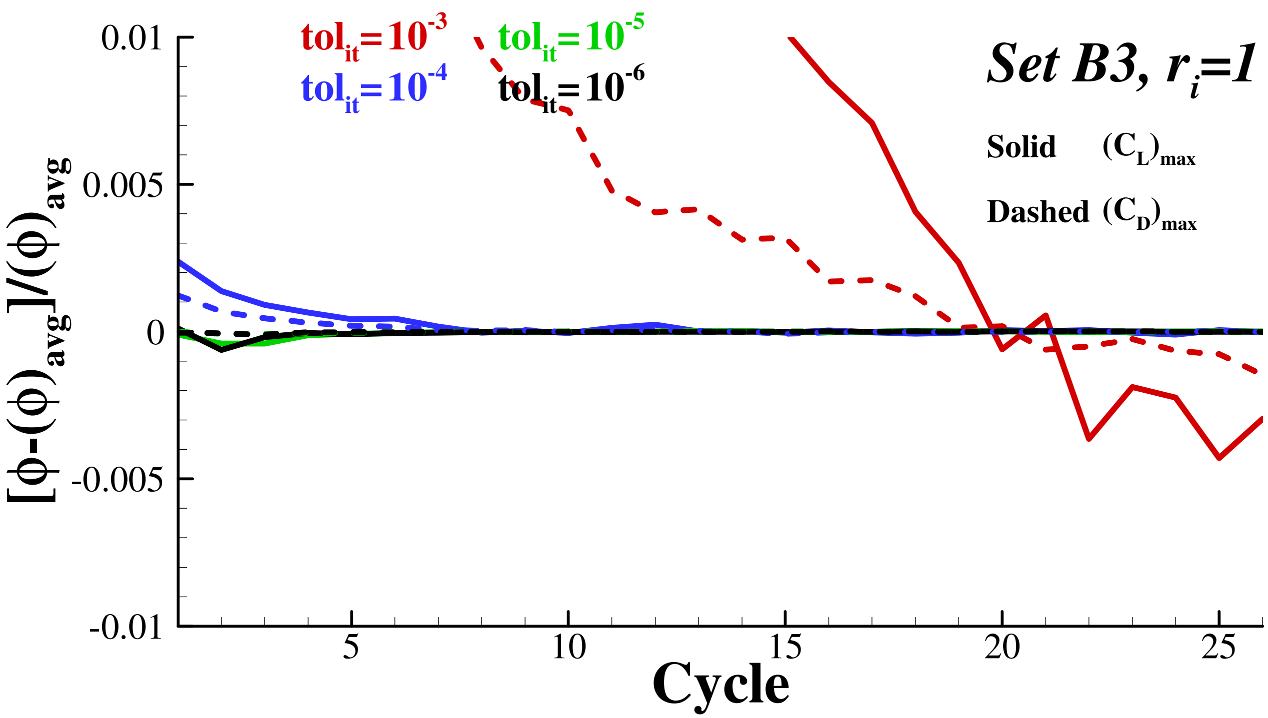

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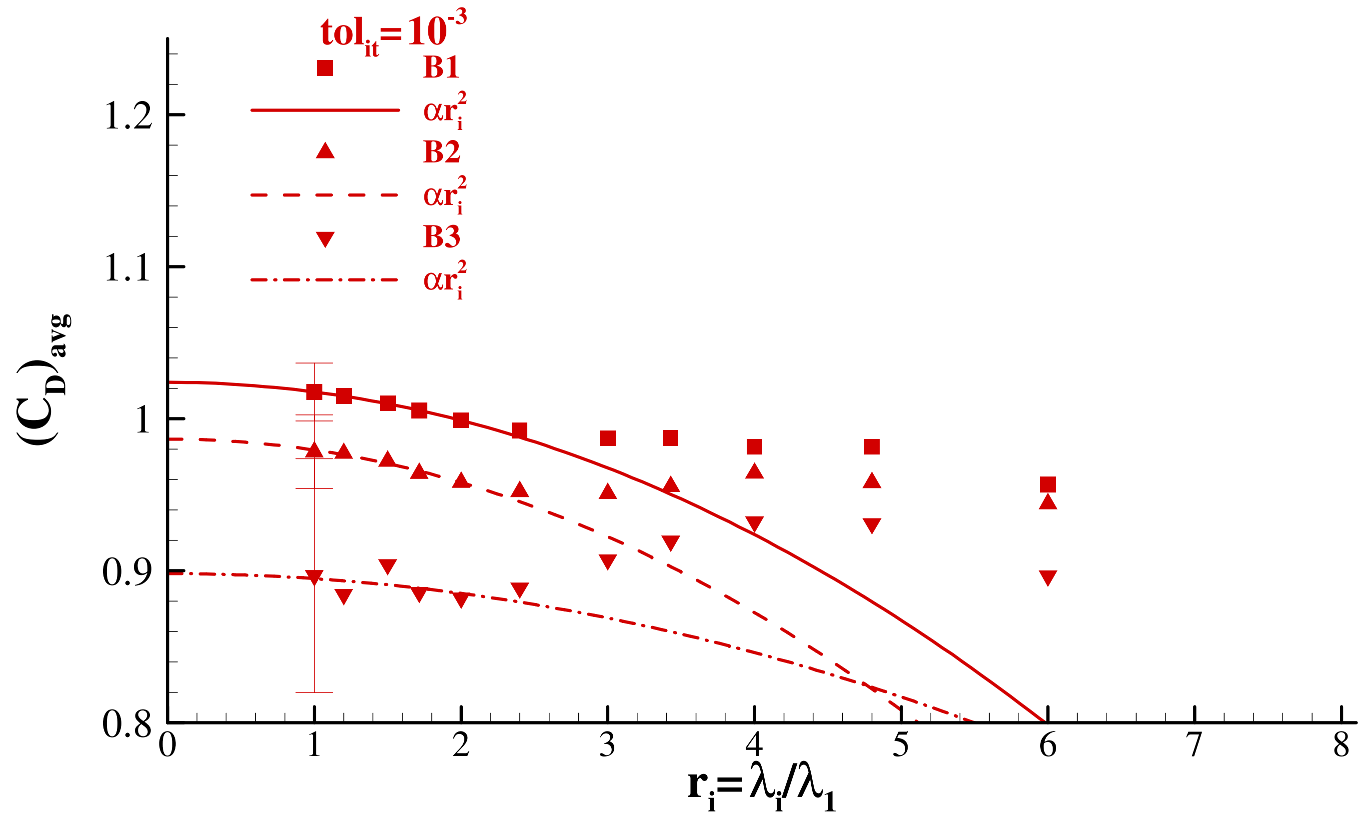

