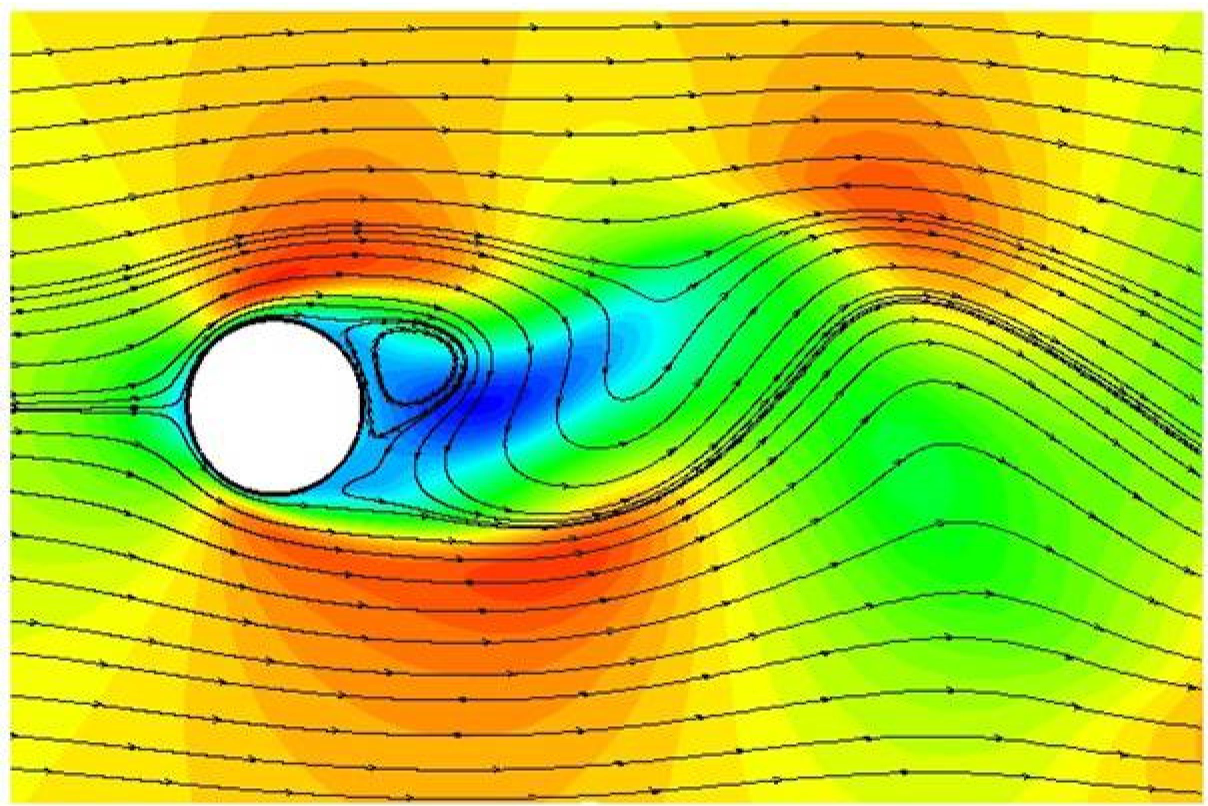
MARIN

TÉCNICO LISBOA

Workshop on Iterative Errors in Unsteady Flow Simulations

L. Eça, G. Vaz and M. Hoekstra



ASME SETTING THE STANDARD

3-5 May 2017

V&V Verification and Validation Symposium

The Westin Las Vegas Hotel, Las Vegas, Nevada

V&V 20 VERIFICATION AND VALIDATION IN COMPUTATIONAL FLUID DYNAMICS AND HEAT TRANSFER

Contents

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- Test Case
  - Definition of flow problem
  - Quantities of interest
- Participants
- Overview of Codes and Solution Strategies
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- Observations and Future Work

Objective

- Investigate the influence of iterative errors on unsteady flow simulations performed with flow solvers using implicit time integration
  - Check if different flow solvers exhibit the the same trends.
  - Create awareness to the problem.
  - Use the available data to develop iterative error estimators that can be used in the so-called “practical applications” where tight iterative convergence criteria may become too expensive.

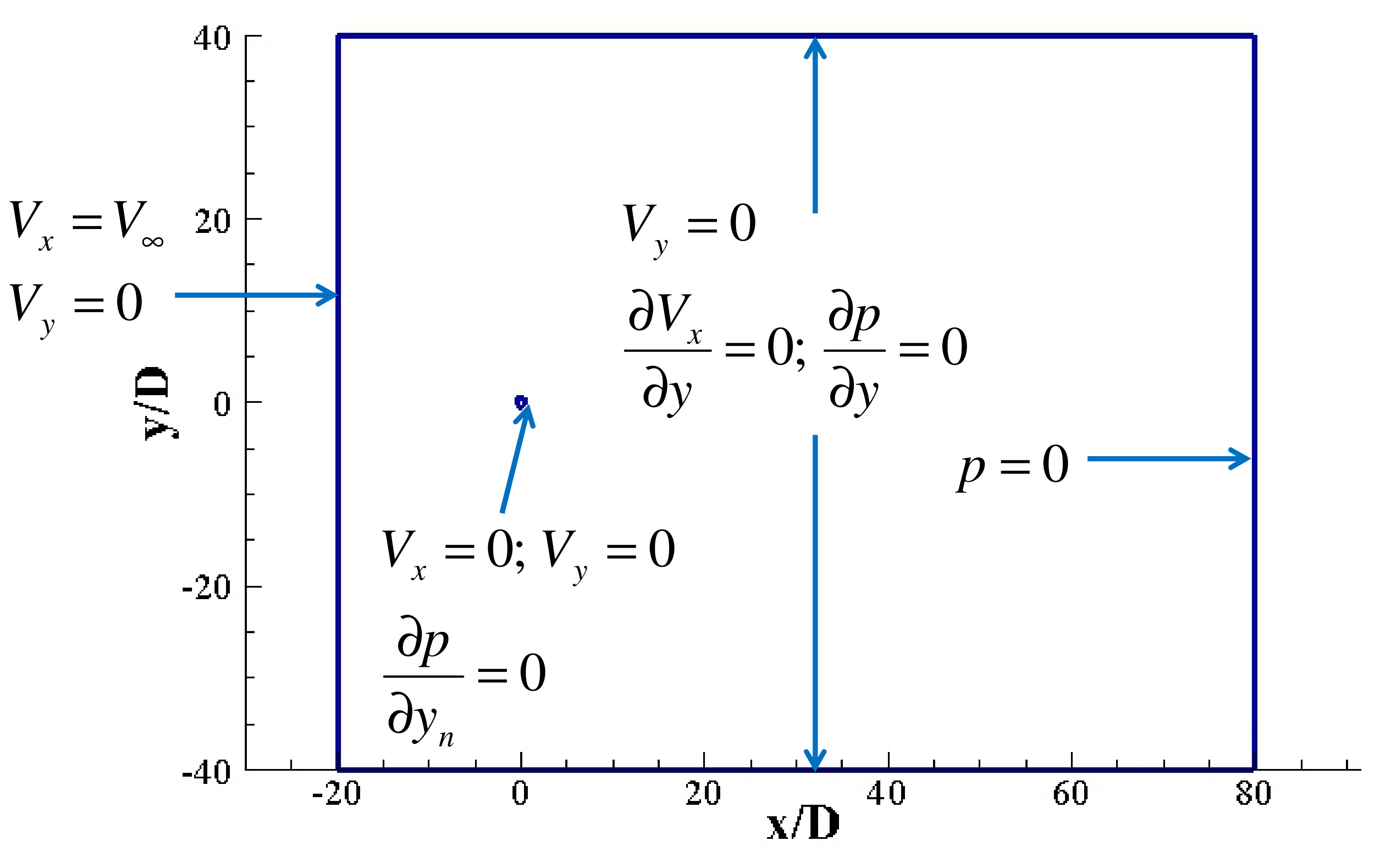
Test Case

- Flow around a circular cylinder with Reynolds number equal to 100 or 150. Two-dimensional flow of an incompressible fluid. (Nearly DNS ☺!)

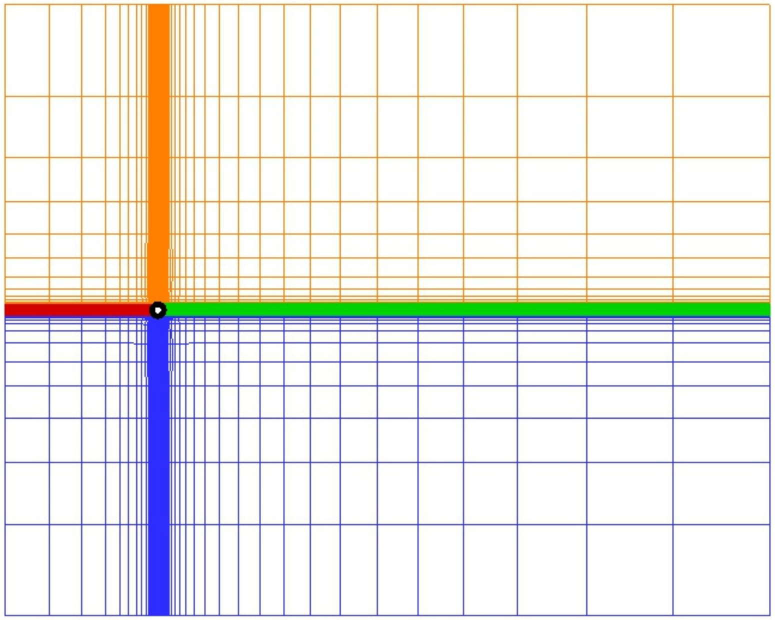
$$Re = \frac{V_\infty D}{\nu}$$

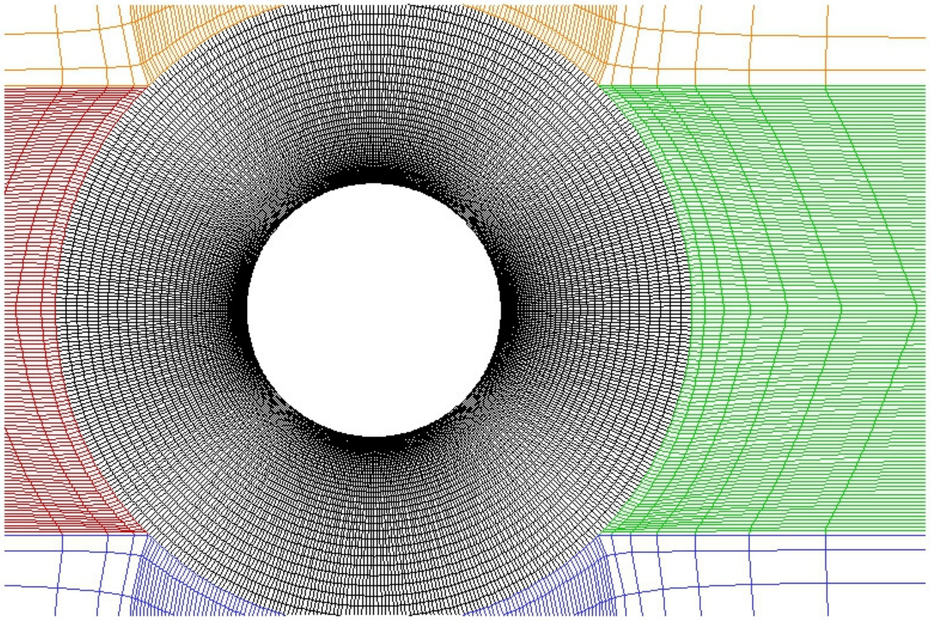
- Fixed computational domain and boundary conditions.
- Four multiblock structured grids available in different formats (CGNS, MSH, CFX, OpenFoam).

Test Case


$V_x = V_\infty$
$V_y = 0$
$V_y = 0$
$\frac{\partial V_x}{\partial y} = 0; \frac{\partial p}{\partial y} = 0$
$p = 0$
$V_x = 0; V_y = 0$
$\frac{\partial p}{\partial y_n} = 0$
40
20
0
-20
-40
-20
0
20
40
60
80
y/D
x/D

Test Case





Number of cells and grid refinement ratio of the set

Grid	Number of cells	Number of Faces on cylinder surface	$\frac{h_i}{h_1}$
1	503640	1920	1
2	282174	1440	1.33
3	196266	1200	1.6
4	125910	960	2

Test Case

- Quantities of interest:
  - Time-averaged $(C_D)_{\text{avg}}$ and standard deviation $(C_D)_{\text{std}}$ of the drag coefficient C_D
  - Standard deviation $(C_L)_{\text{std}}$ of the lift coefficient C_L
  - Strouhal number St
  - Time-averaged base pressure coefficient, $(Cp_b)_{\text{avg}}$
  - Time-averaged flow separation point, $(\theta_{sep})_{\text{avg}}$

Participants

- A. Jones (Rolls-Royce PLC)
- S. Guda, I. Çelik (West Virgina University)
- Y. Chen, K.J. Maki, H. Ye (University of Michigan)
- Sanjeeb Pal (ASME member)
- L. Eça, G.Vaz, M.Hoekstra (MARIN/IST)

Overview of Codes

- ANSYS Fluent
- CFX 14.5
- OpenFoam (pimpleFoam)
- ReFRESCO 2.1
- SATURNE

Solution Strategies

- Pressure-velocity coupling
  - Fully-coupled
  - SIMPLE, SIMPLEC
  - PISO/SIMPLE
  - PISO
- Time discretization
  - First-order backward differencing
  - Second-order backward differencing
- Space discretization
  - Second-order diffusion
  - Convection: Linear upwind (β=1);
    Second-order upwind
    Central differences

Solution Strategies

- Iterative convergence criteria at each time step:

  - Normalized residuals corresponding to a solution change in a simple Jacobi iteration (Maximum or RMS values)

  - Average normalized residuals (absolute value)

  - Global sum of squares of cells residuals

  - Maximum number of iterations

Submitted Results

- Re=100

  - PISO; Second order upwind for convection;
  Second-order backwards for time.
  Normalized absolute residual (average value) with a maximum of 100 iterations (L_2a).
  Grids 3 and 4 with Δt=0.01

  - SIMPLE; Second order upwind for convection;
  Second-order backwards for time.
  Normalized residual (maximum value, L_∞)
  Grids 1, 2, 3 and 4 with several Δt

Submitted Results

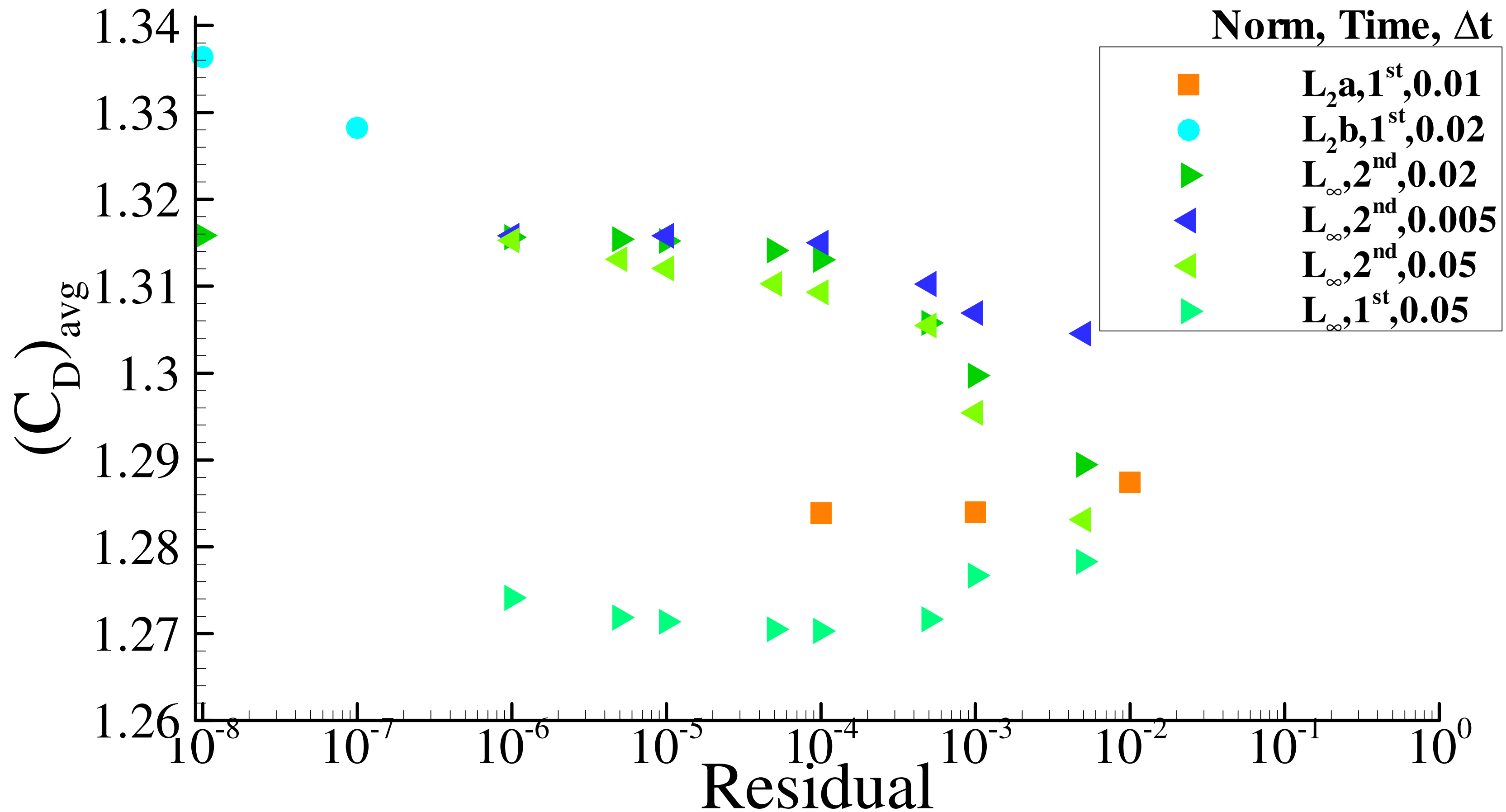
- Re=100

  - SIMPLE; Second order upwind for convection;
  First-order backwards for time.
  Normalized residual (maximum value, L_∞)
  Grid 4 with Δt =0.05

  - SIMPLEC; Central differences for convection
  First-order backwards for time.
  Global sum of squares of cells residuals (L_2b)
  Grids 1, 2, 3 and 4 with Δt =0.01 to Δt =0.02