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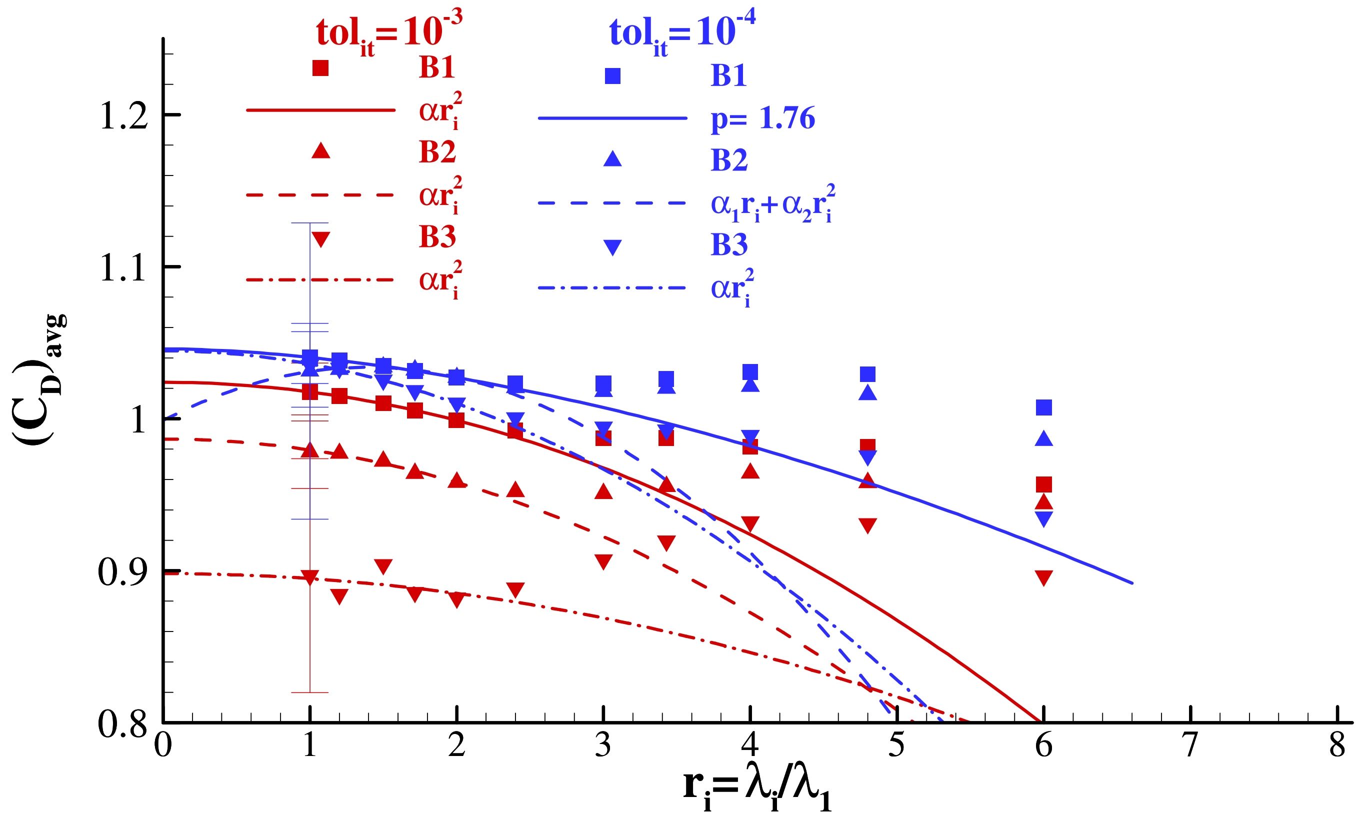

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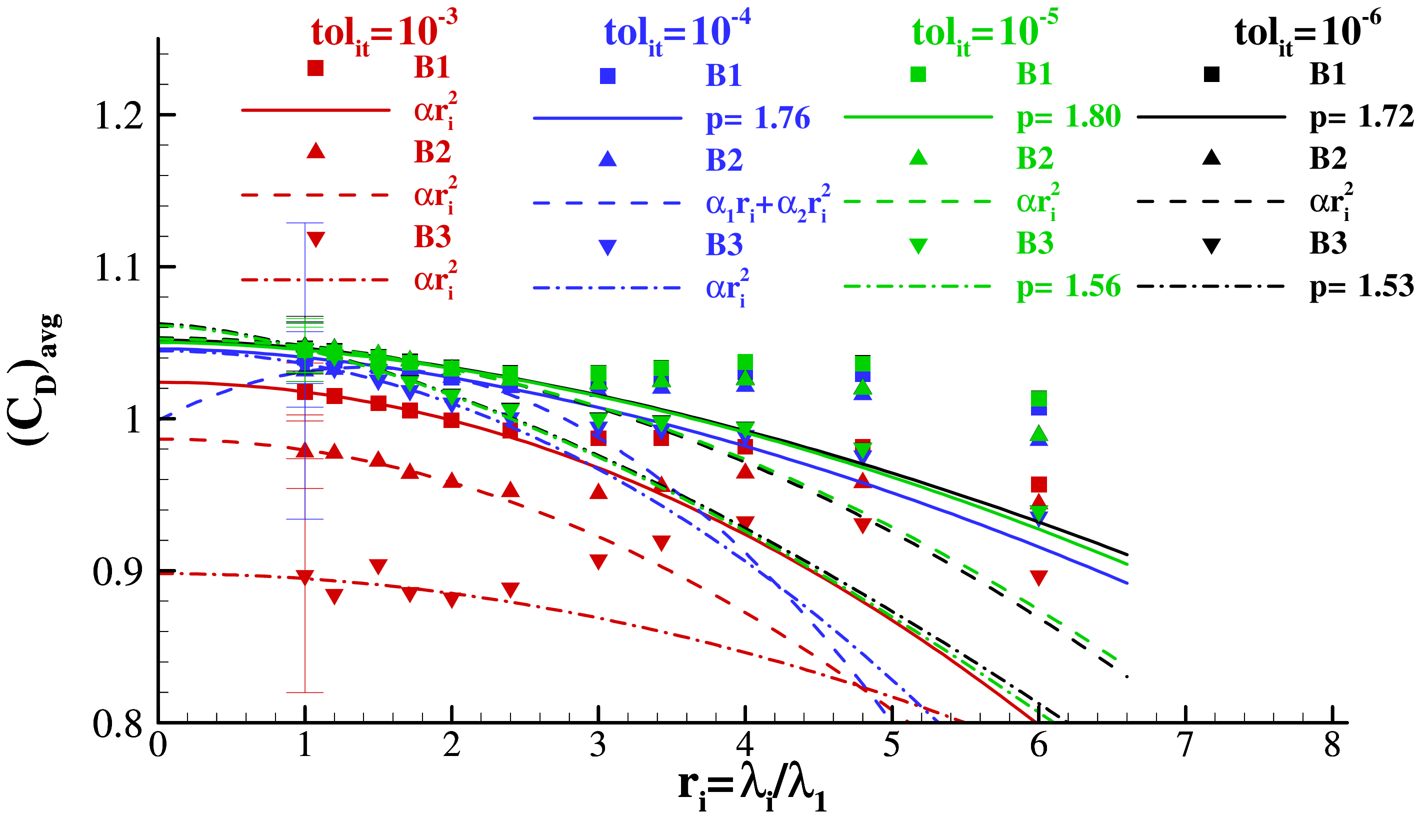

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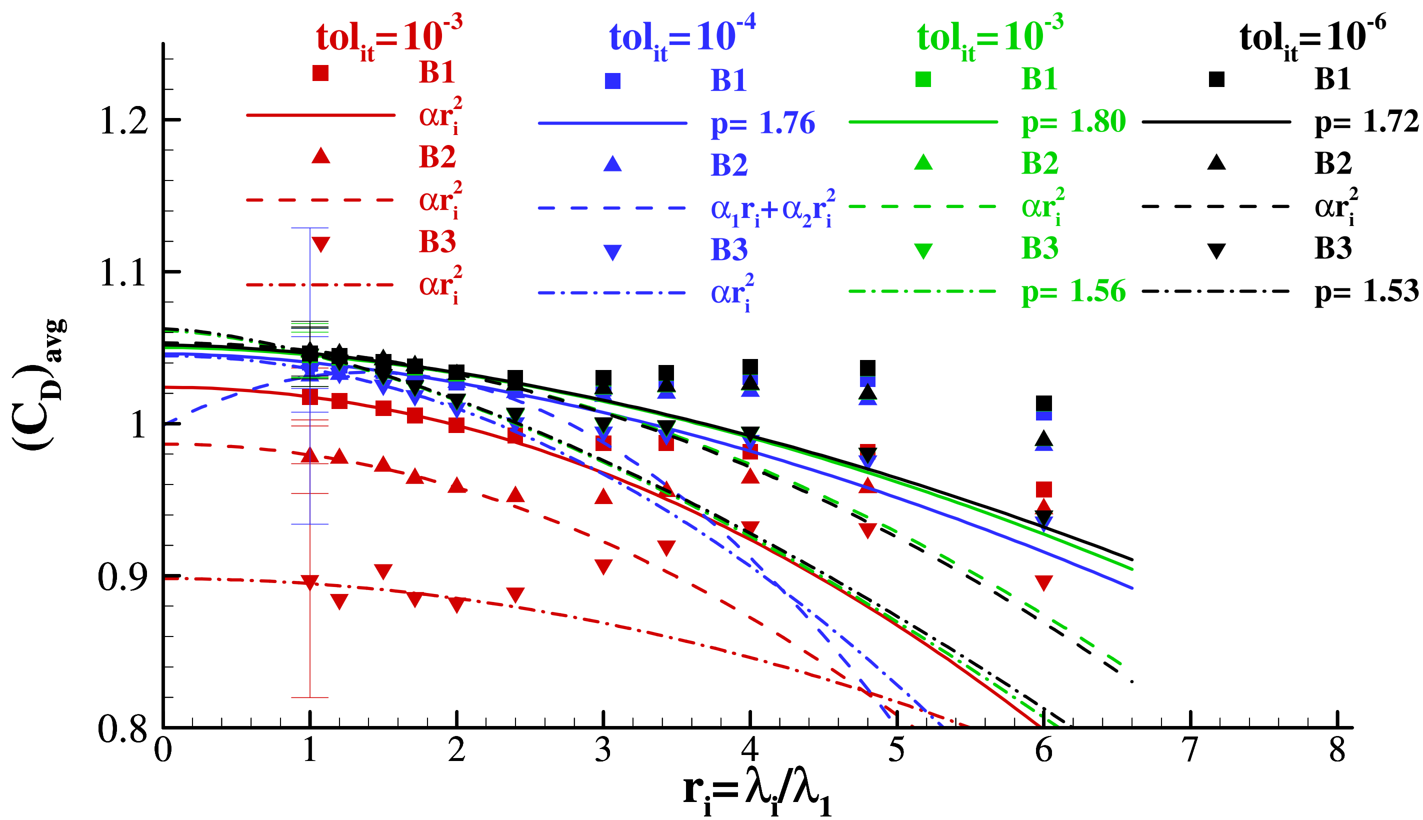

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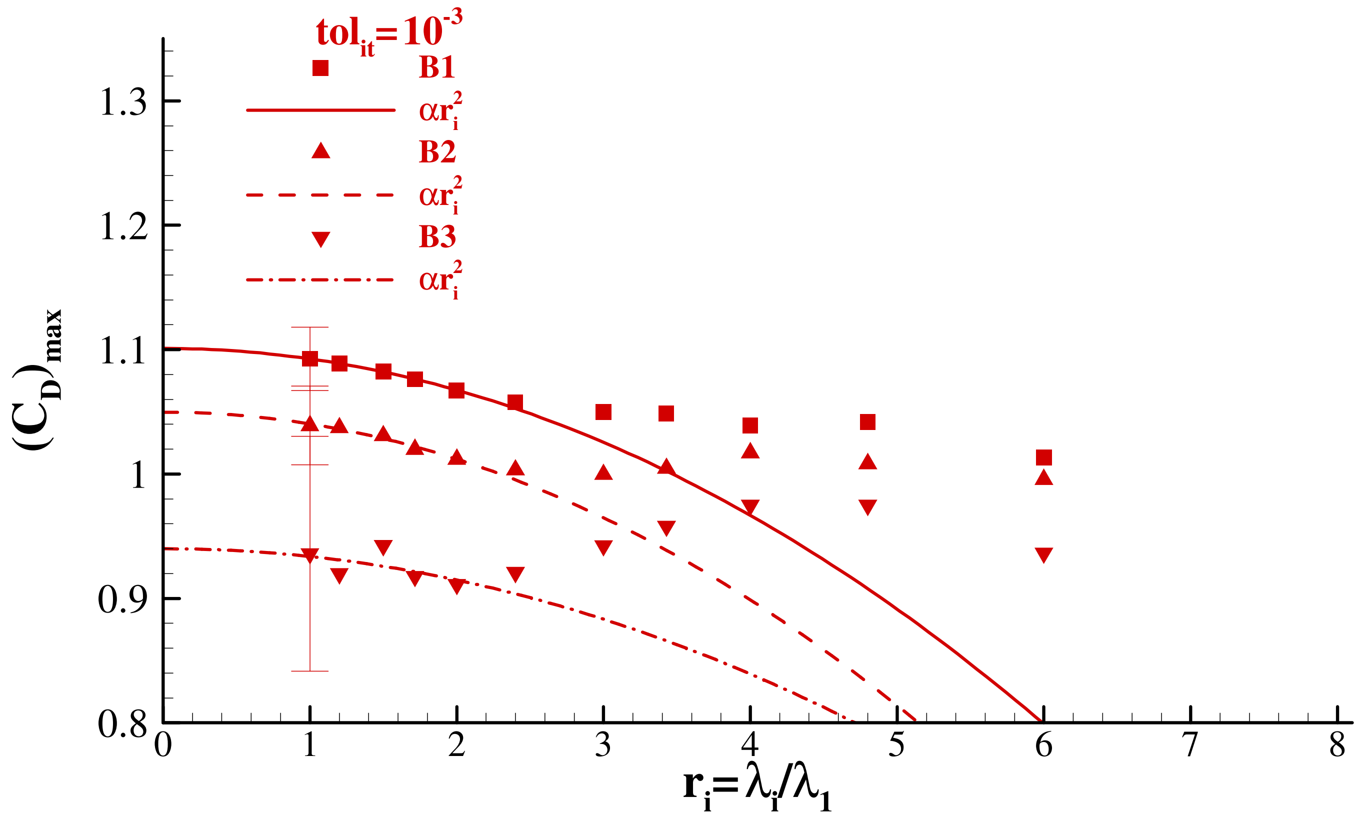

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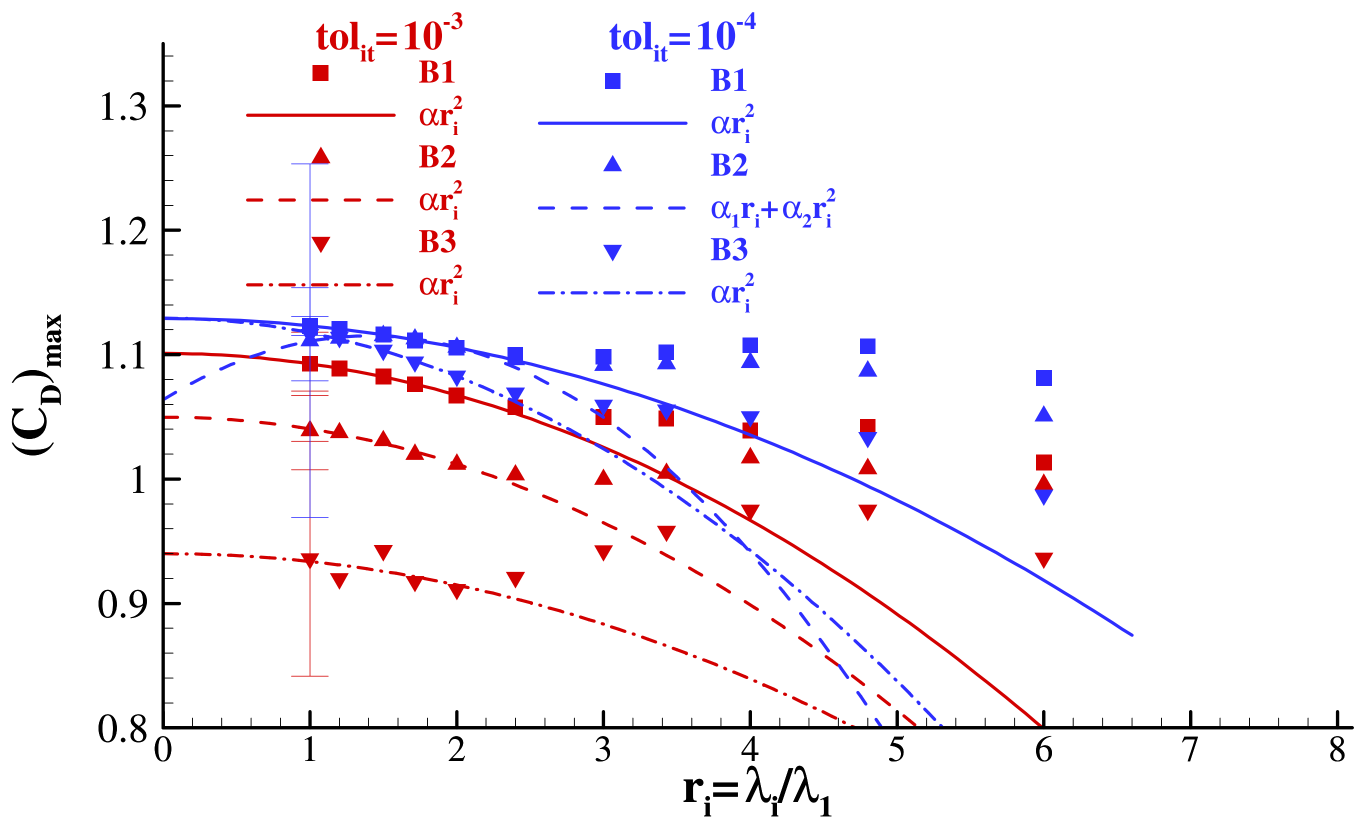