Submitted Results

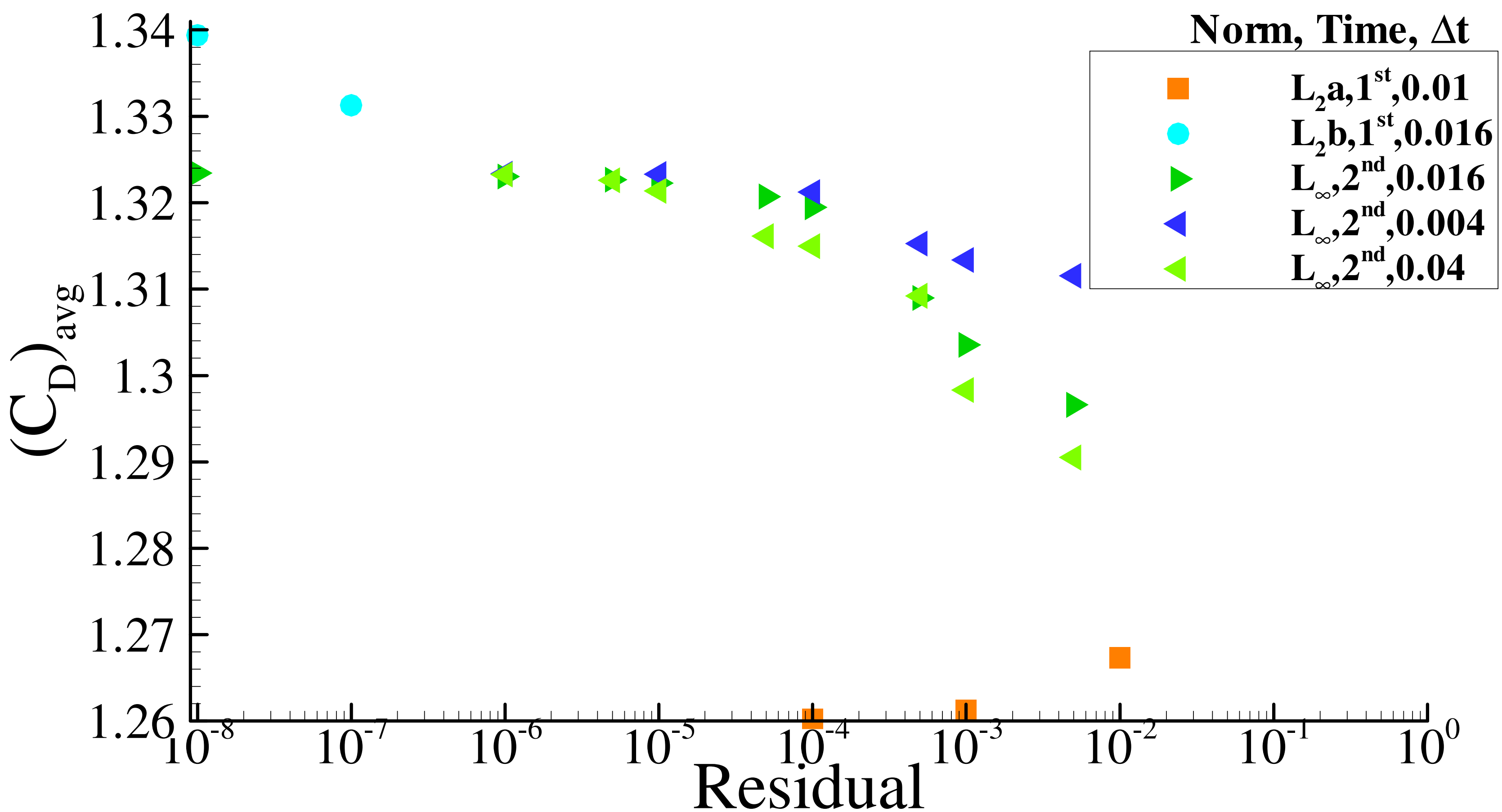
- Re=100, Grid 4



Time-averaged drag coefficient

Submitted Results

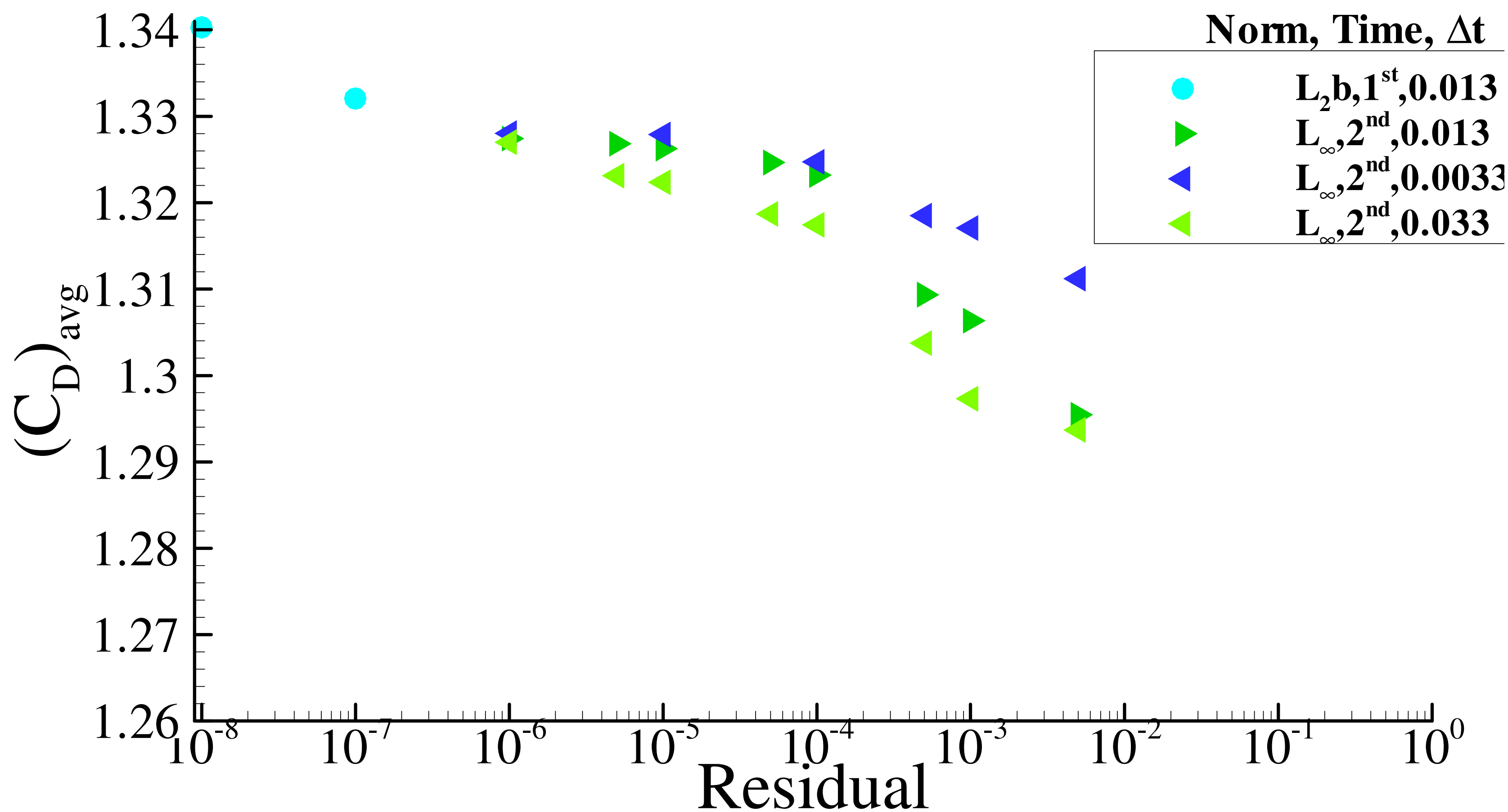
- Re=100, Grid 3



Time-averaged drag coefficient

Submitted Results

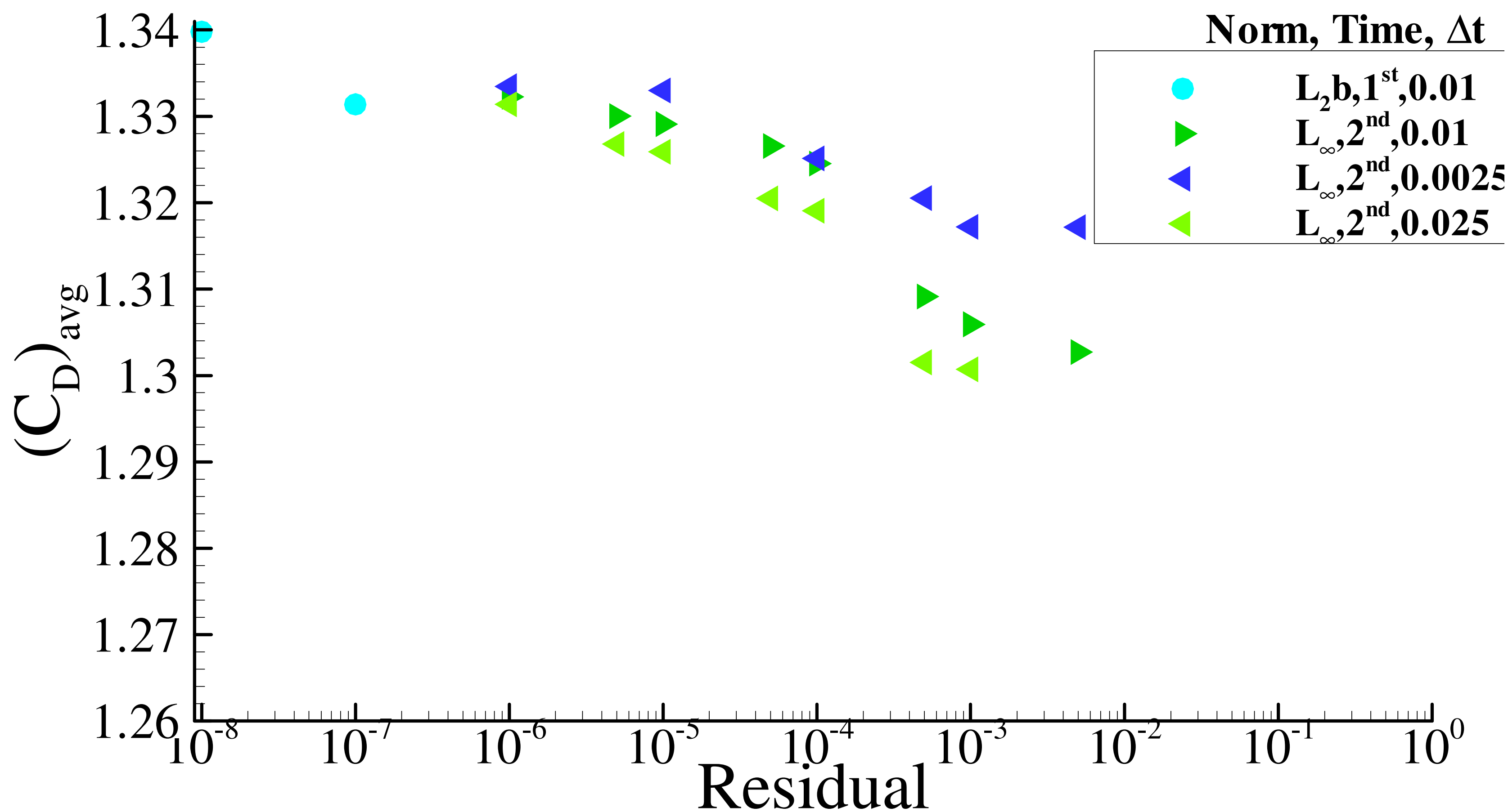
- Re=100, Grid 2



Time-averaged drag coefficient

Submitted Results

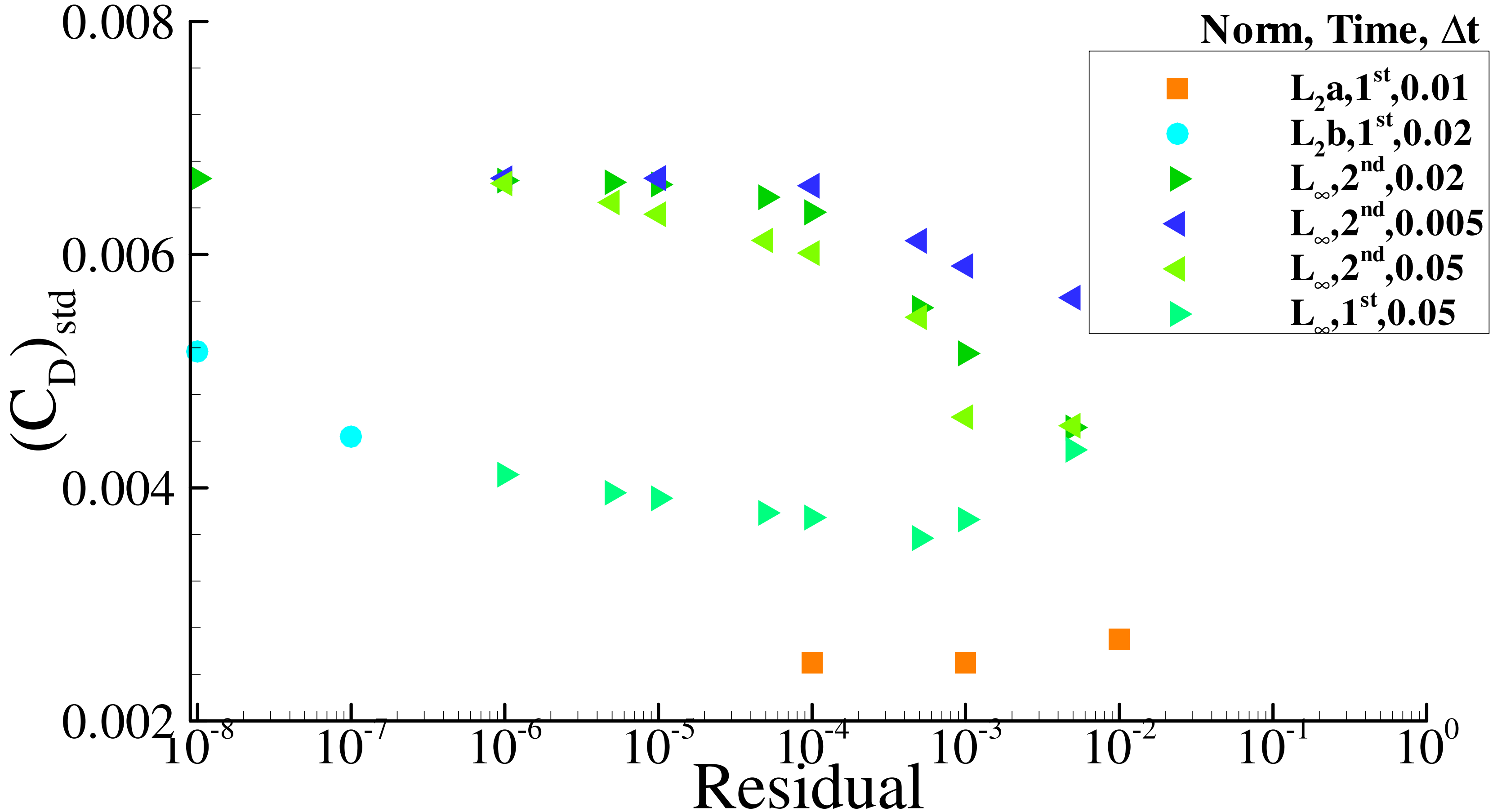
- Re=100, Grid 1



Time-averaged drag coefficient

Submitted Results

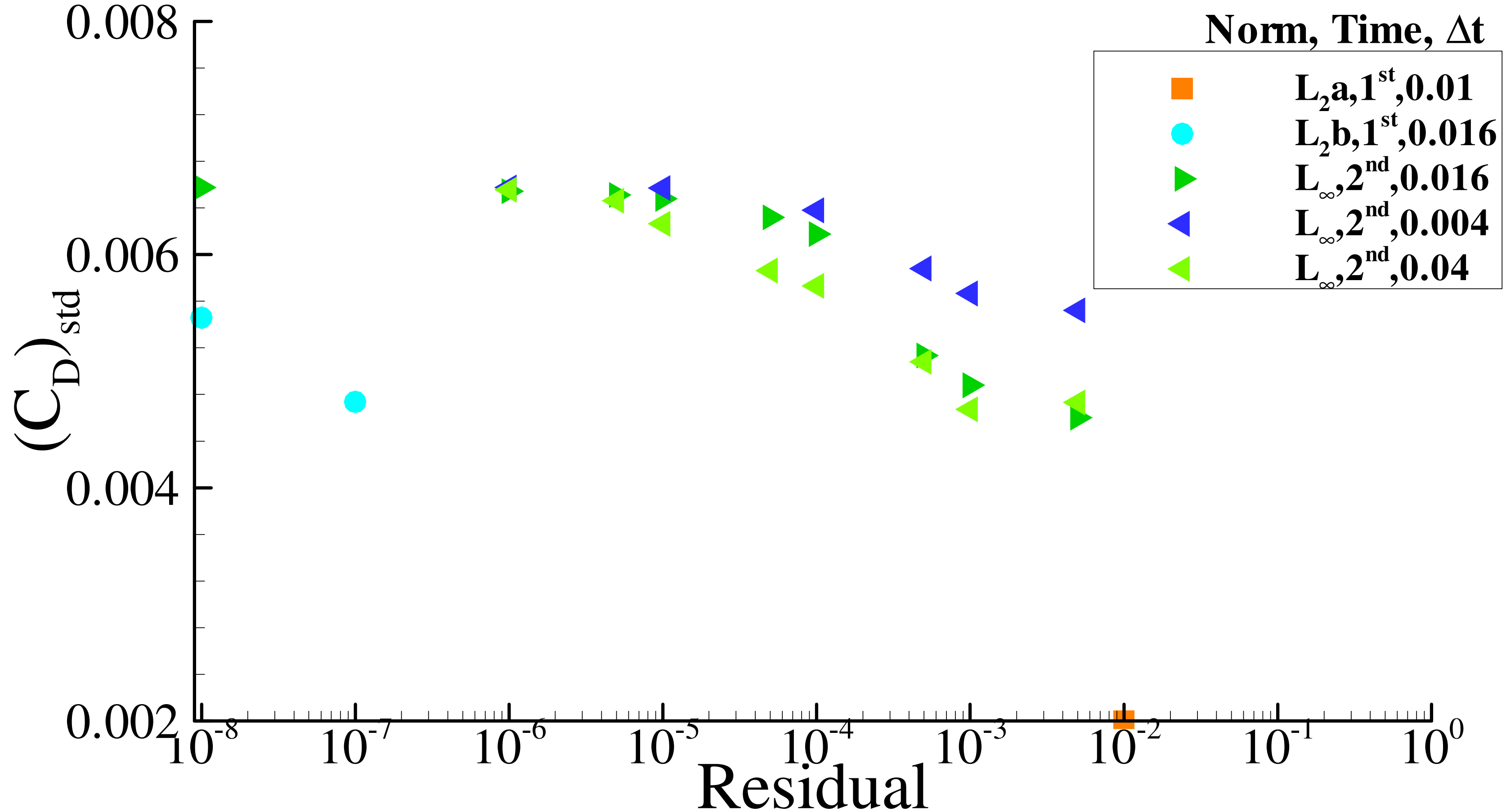
- Re=100, Grid 4



Standard deviation drag coefficient

Submitted Results

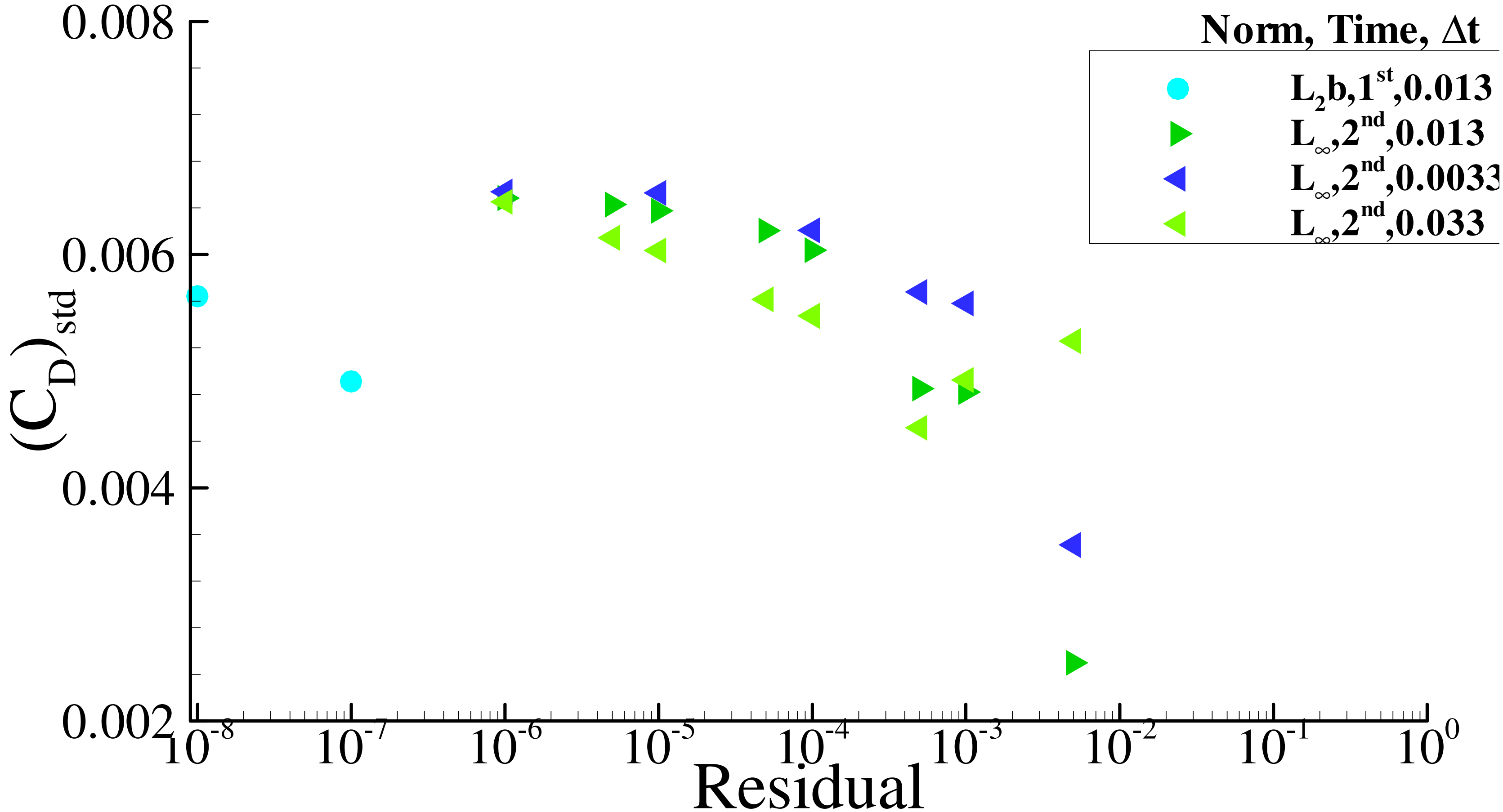
- Re=100, Grid 3



Standard deviation drag coefficient

Submitted Results

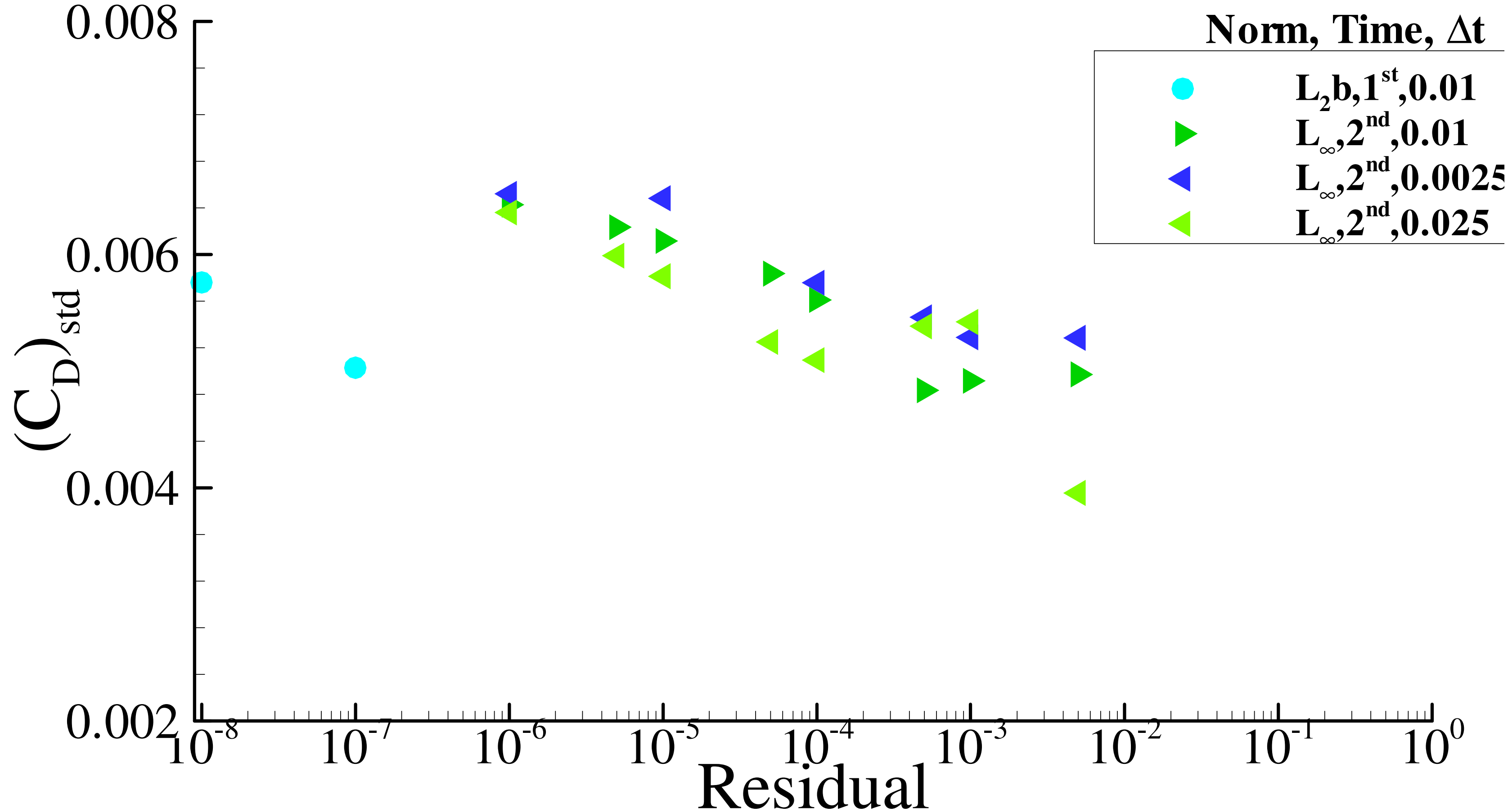
- Re=100, Grid 2



Standard deviation drag coefficient

Submitted Results

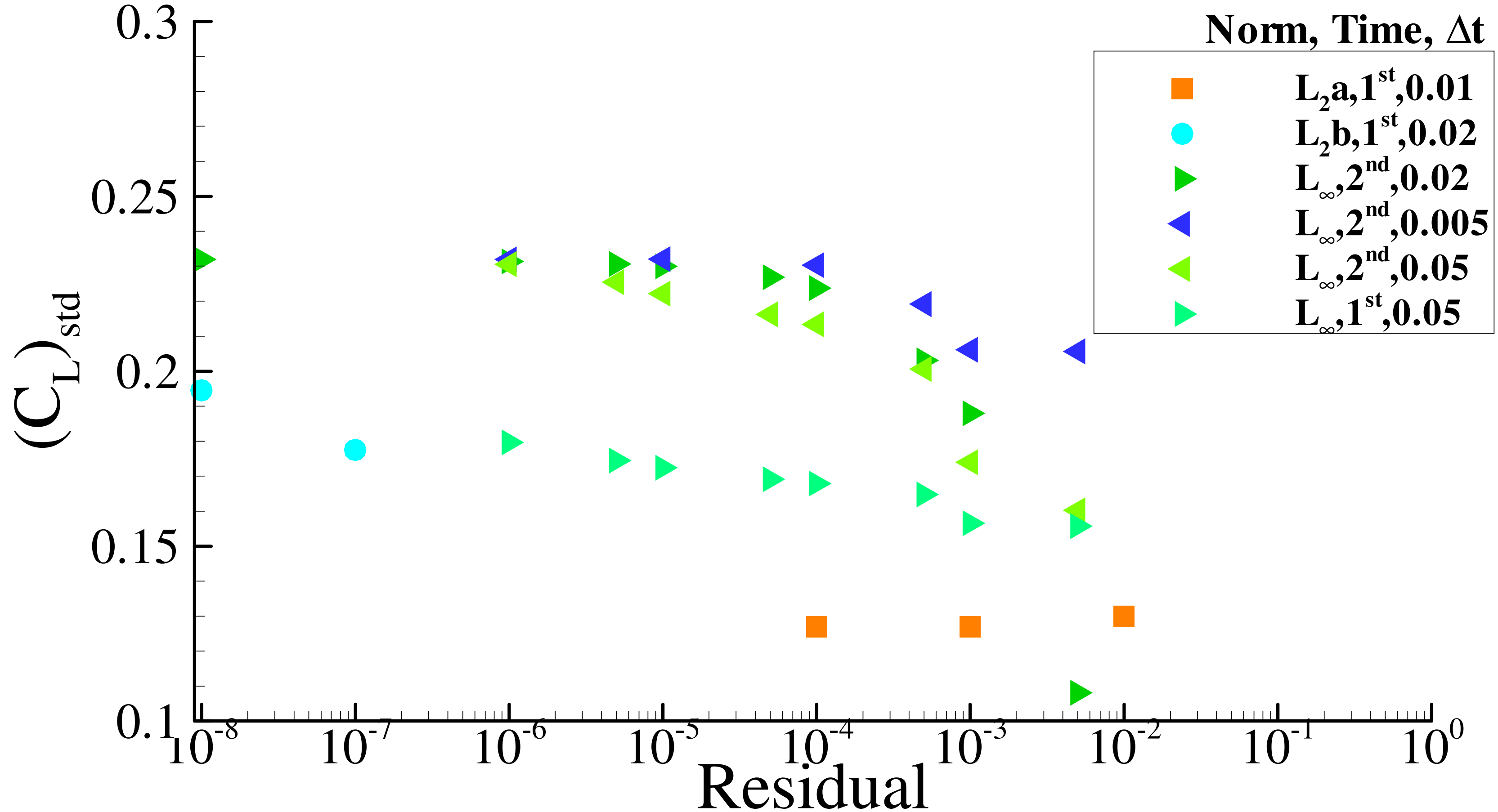
- Re=100, Grid 1



Standard deviation drag coefficient