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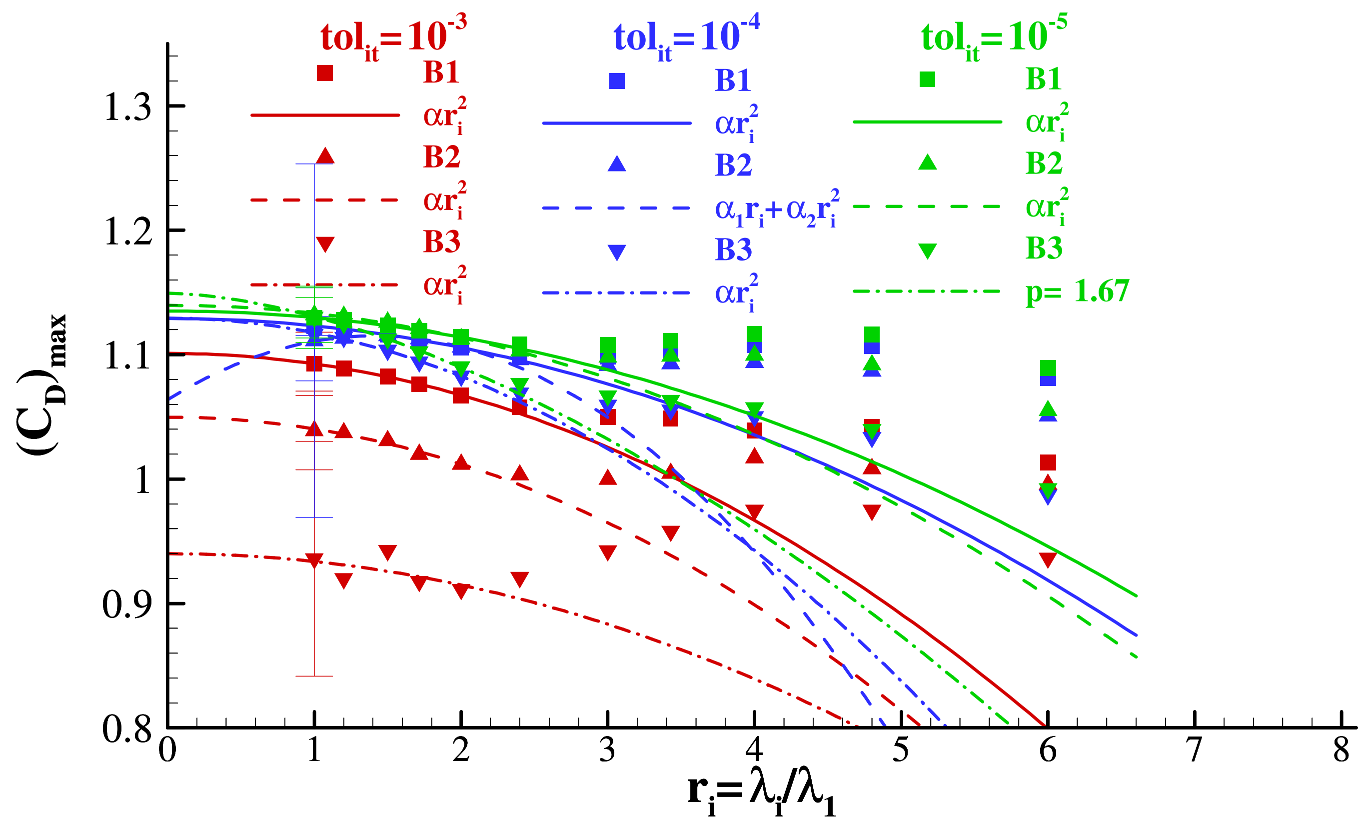

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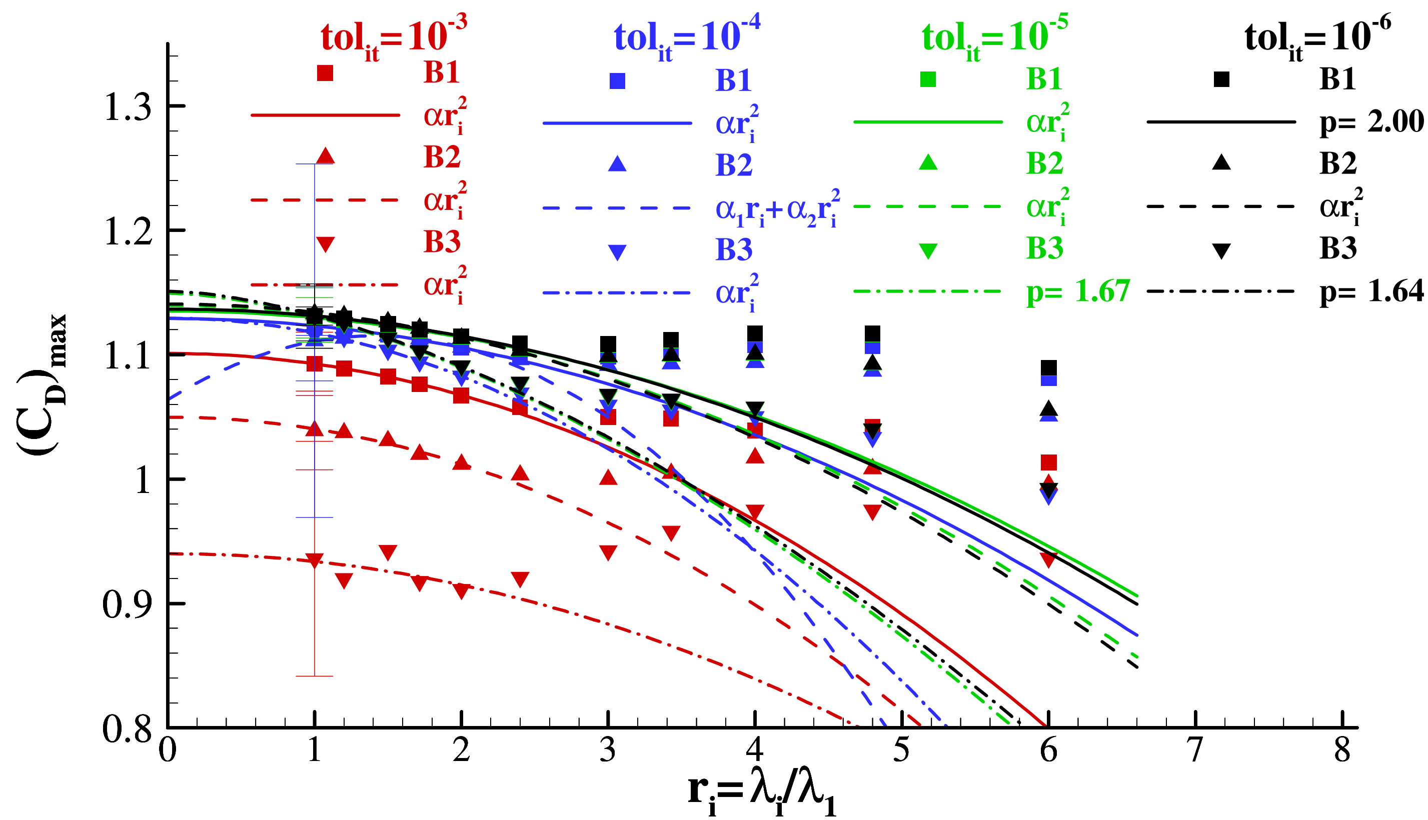

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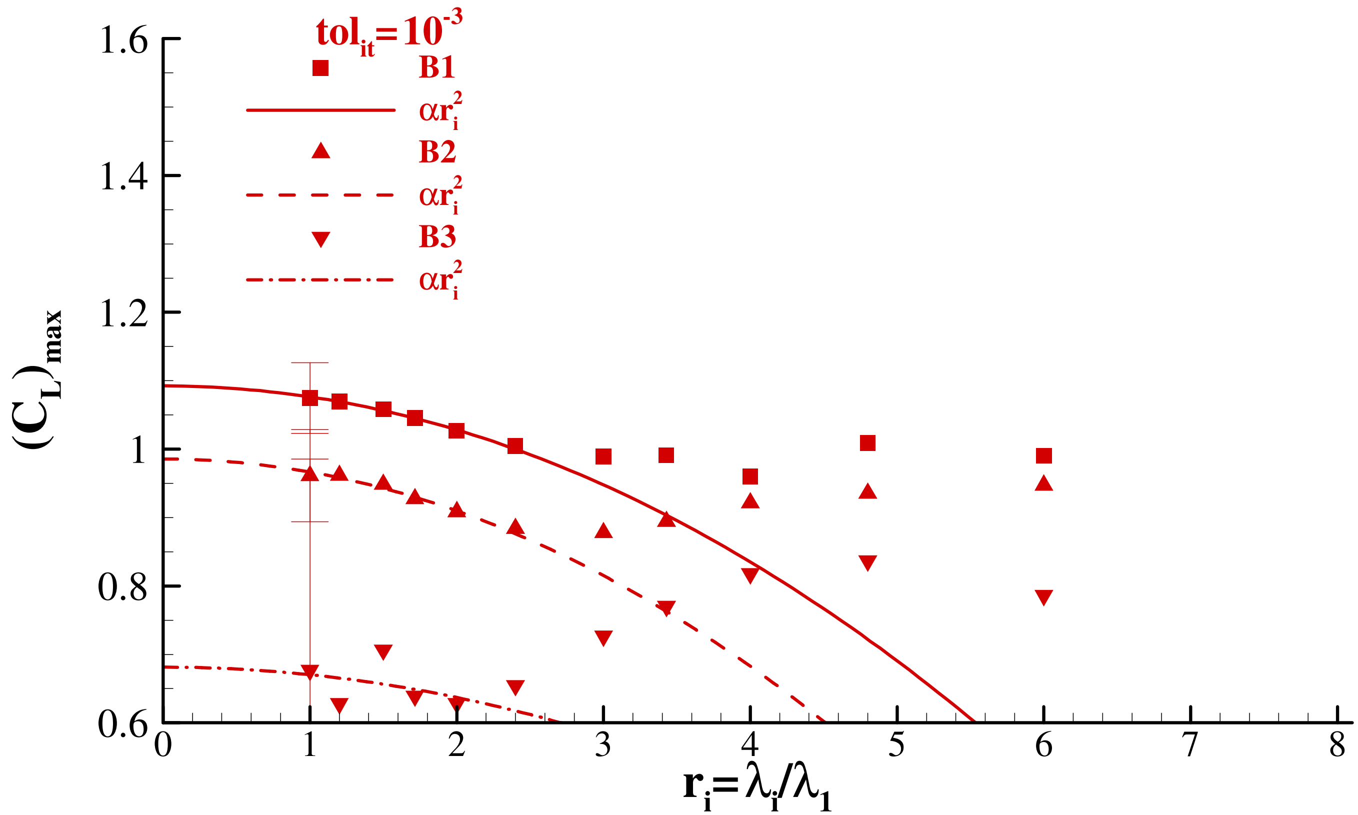

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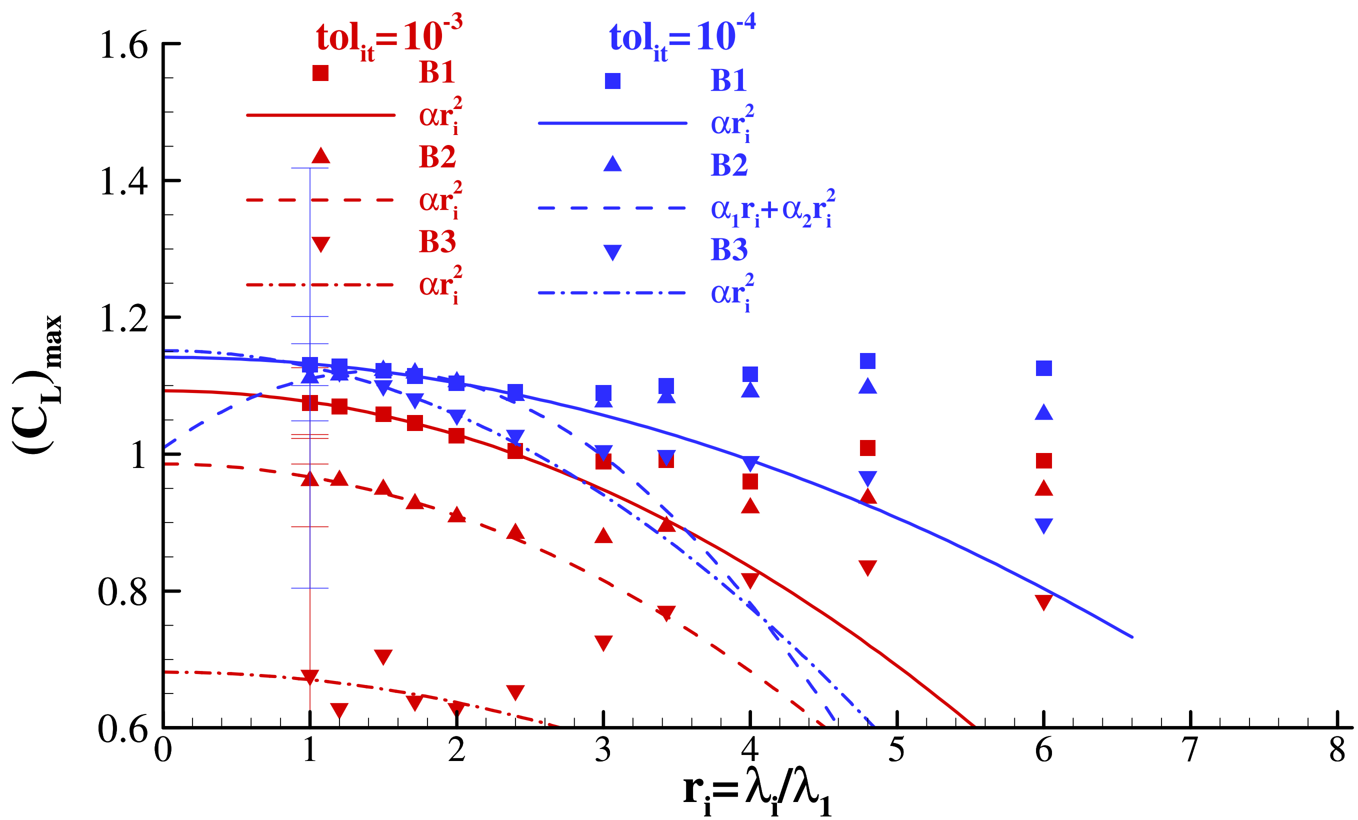