Submitted Results

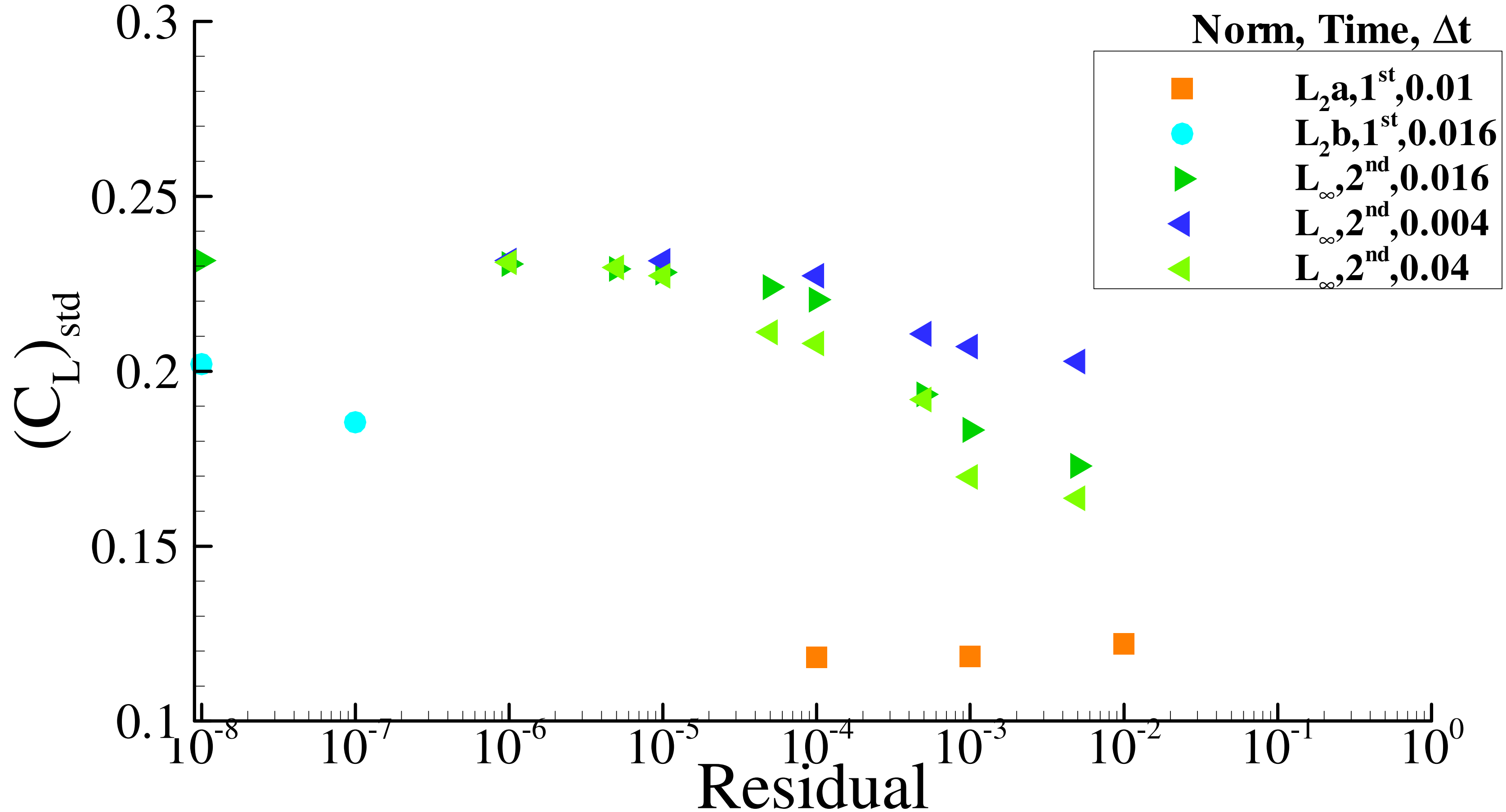
- Re=100, Grid 4



Standard deviation lift coefficient

Submitted Results

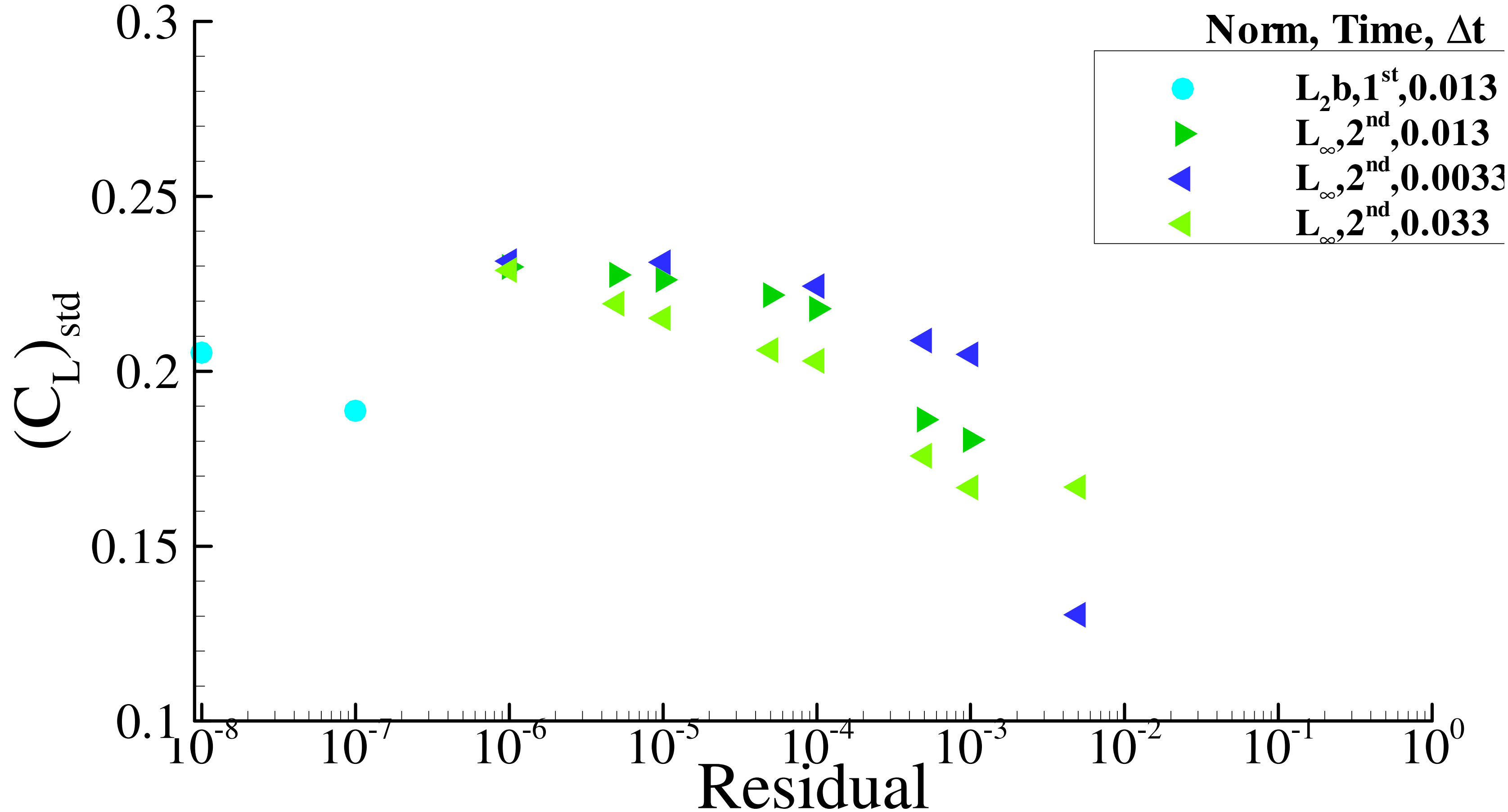
- Re=100, Grid 3



Standard deviation lift coefficient

Submitted Results

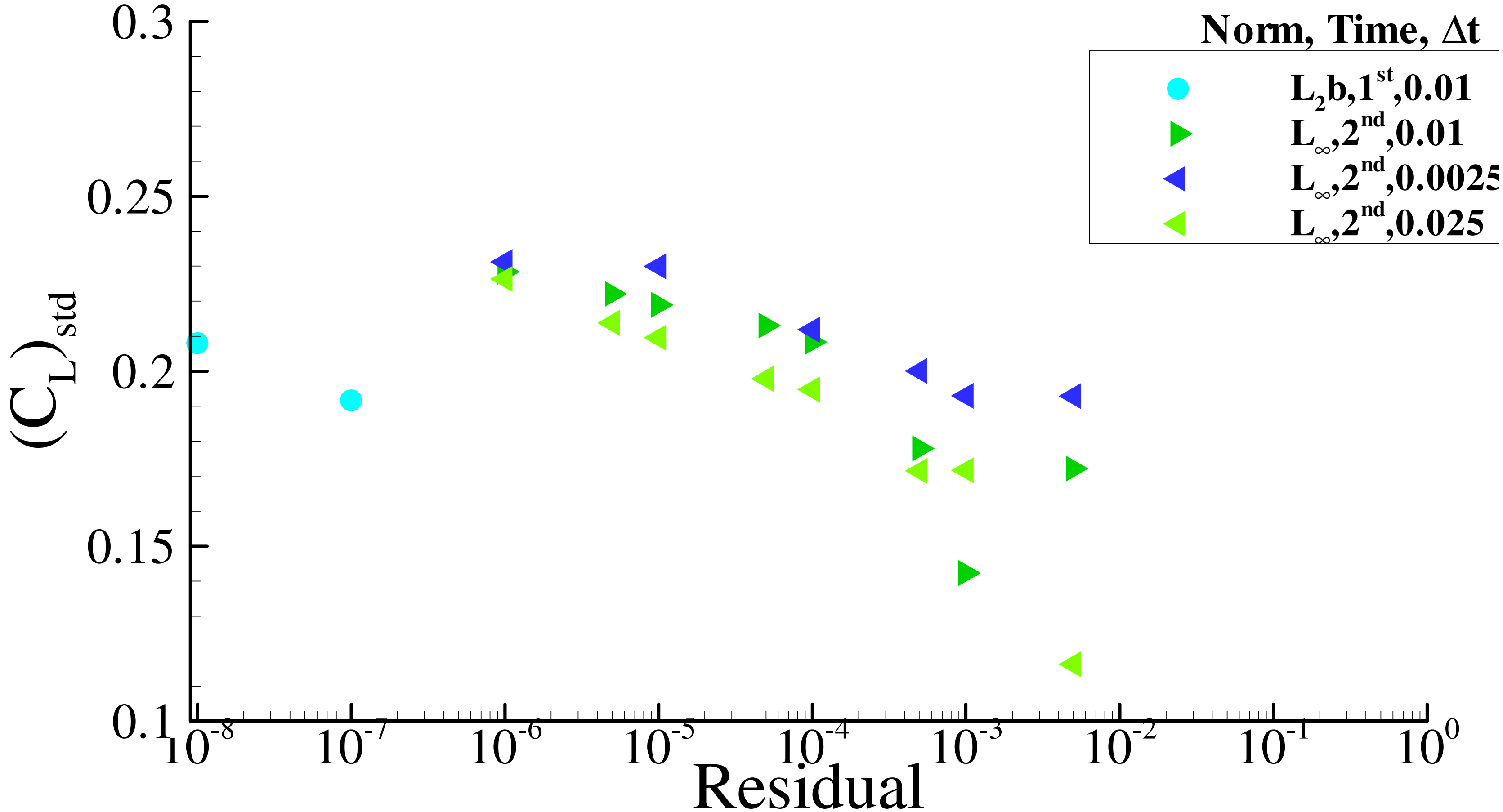
- Re=100, Grid 2



Standard deviation lift coefficient

Submitted Results

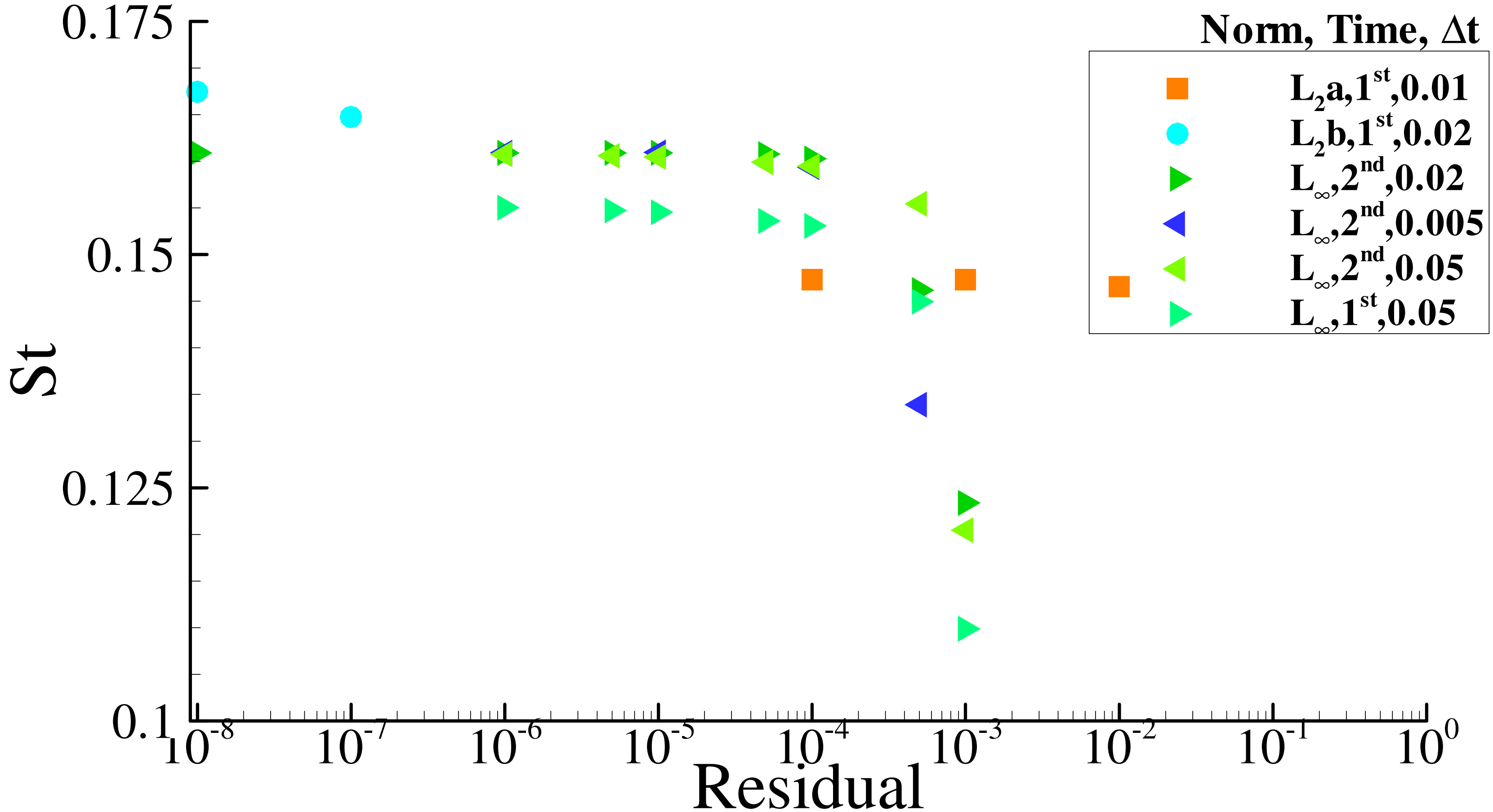
- Re=100, Grid 1



Standard deviation lift coefficient

Submitted Results

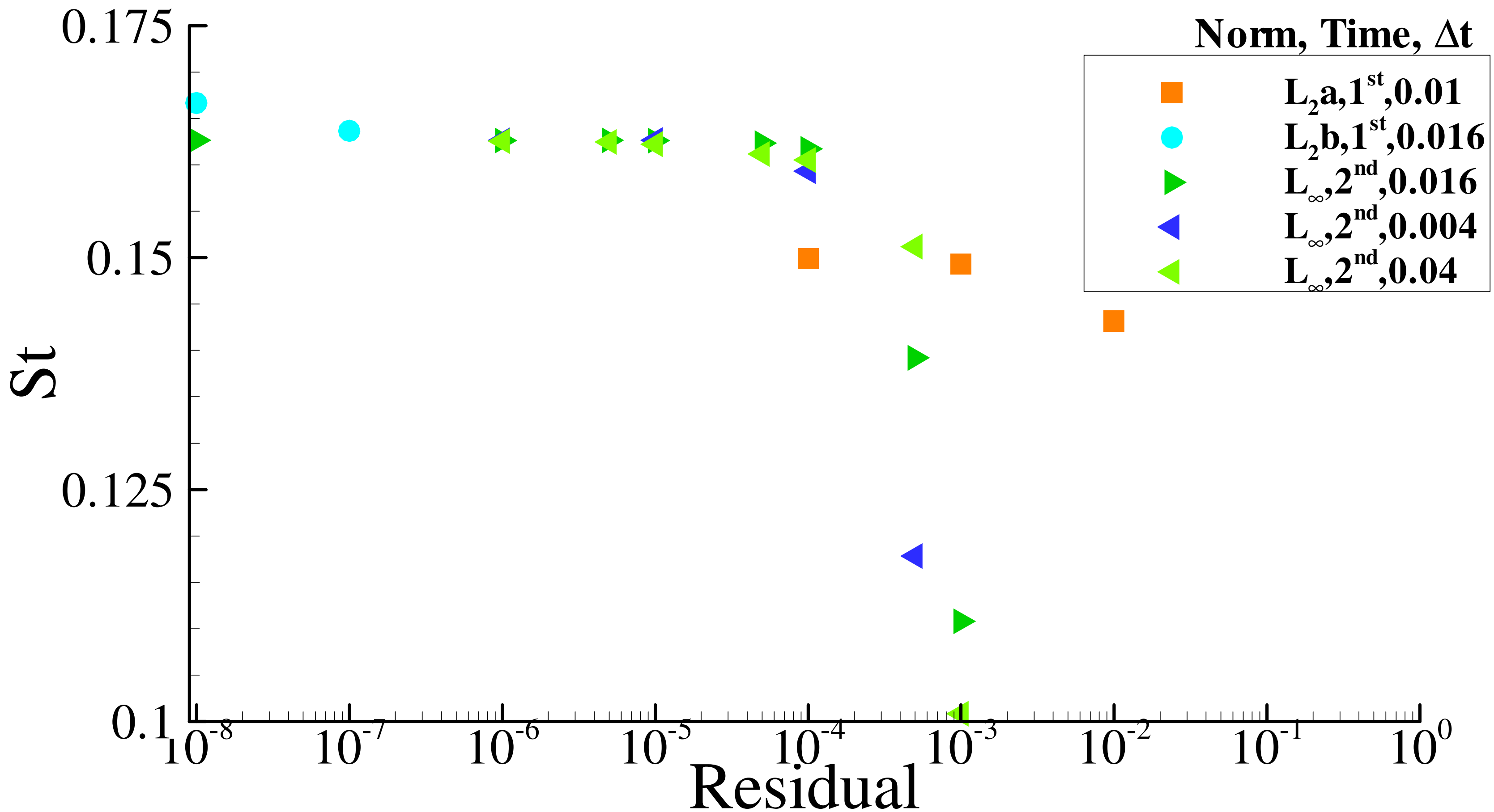
- Re=100, Grid 4



Strouhal number

Submitted Results

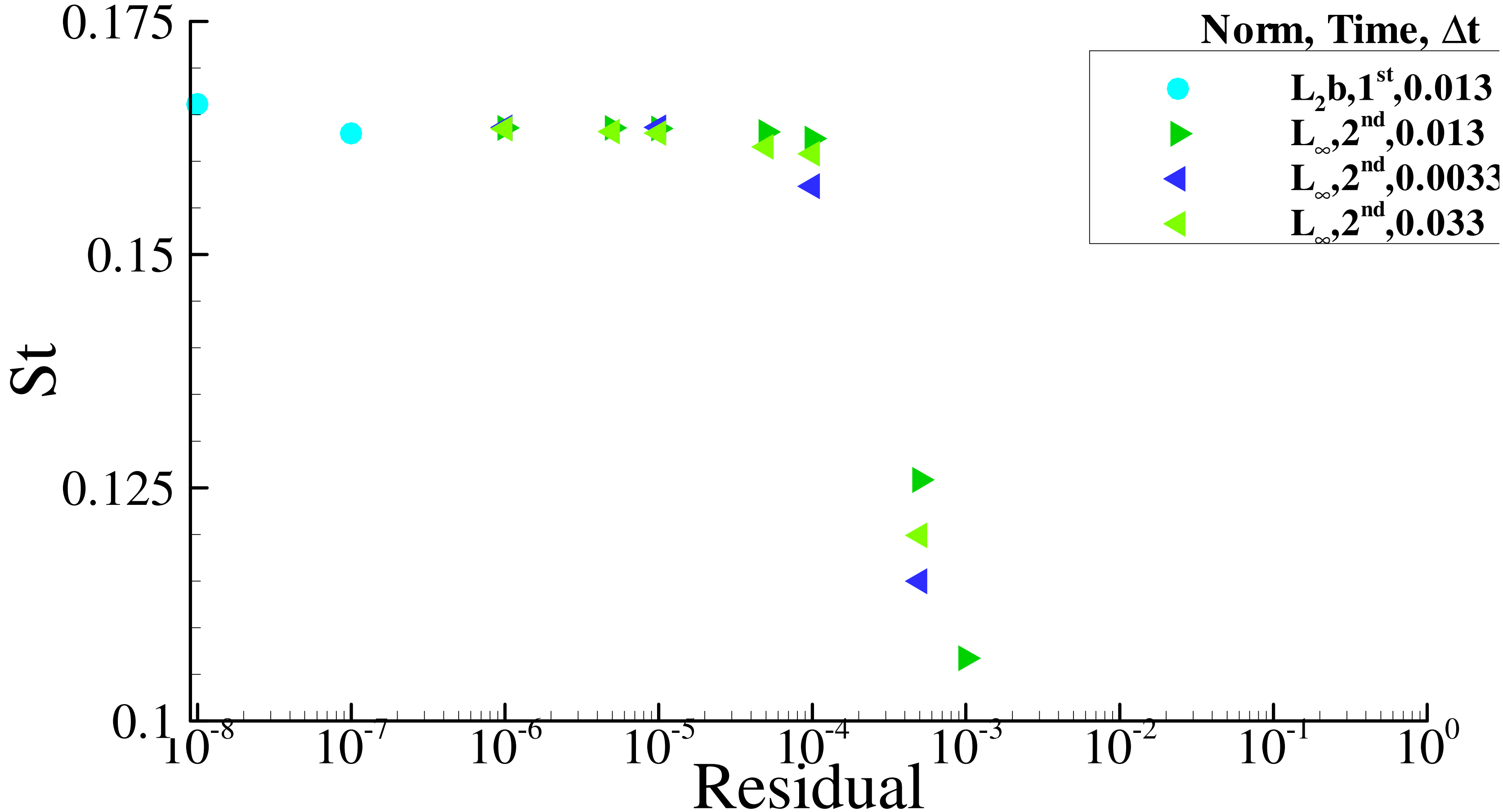
- Re=100, Grid 3



Strouhal number

Submitted Results

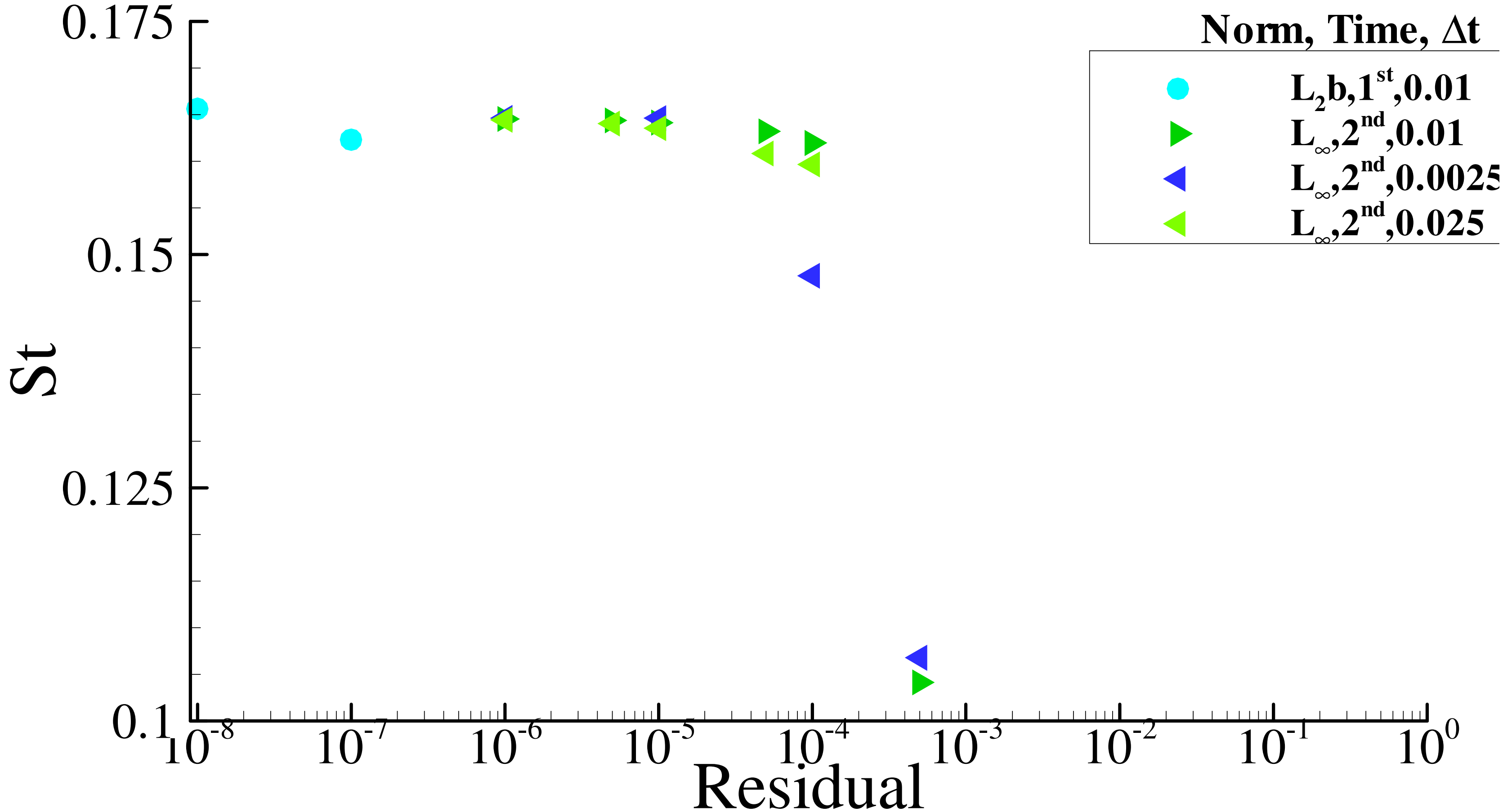
- Re=100, Grid 2



Strouhal number

Submitted Results

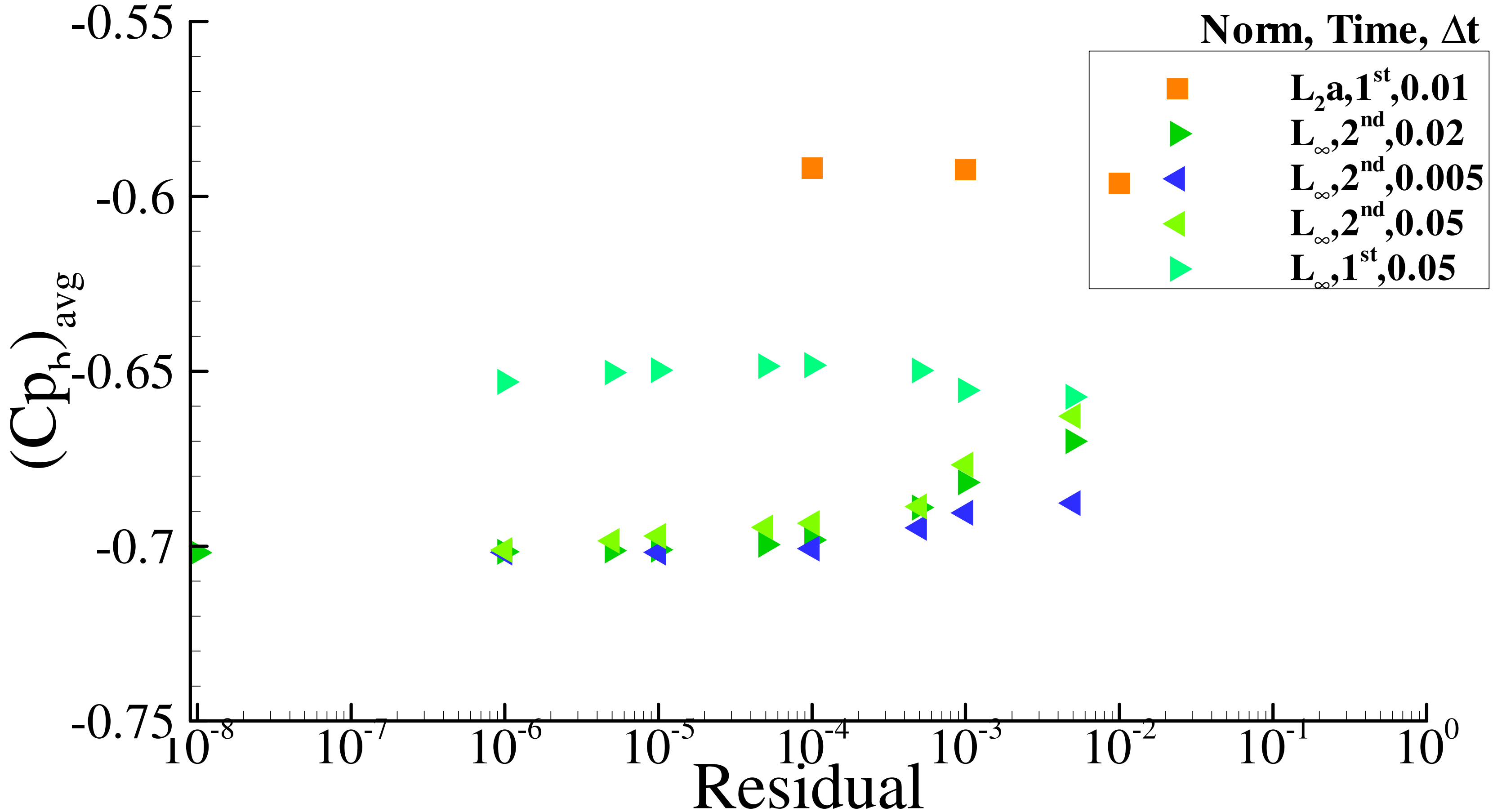
- Re=100, Grid 1



Strouhal number

Submitted Results

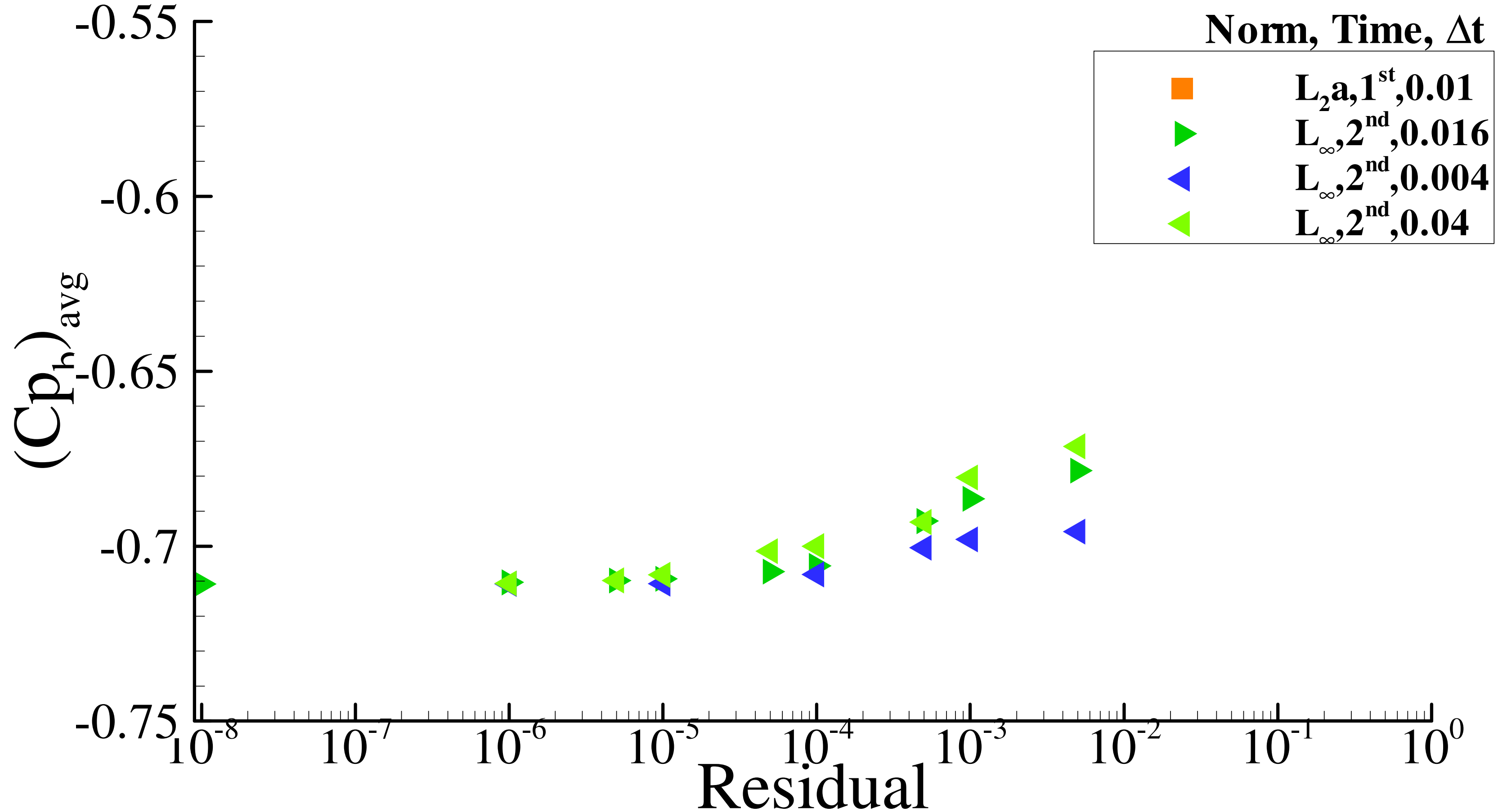
- Re=100, Grid 4



Time-averaged base pressure coefficient

Submitted Results

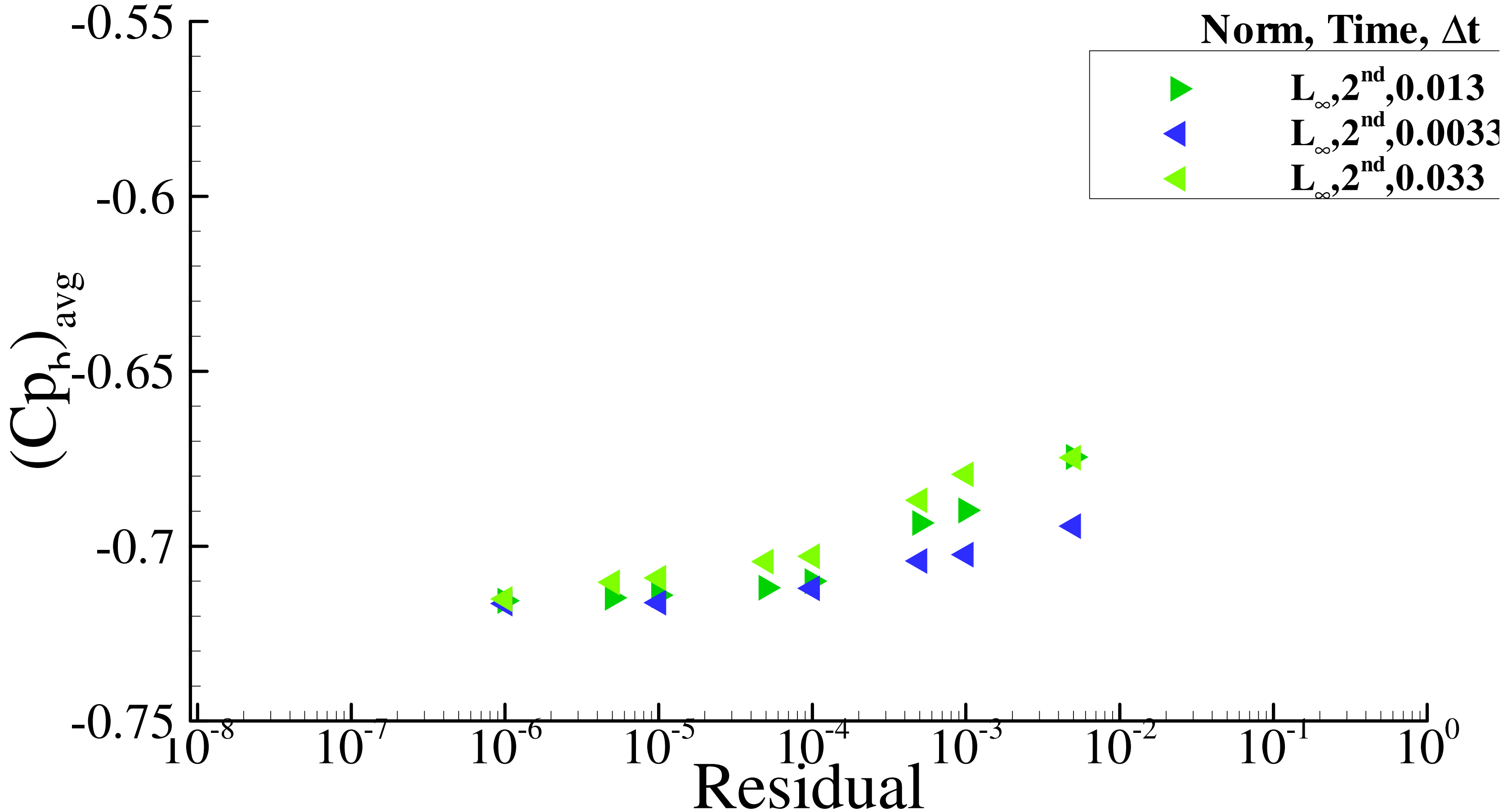
- Re=100, Grid 3



Time-averaged base pressure coefficient

Submitted Results

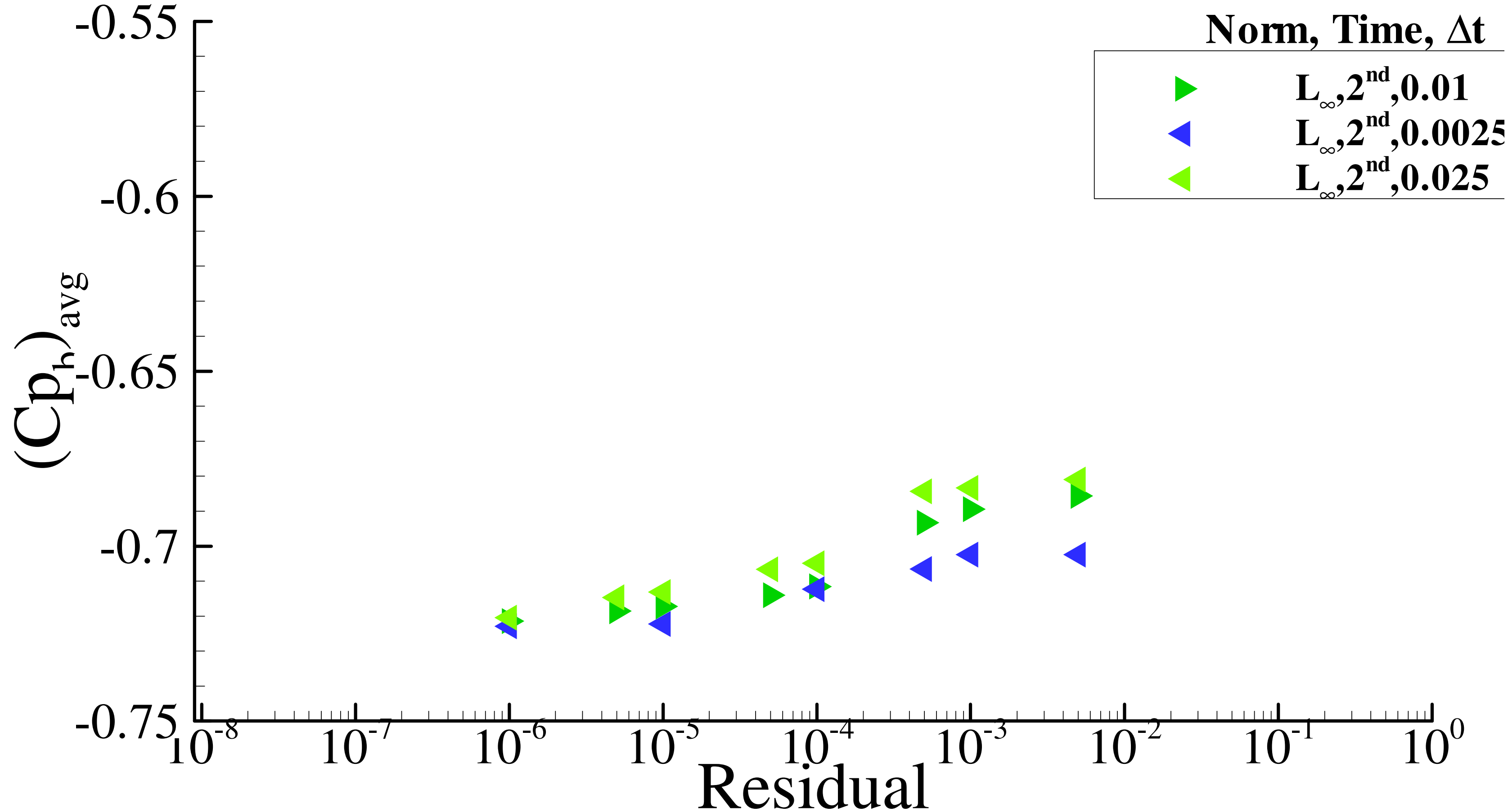
- Re=100, Grid 2



Time-averaged base pressure coefficient

Submitted Results

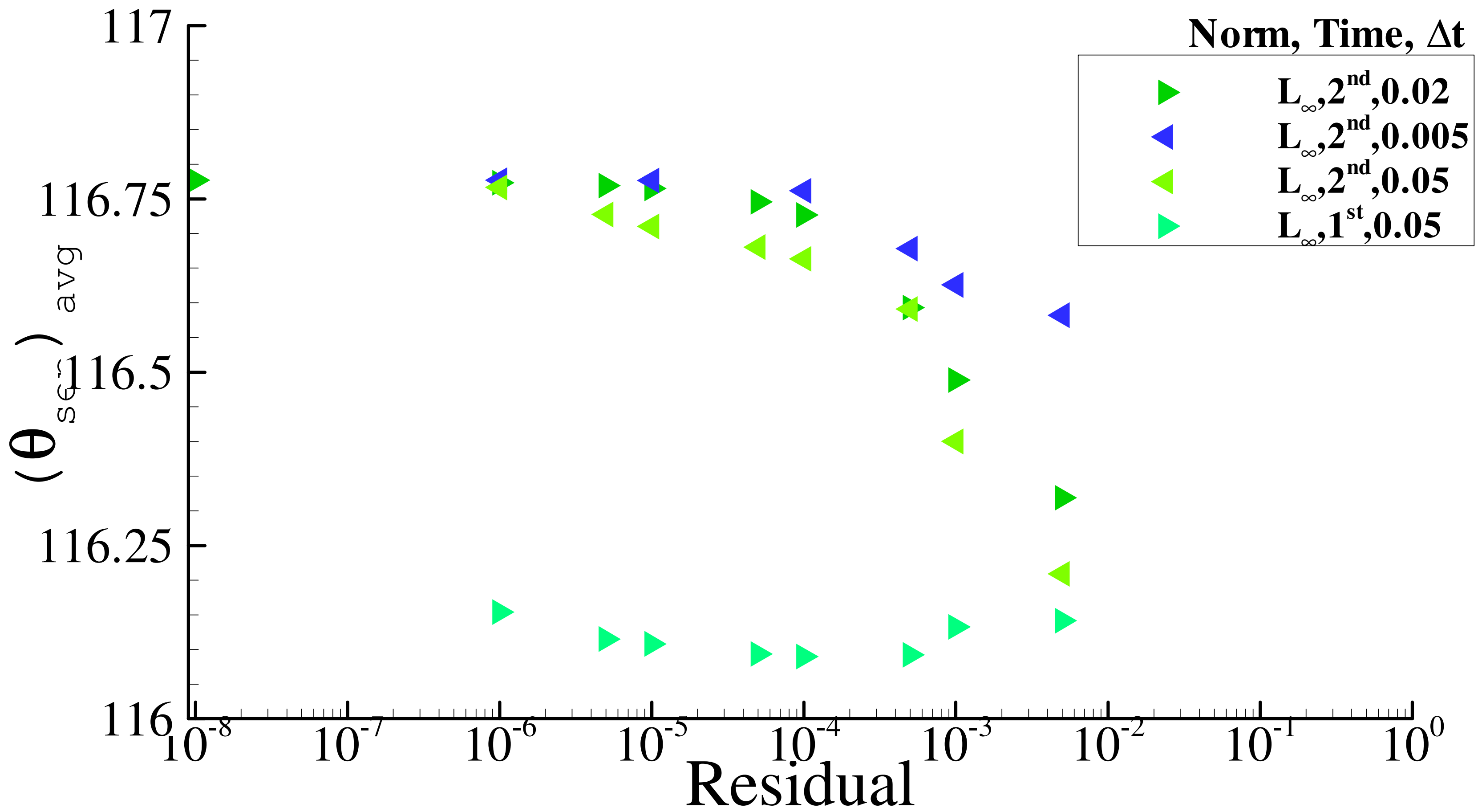
- Re=100, Grid 1



Time-averaged base pressure coefficient

Submitted Results

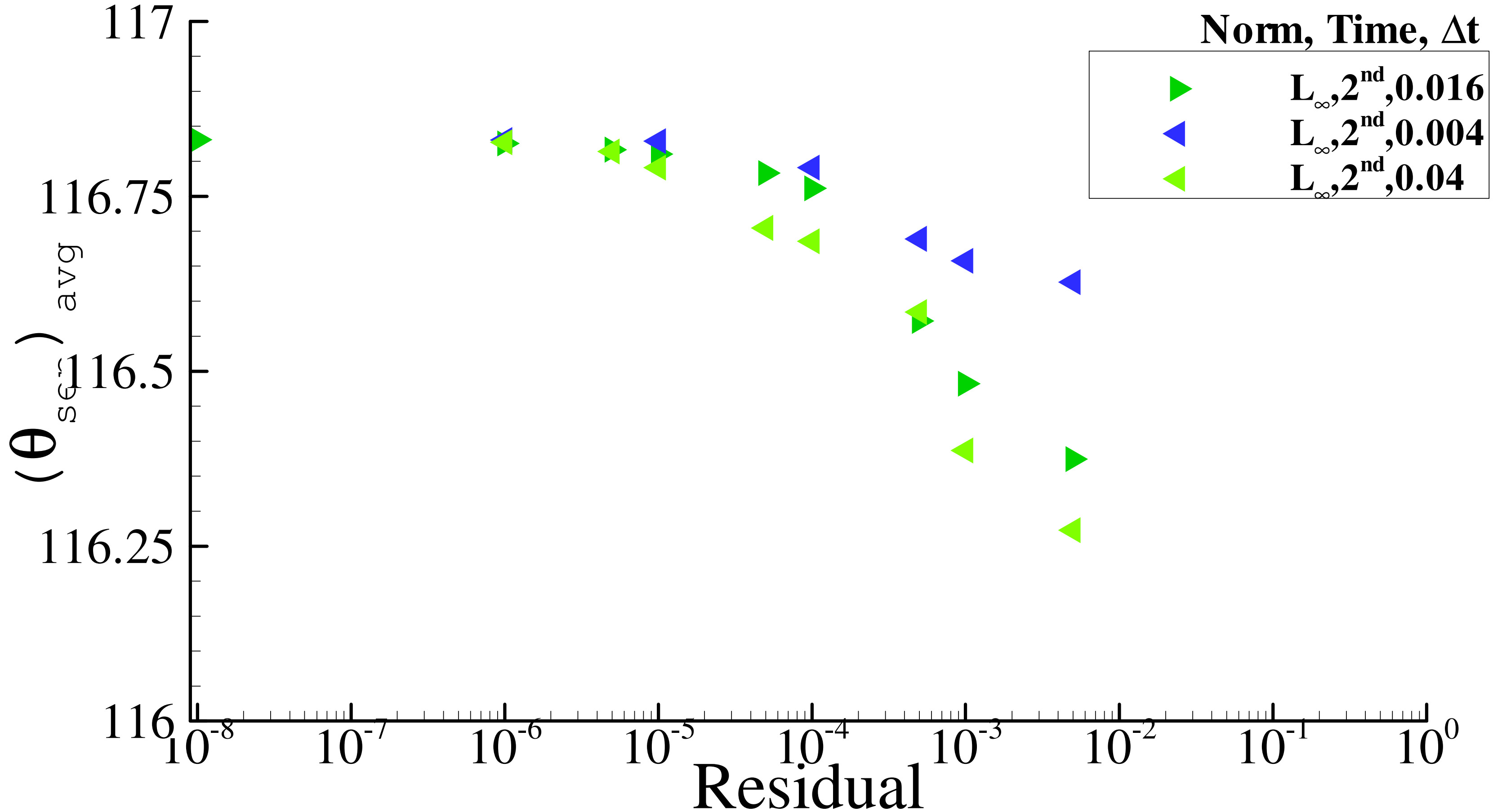
- Re=100, Grid 4



Time-averaged separation point

Submitted Results

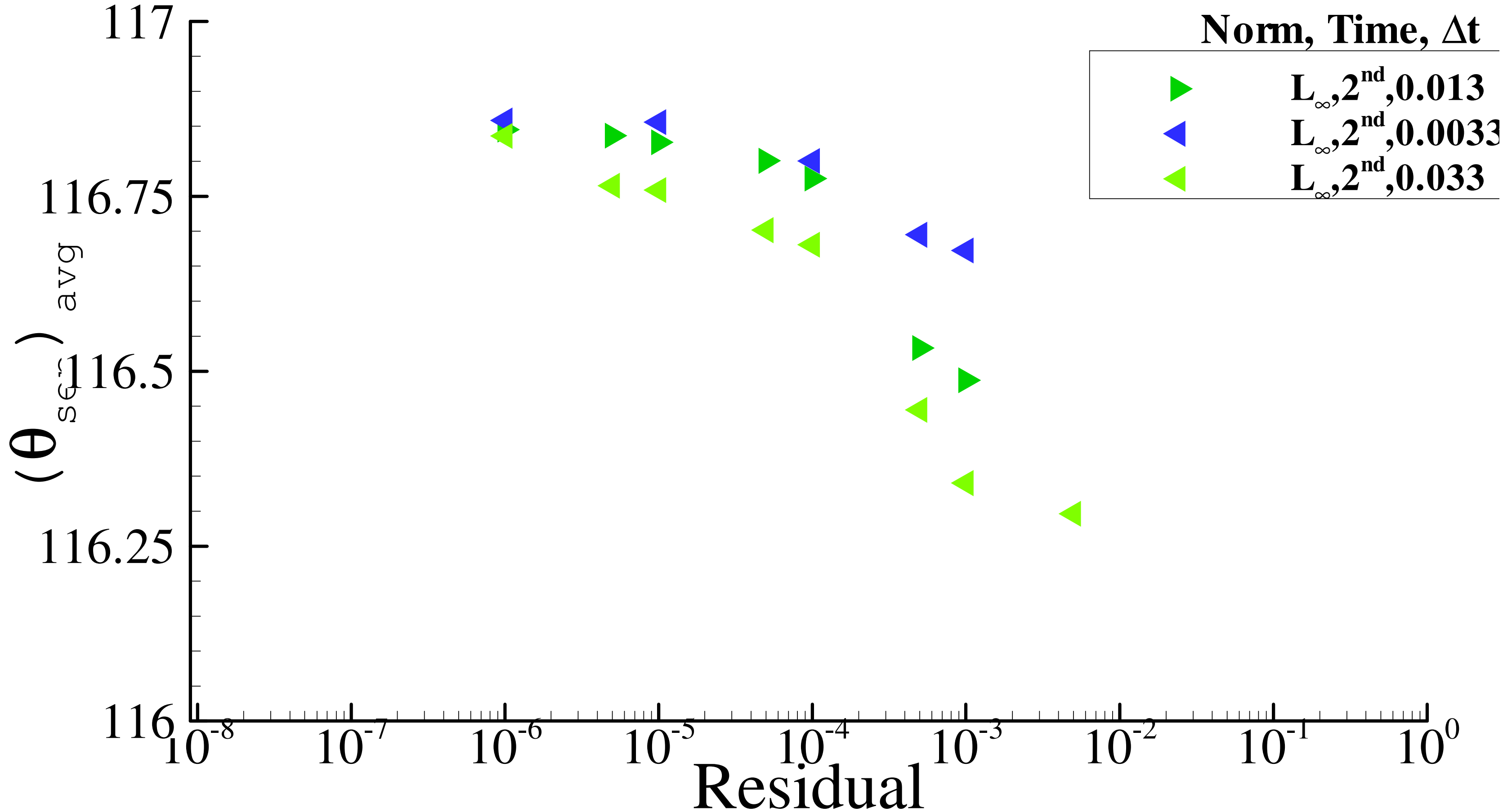
- Re=100, Grid 3



Time-averaged separation point

Submitted Results

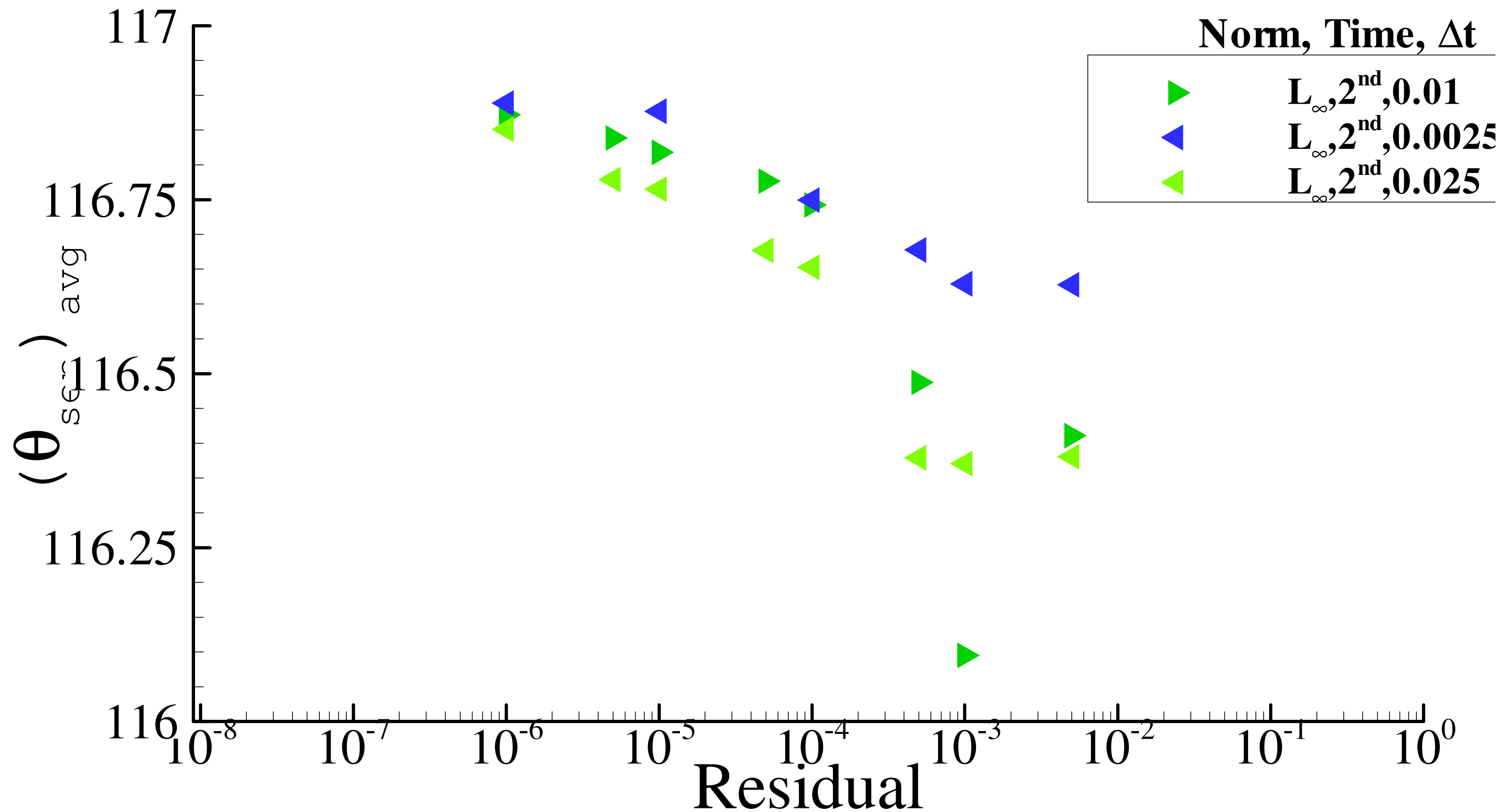
- Re=100, Grid 2



Time-averaged separation point

Submitted Results

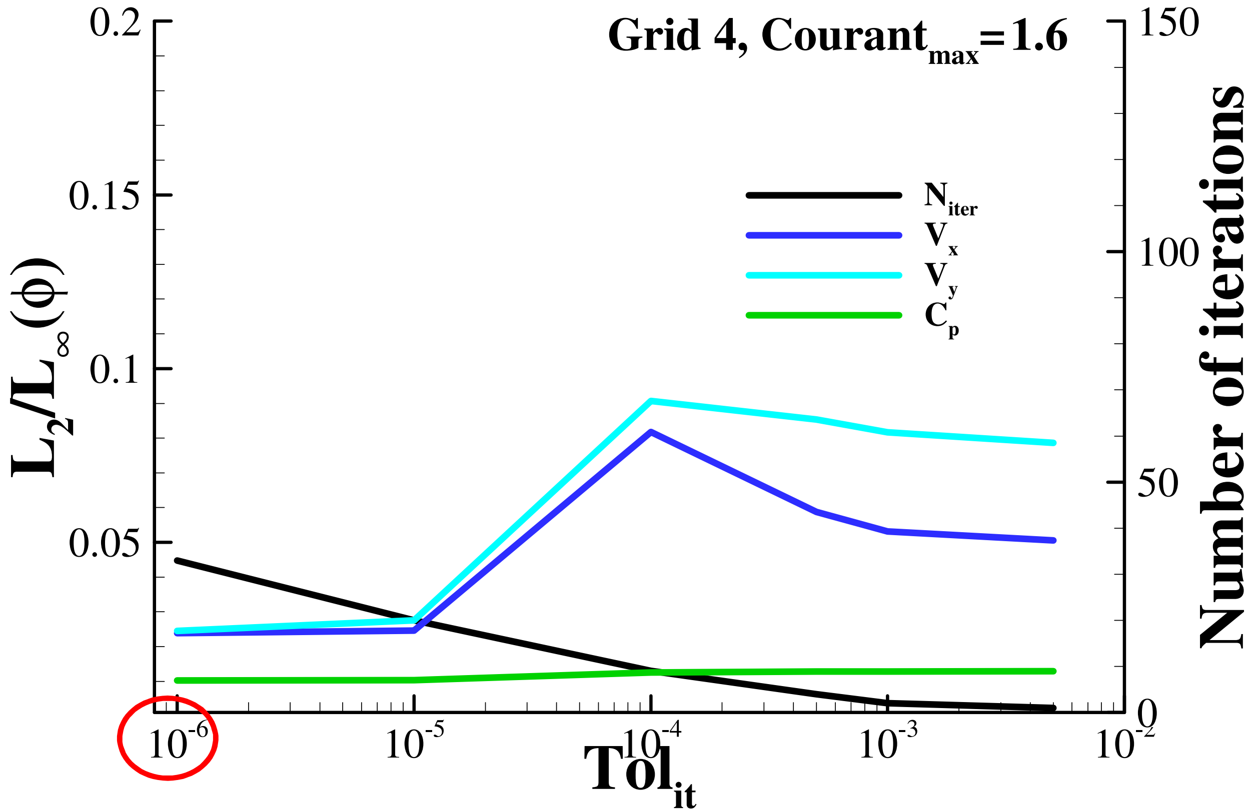
- Re=100, Grid 1



Time-averaged separation point

Submitted Results