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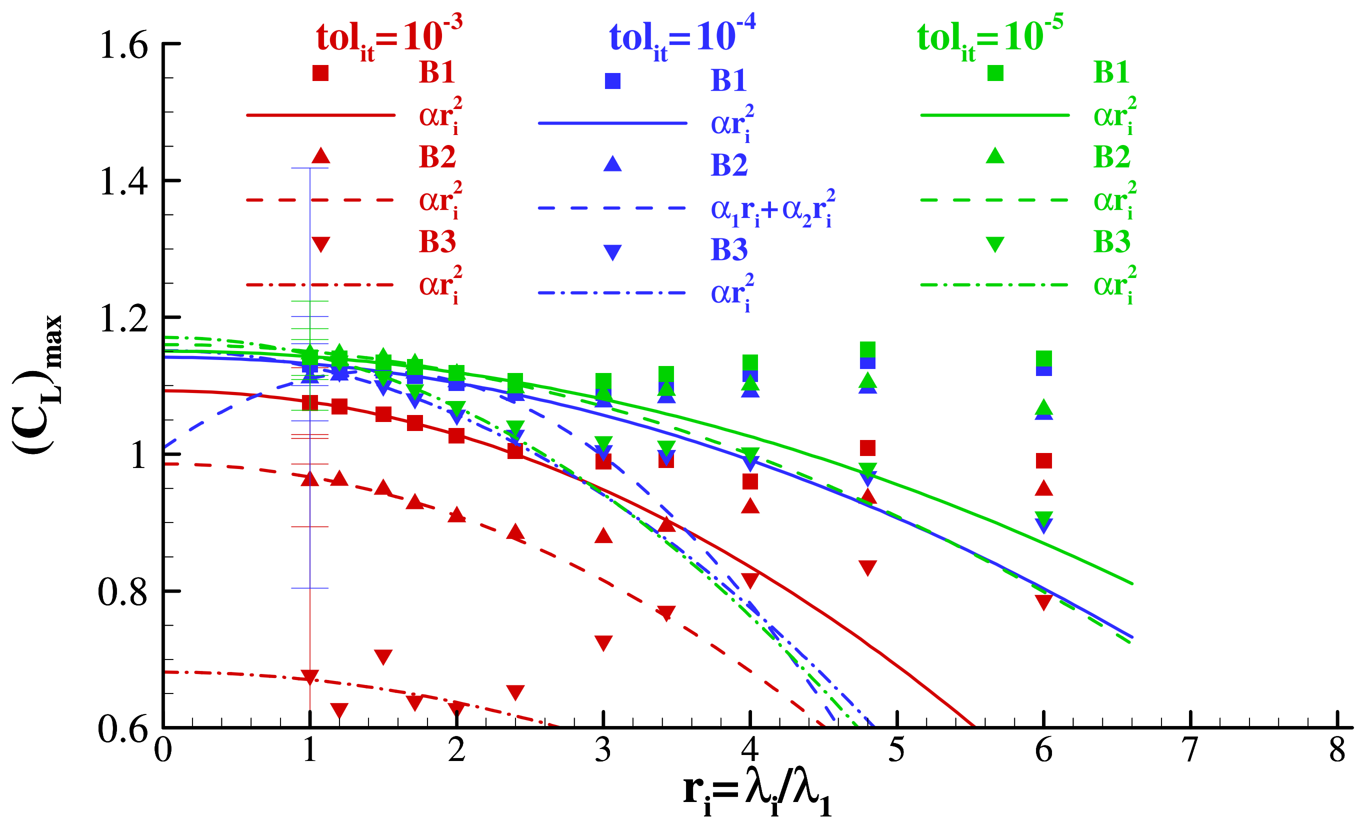

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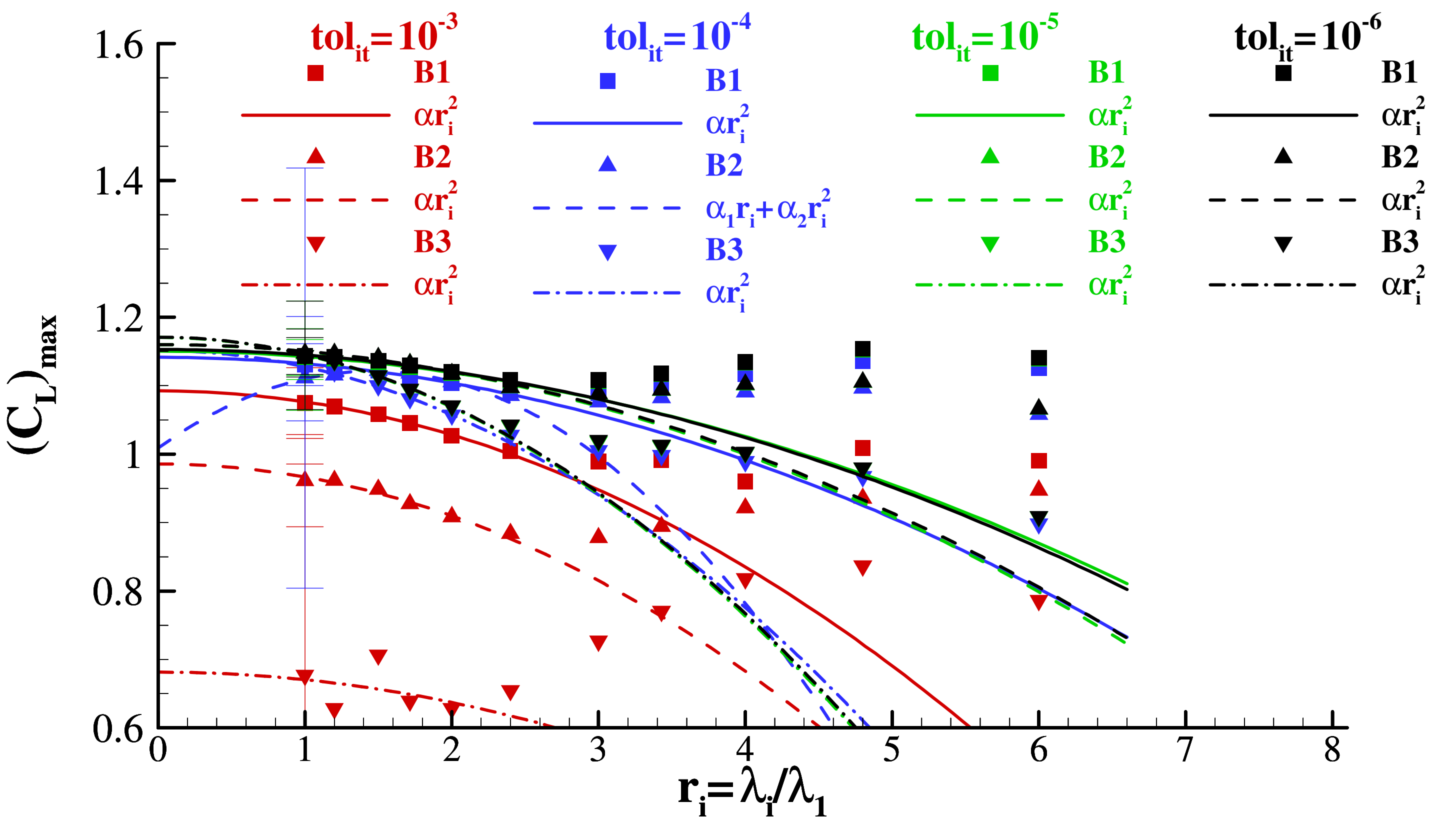

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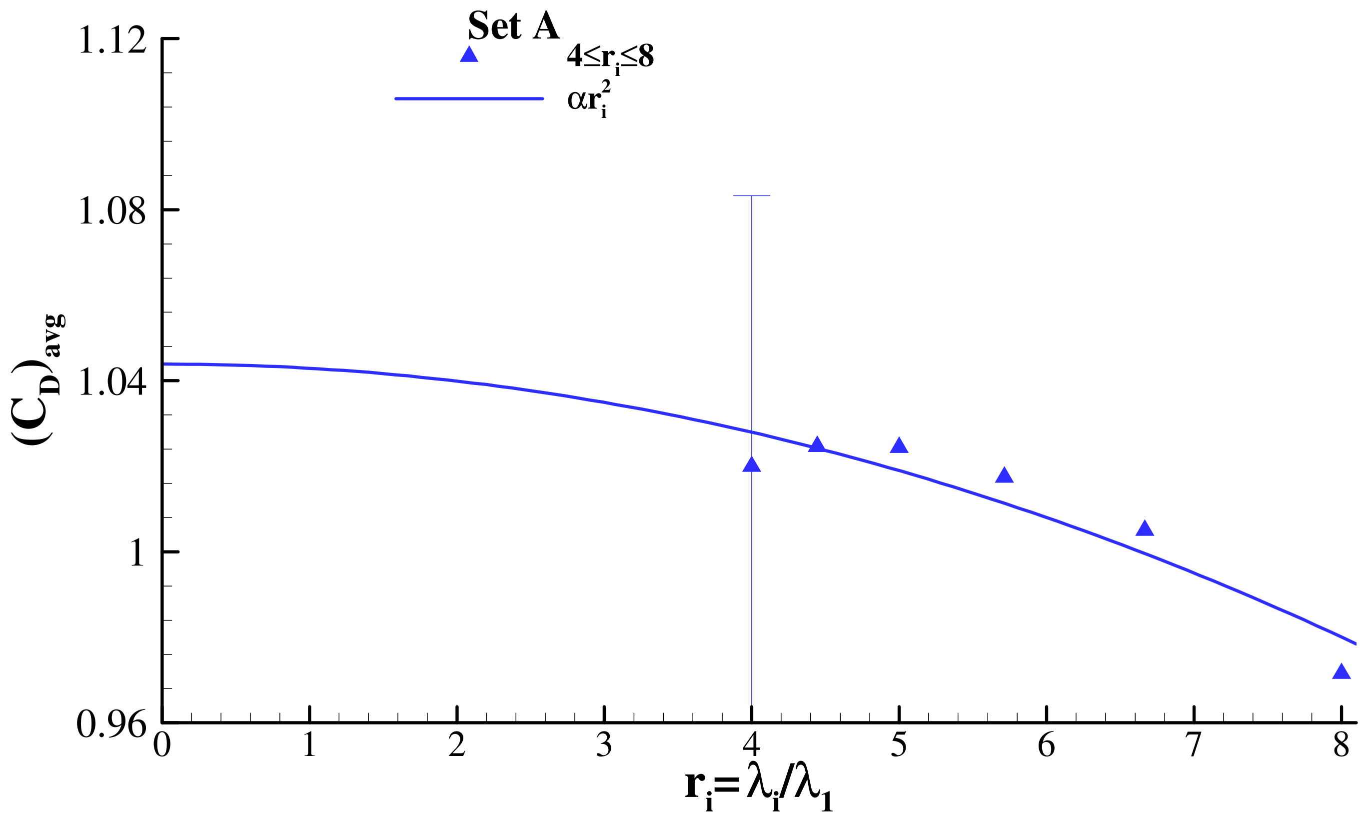

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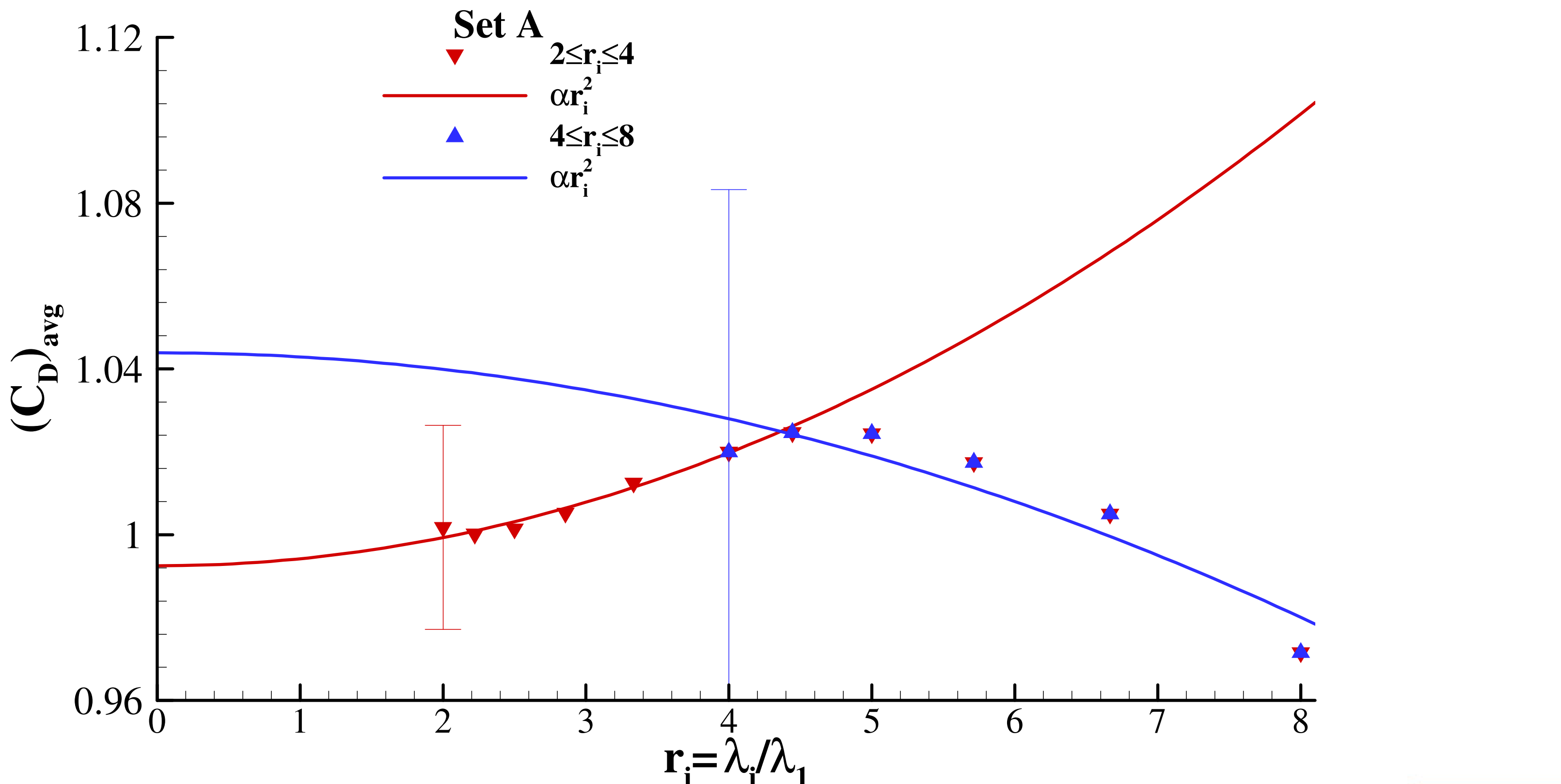