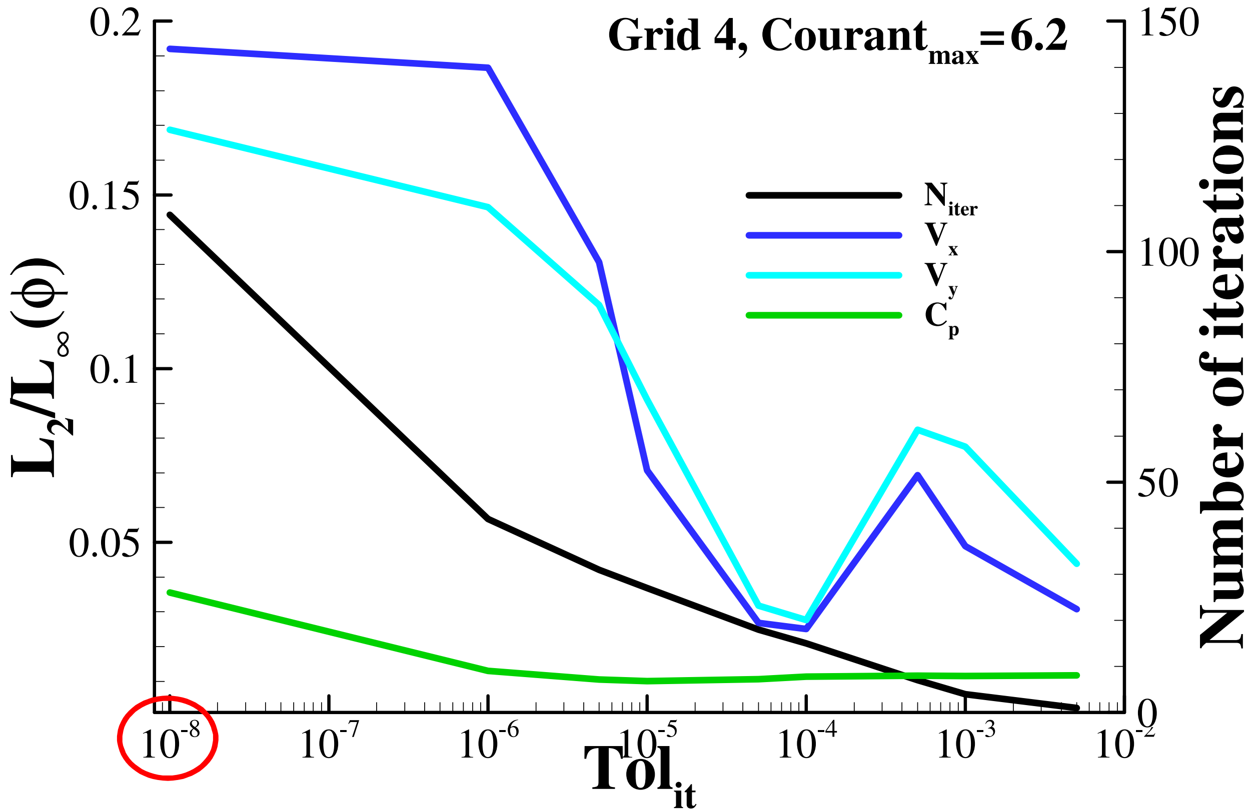
- Re=100, Grid 4



Influence of iterative convergence criteria at each time step (Tol_{it}) on the number of iterations performed (N_{iter}) and ratio between L_2 and L_∞ norms of the residuals

Submitted Results

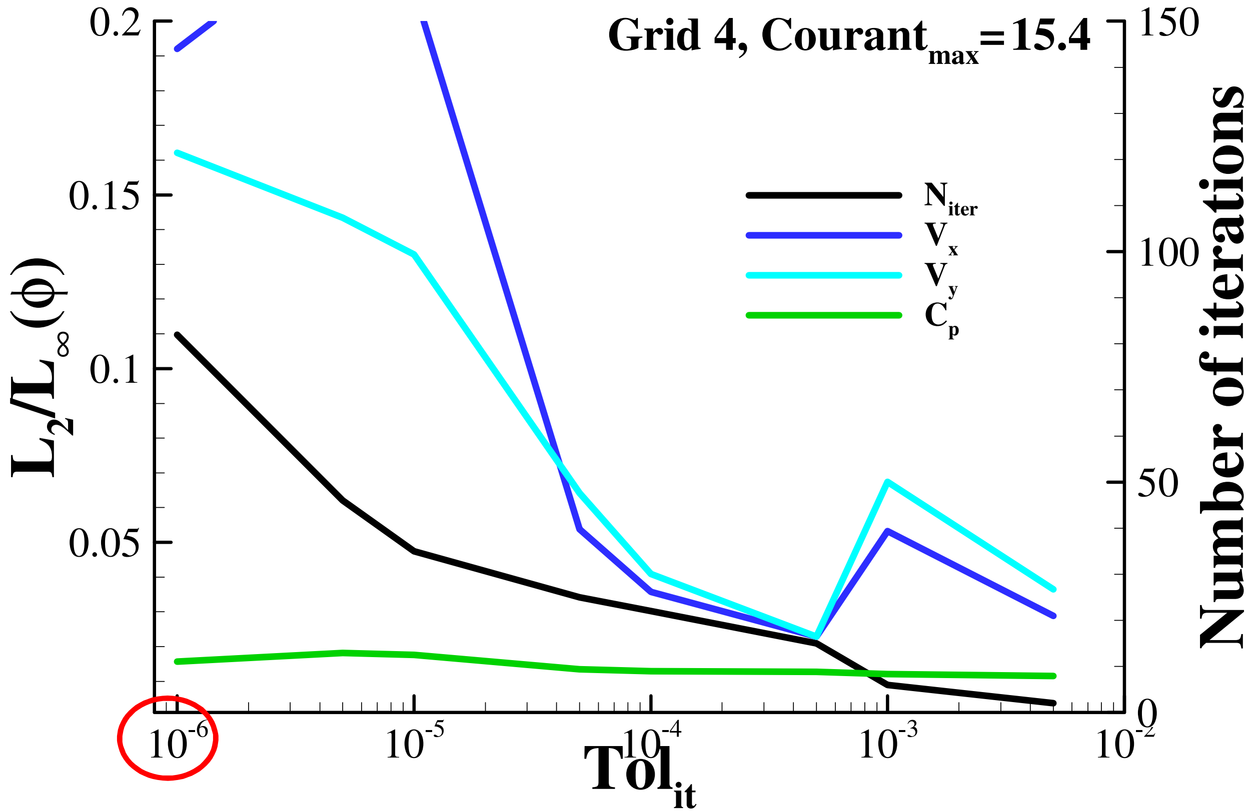
- Re=100, Grid 4



Influence of iterative convergence criteria at each time step (Tol_{it}) on the number of iterations performed (N_{iter}) and ratio between L_2 and L_∞ norms of the residuals

Submitted Results

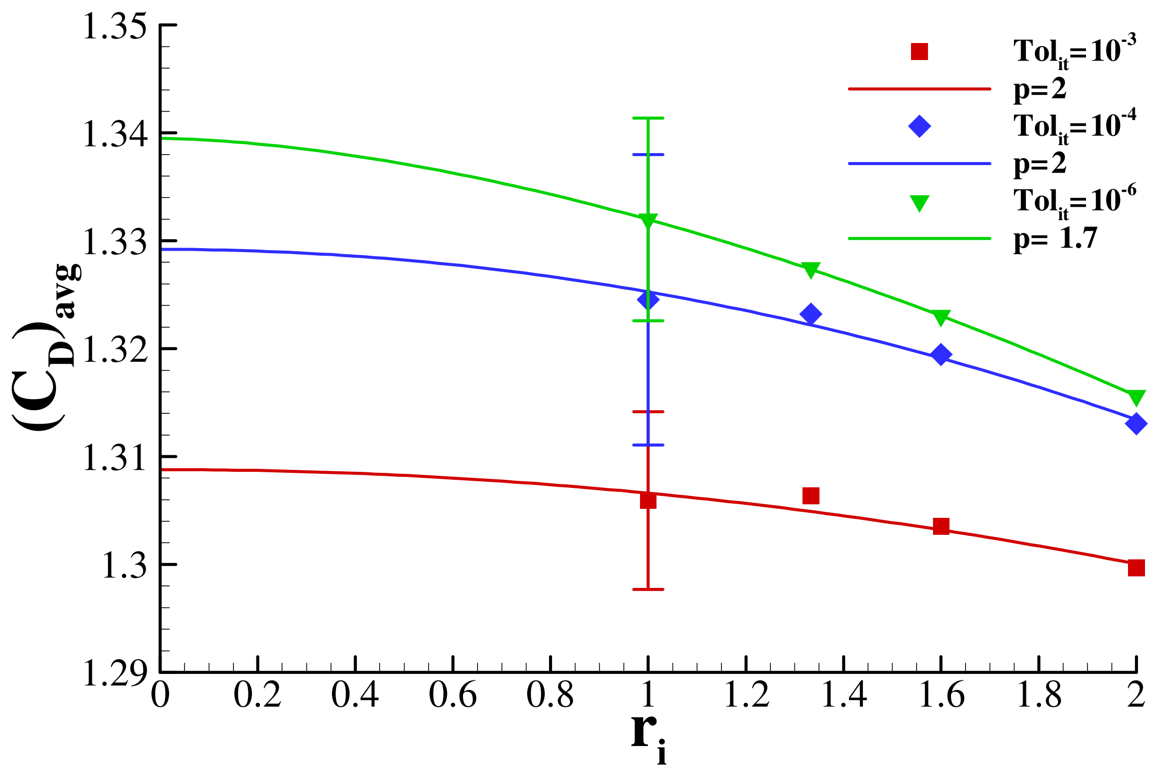
- Re=100, Grid 4



Influence of iterative convergence criteria at each time step (Tol_{it}) on the number of iterations performed (N_{iter}) and ratio between L_2 and L_∞ norms of the residuals

Submitted Results

- Re=100



- Estimation of the discretization error of the Time-averaged drag coefficient using data from three different levels of Tol_{it}.

Submitted Results

- Re=150

  - Fully-coupled solution; Linear upwind for convection; Second-order backwards for time.
    RMS of normalized residuals and "Conservation Imbalance" (CI) with a maximum of 10 iterations per time step (L_2a, L_2c).
    Grids 1 (finest) and 4 (coarsest) with Δt=0.1

  - PISO/SIMPLE; Linear upwind for convection; Second-order backwards for time.
    Maximum number of iterations (N_{it}).
    Grid 4 with maximum Courant numbers of 1, 5 and 10

Submitted Results

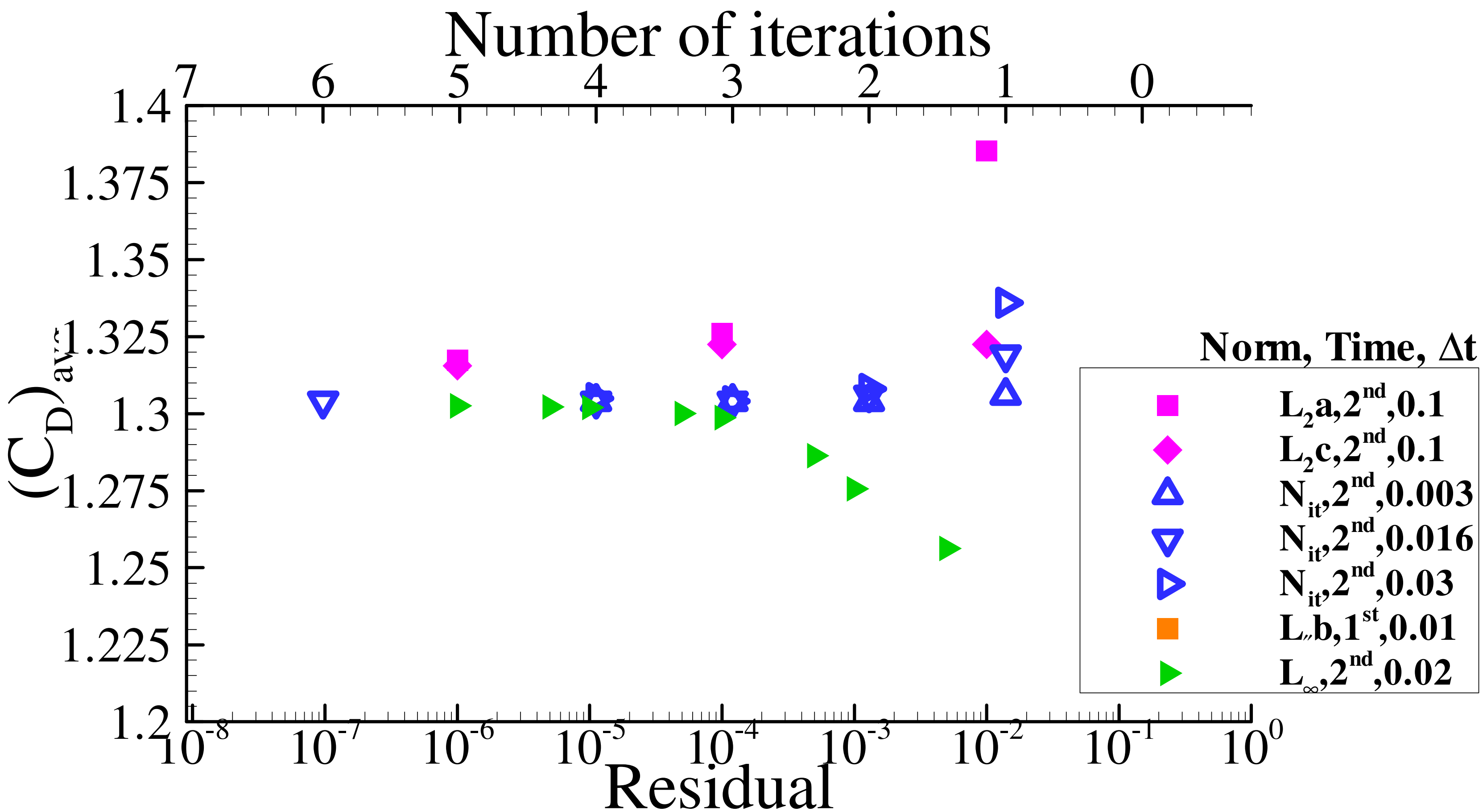
- Re=150

  - PISO; Second order upwind for convection;
    First-order backwards for time.
    Normalized absolute residual (average value) with a maximum of 100 iterations (L_2b).
    Grids 3 and 4 with Δt=0.01

  - SIMPLE; Second order upwind for convection;
    Second-order backwards for time.
    Normalized residual (maximum value, L_∞)
    Grids 1, 2, 3 and 4 with Δt=0.01 to Δt=0.02