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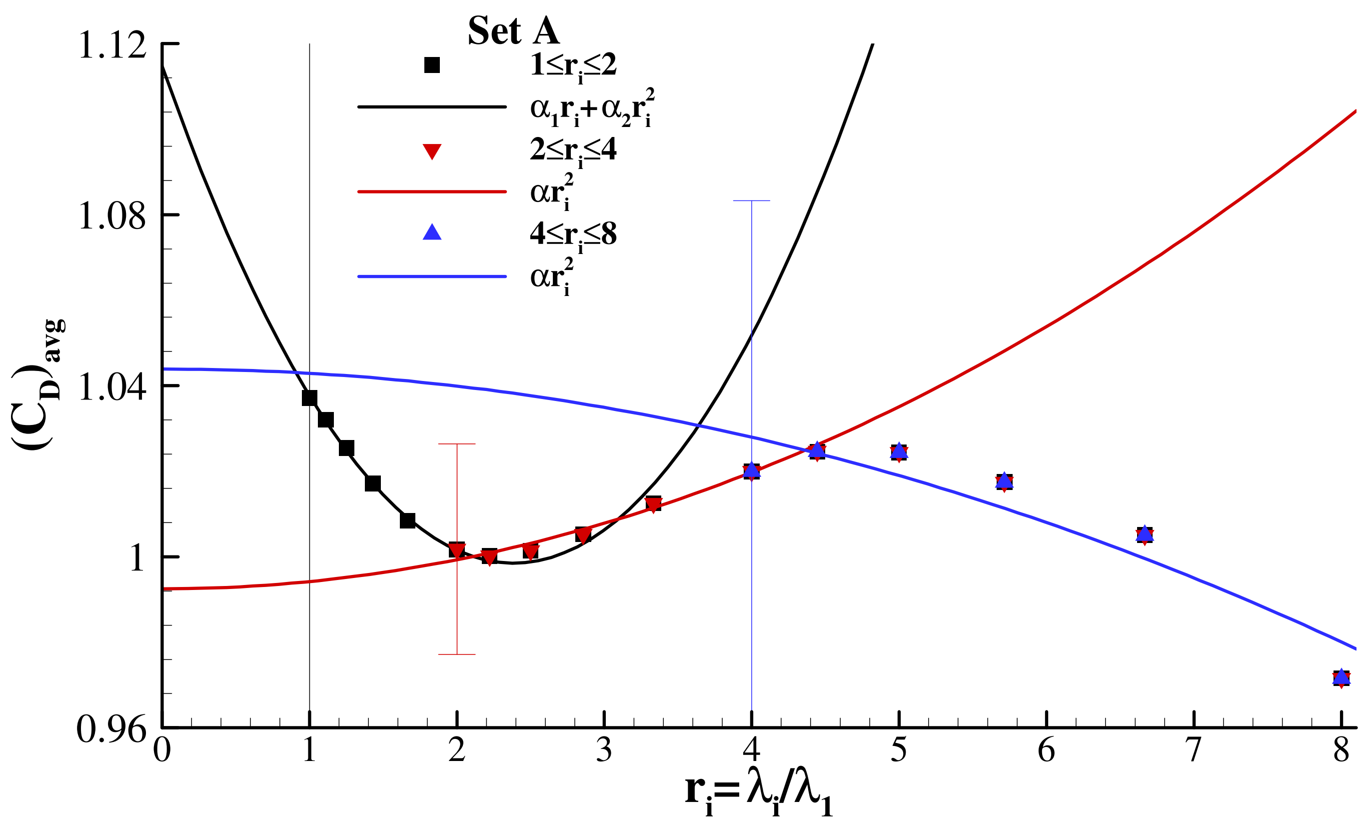

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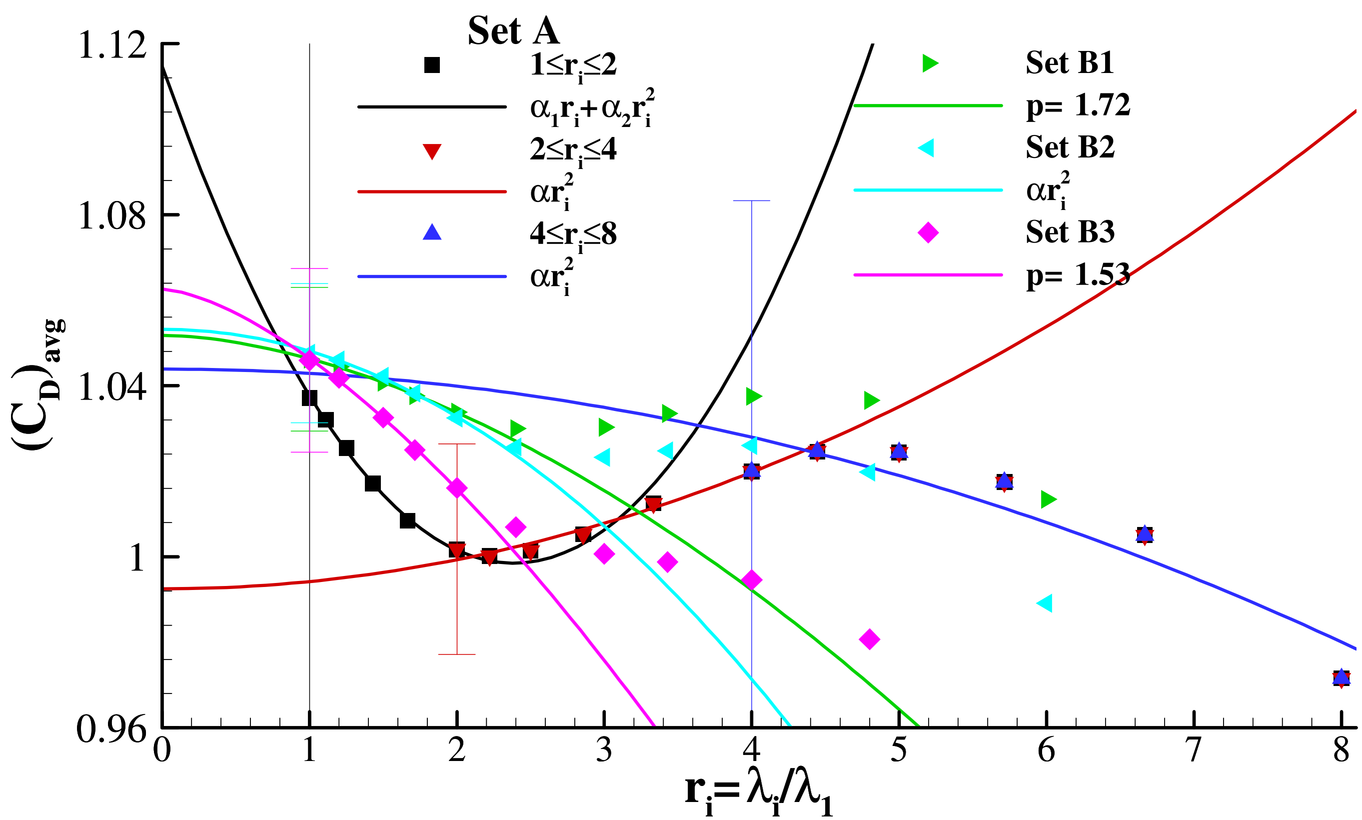

5. Final Remarks

- Solution Verification is an essential part of conscentious CFD applications
- Comparisons of numerical solutions without the knowledge of the numerical uncertainty may lead to misleading conclusions
- Numerical simulations that attempt to capture directly turbulence for "practical applications" at large Reynolds numbers are really a "grand challenge"

5. Final Remarks