Submitted Results

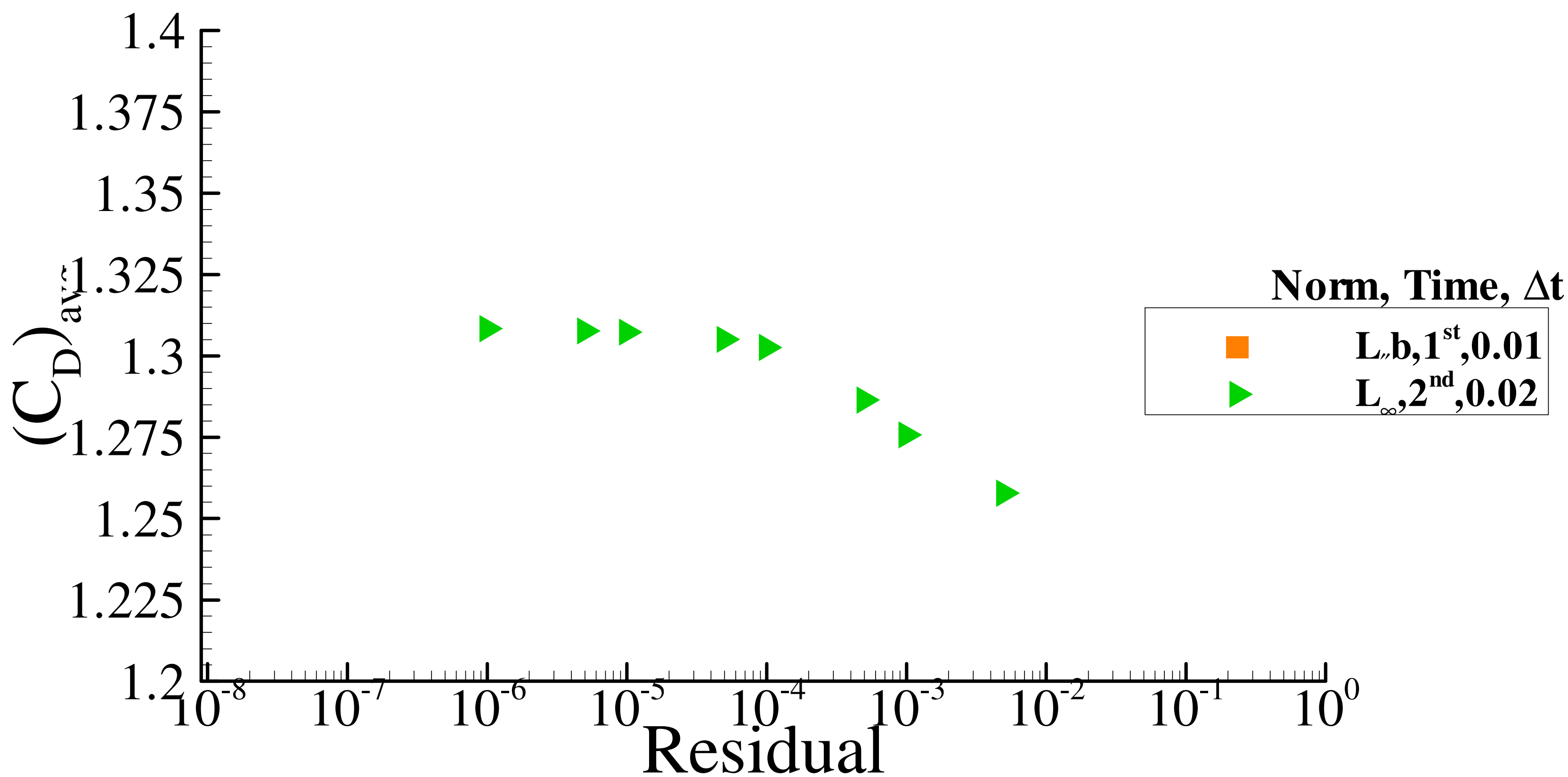
- Re=150, Grid 4



Time-averaged drag coefficient

Submitted Results

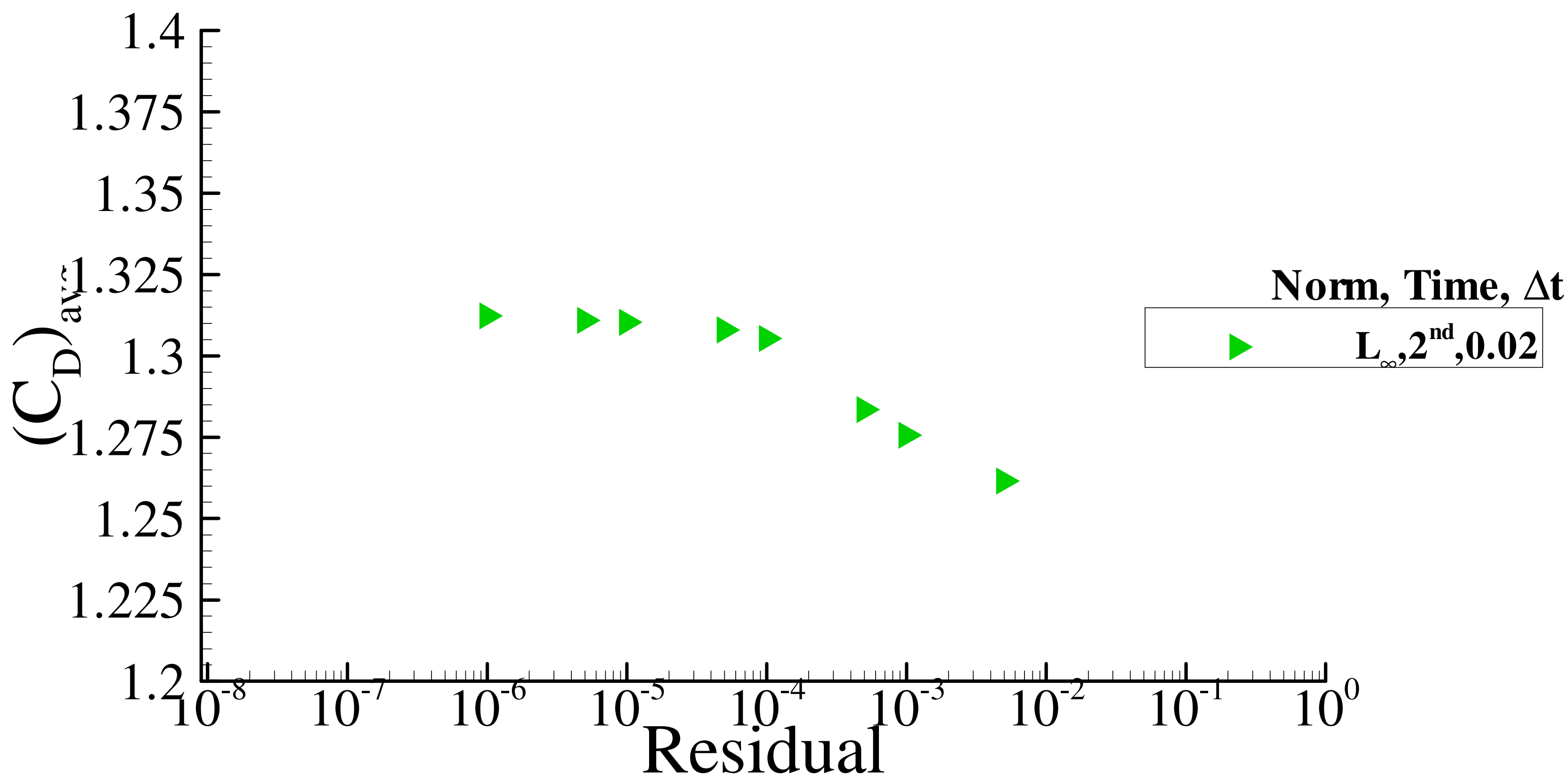
- Re=150, Grid 3



Time-averaged drag coefficient

Submitted Results

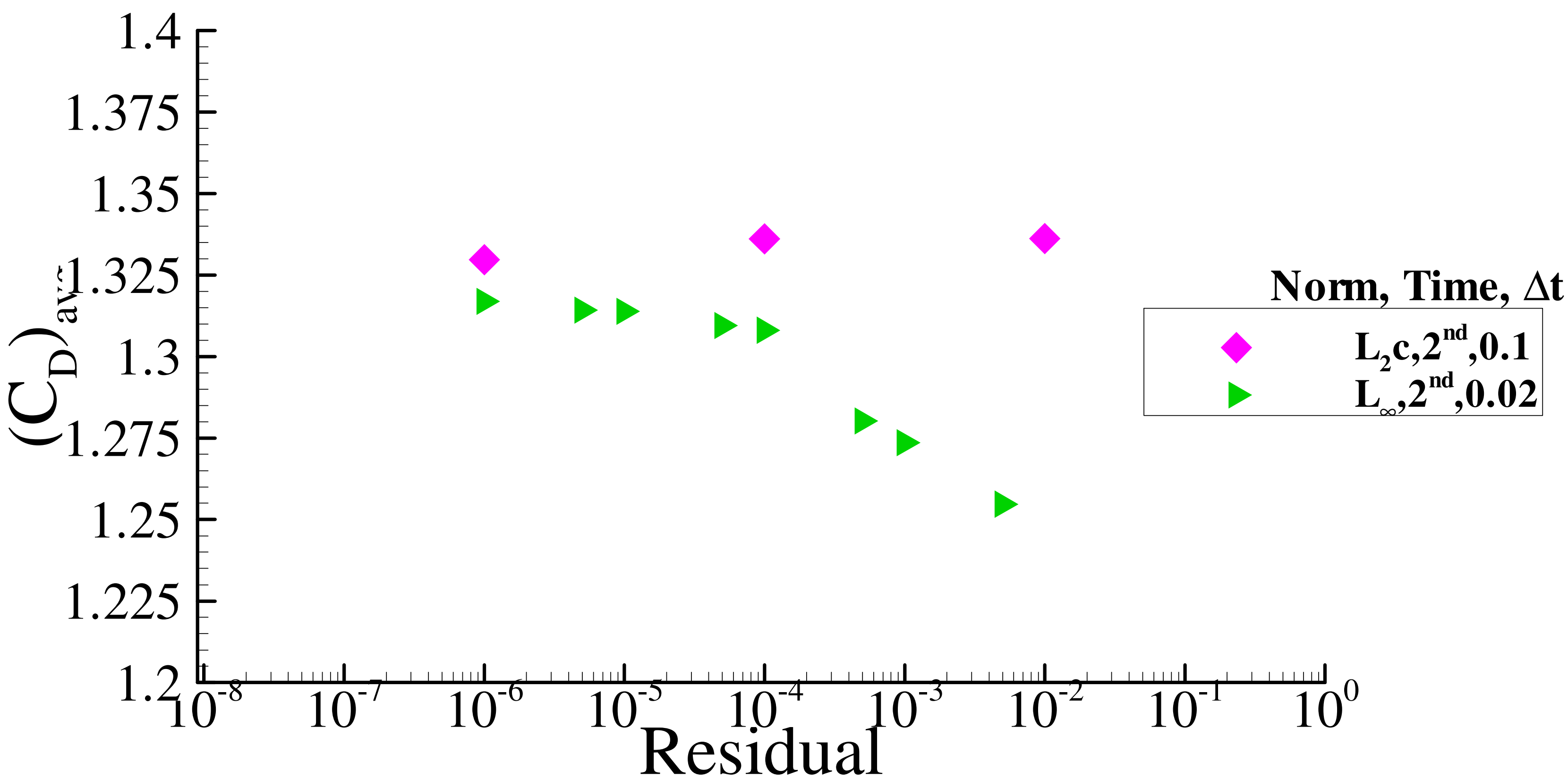
- Re=150, Grid 2



Time-averaged drag coefficient

Submitted Results

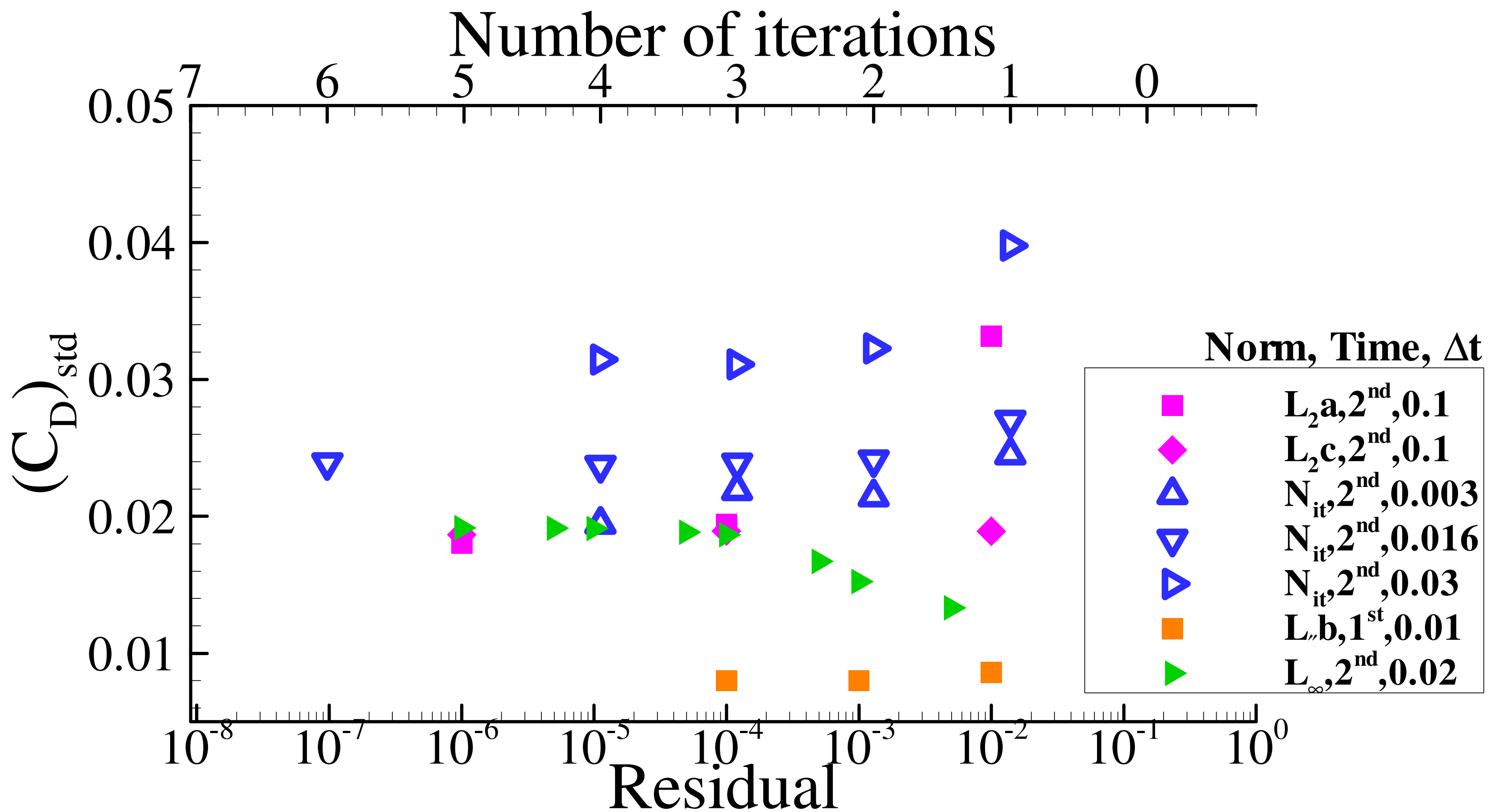
- Re=150, Grid 1



Time-averaged drag coefficient

Submitted Results

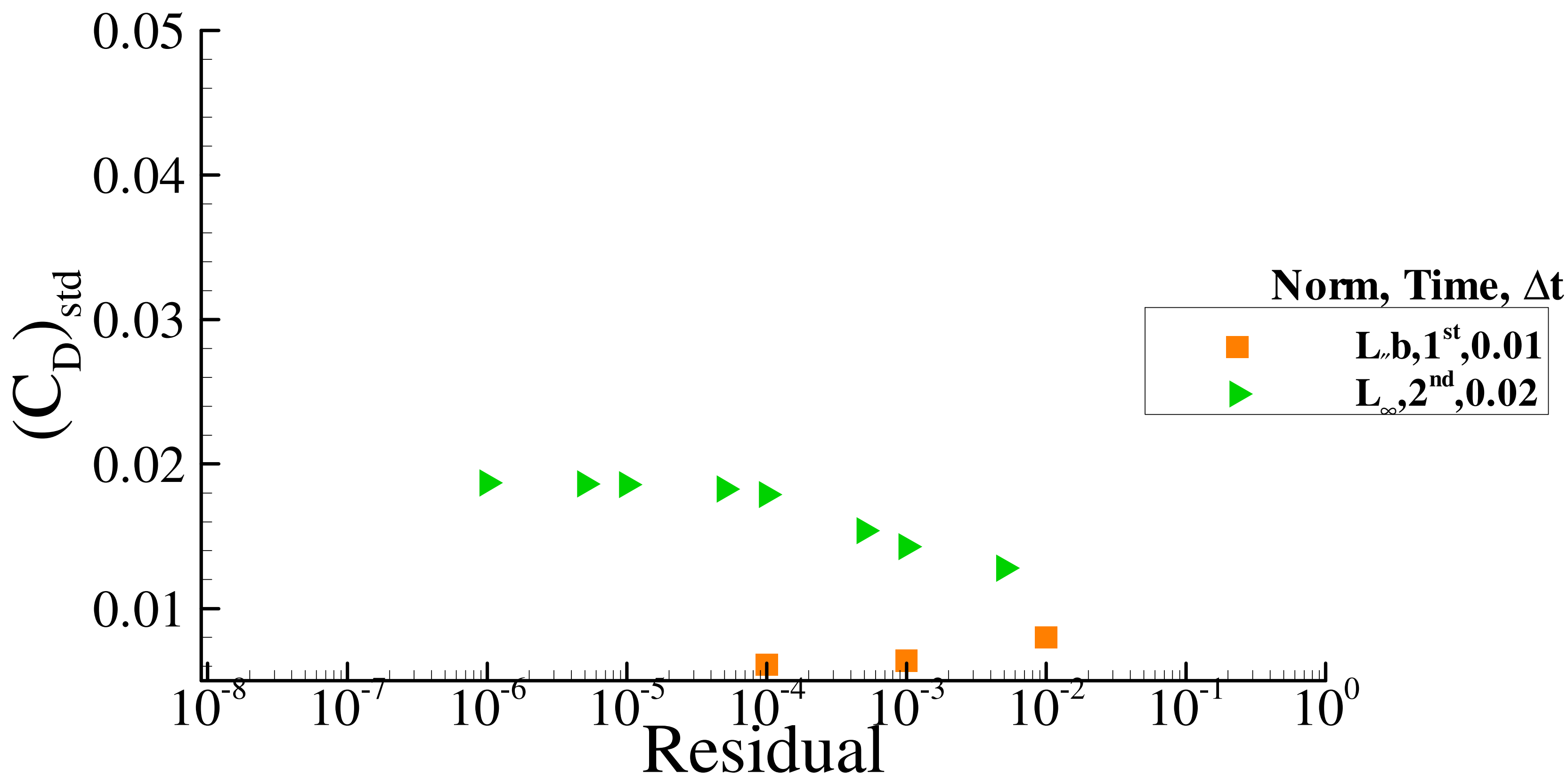
- Re=150, Grid 4



Standard deviation drag coefficient

Submitted Results

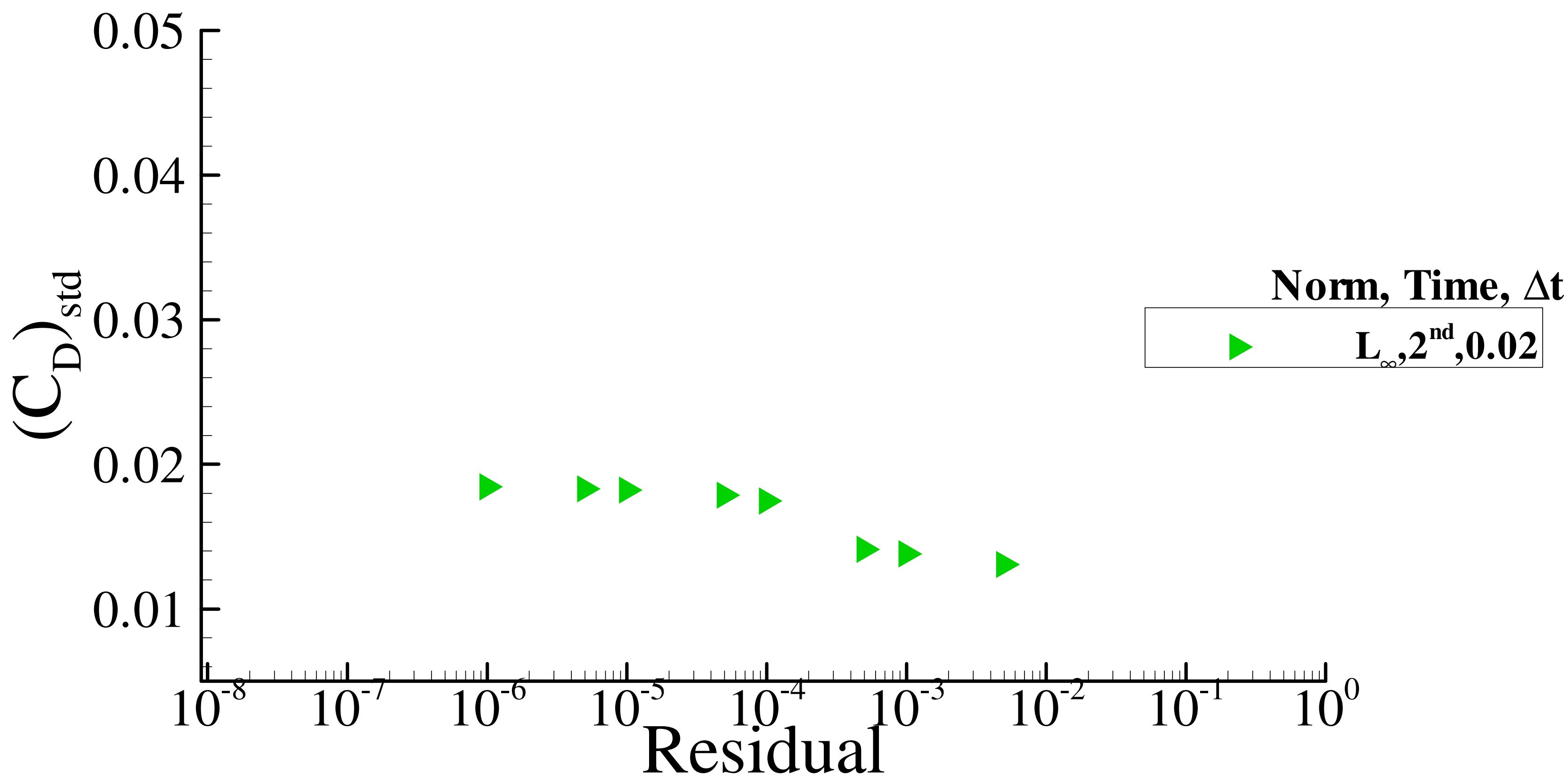
- Re=150, Grid 3



Standard deviation drag coefficient

Submitted Results

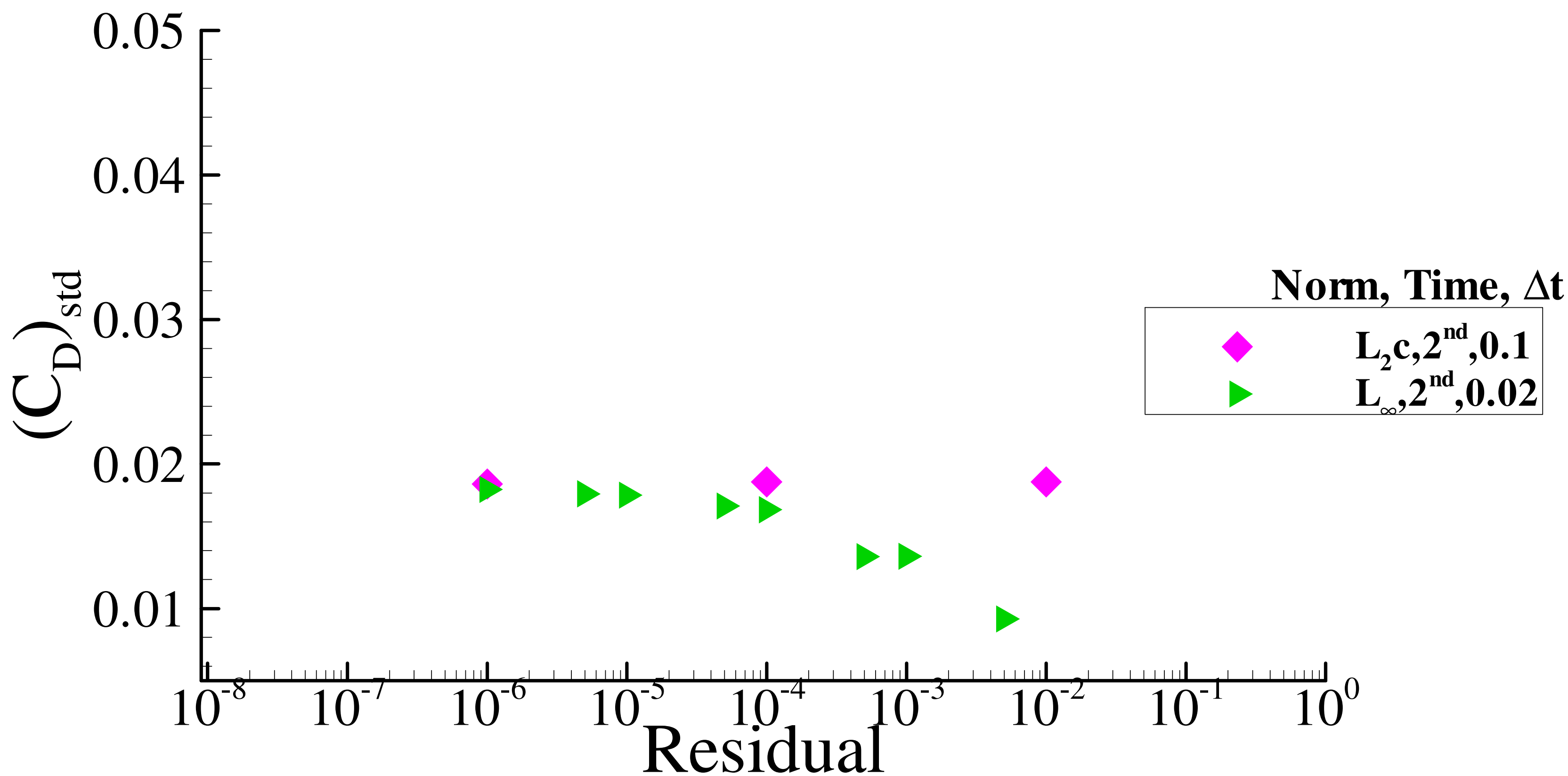
- Re=150, Grid 2



Standard deviation drag coefficient

Submitted Results

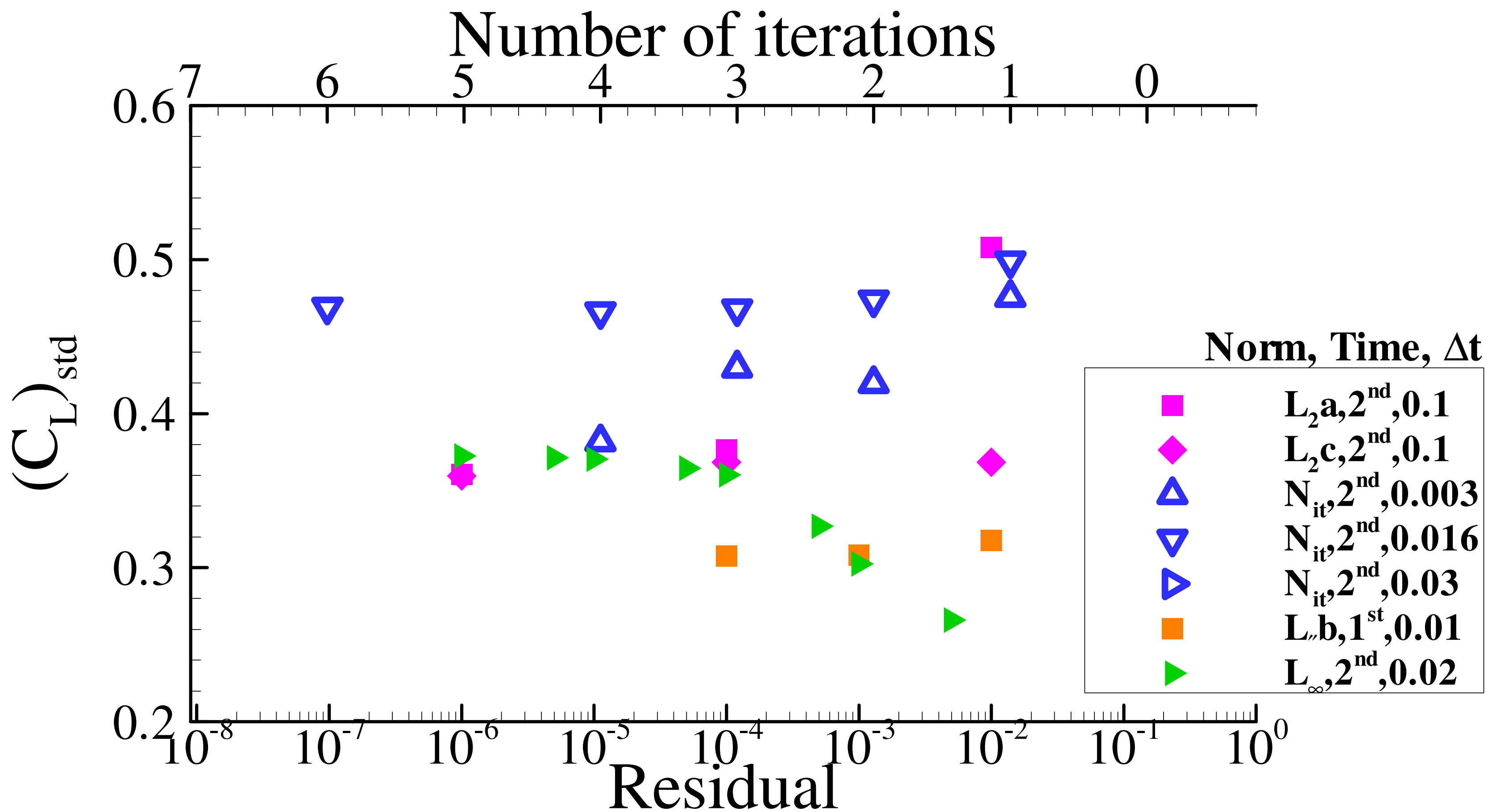
- Re=150, Grid 1



Standard deviation drag coefficient

Submitted Results

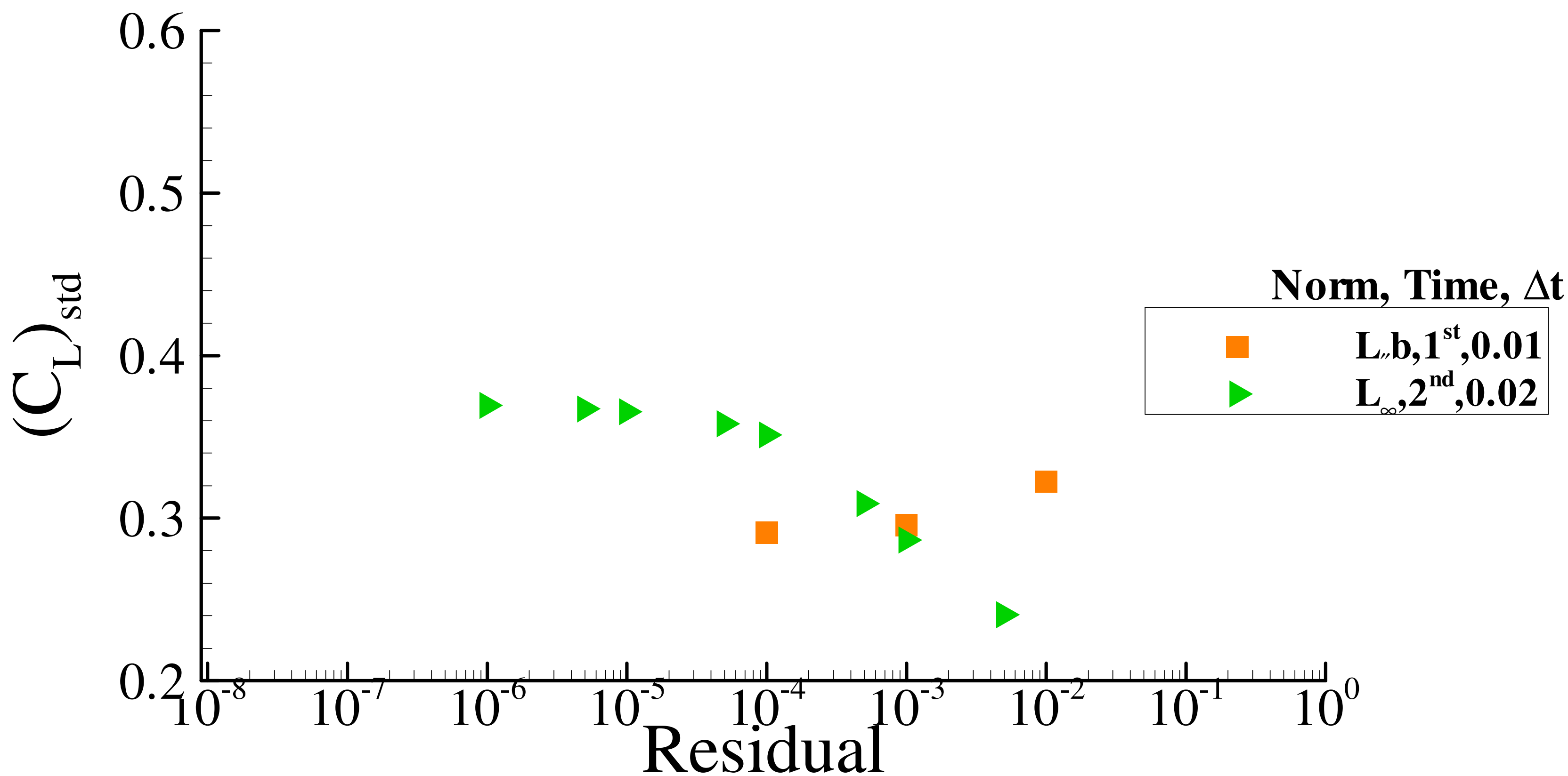
- Re=150, Grid 4



Standard deviation lift coefficient

Submitted Results

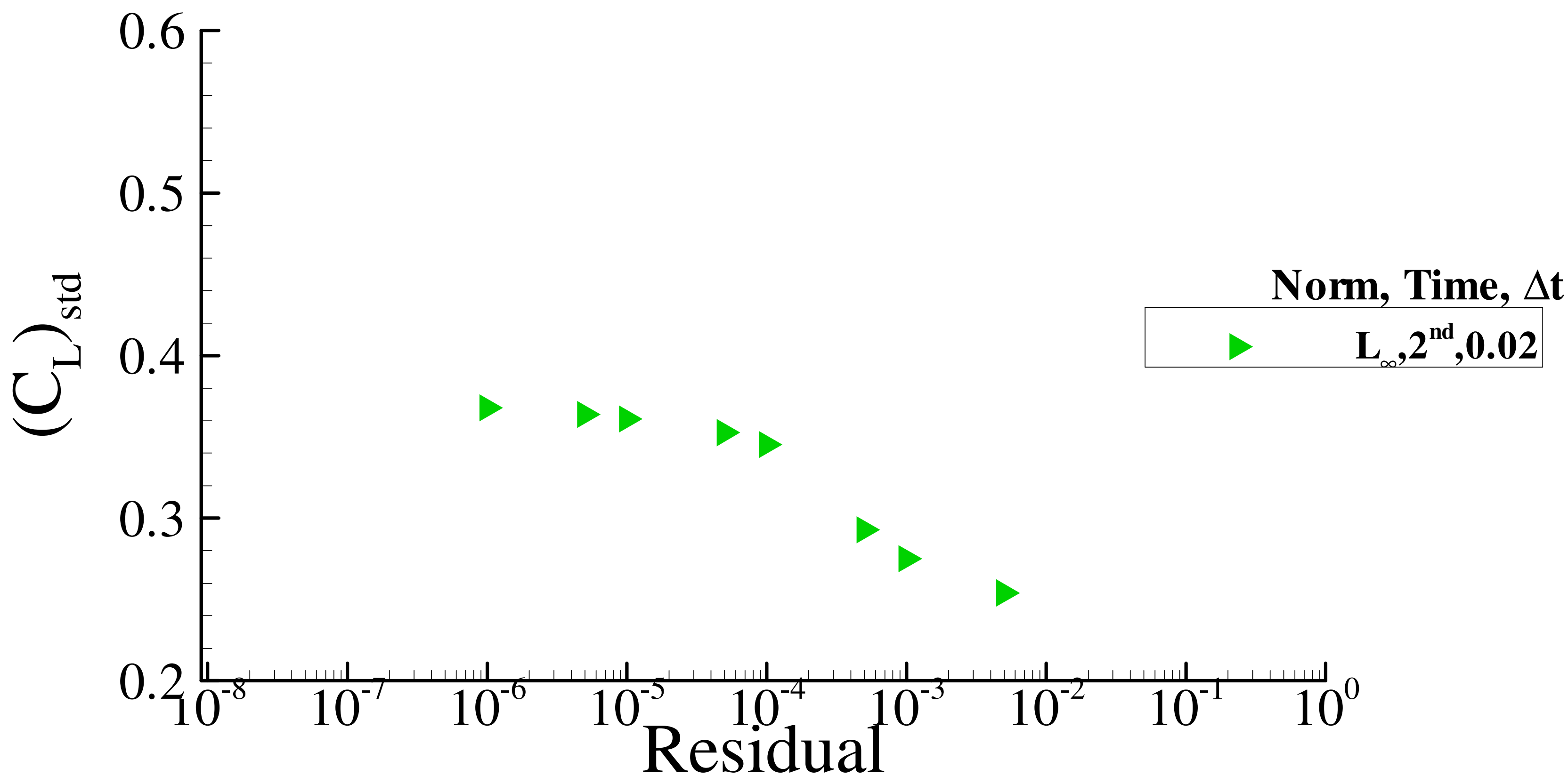
- Re=150, Grid 3



Standard deviation lift coefficient

Submitted Results

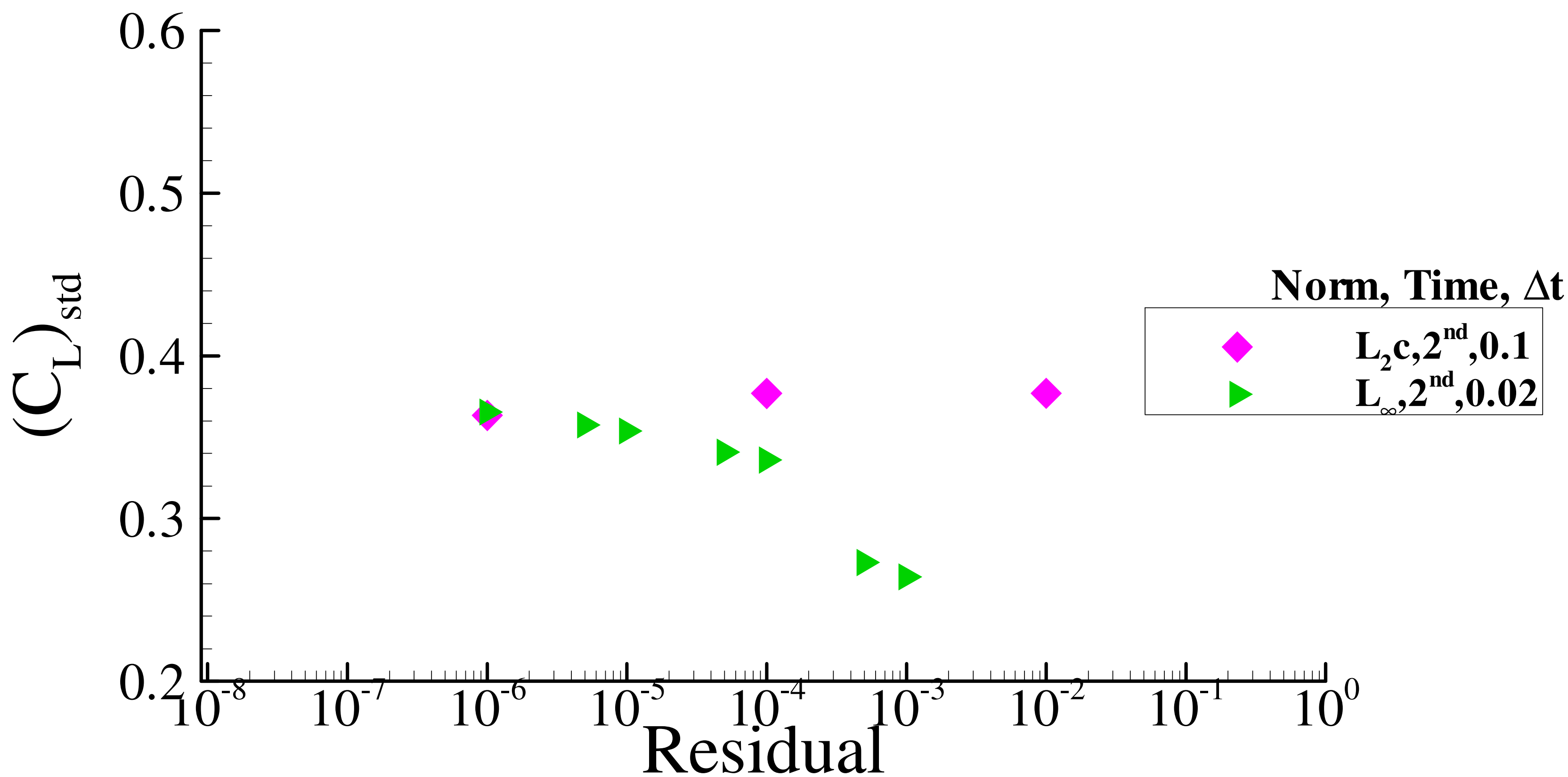
- Re=150, Grid 2



Standard deviation lift coefficient

Submitted Results

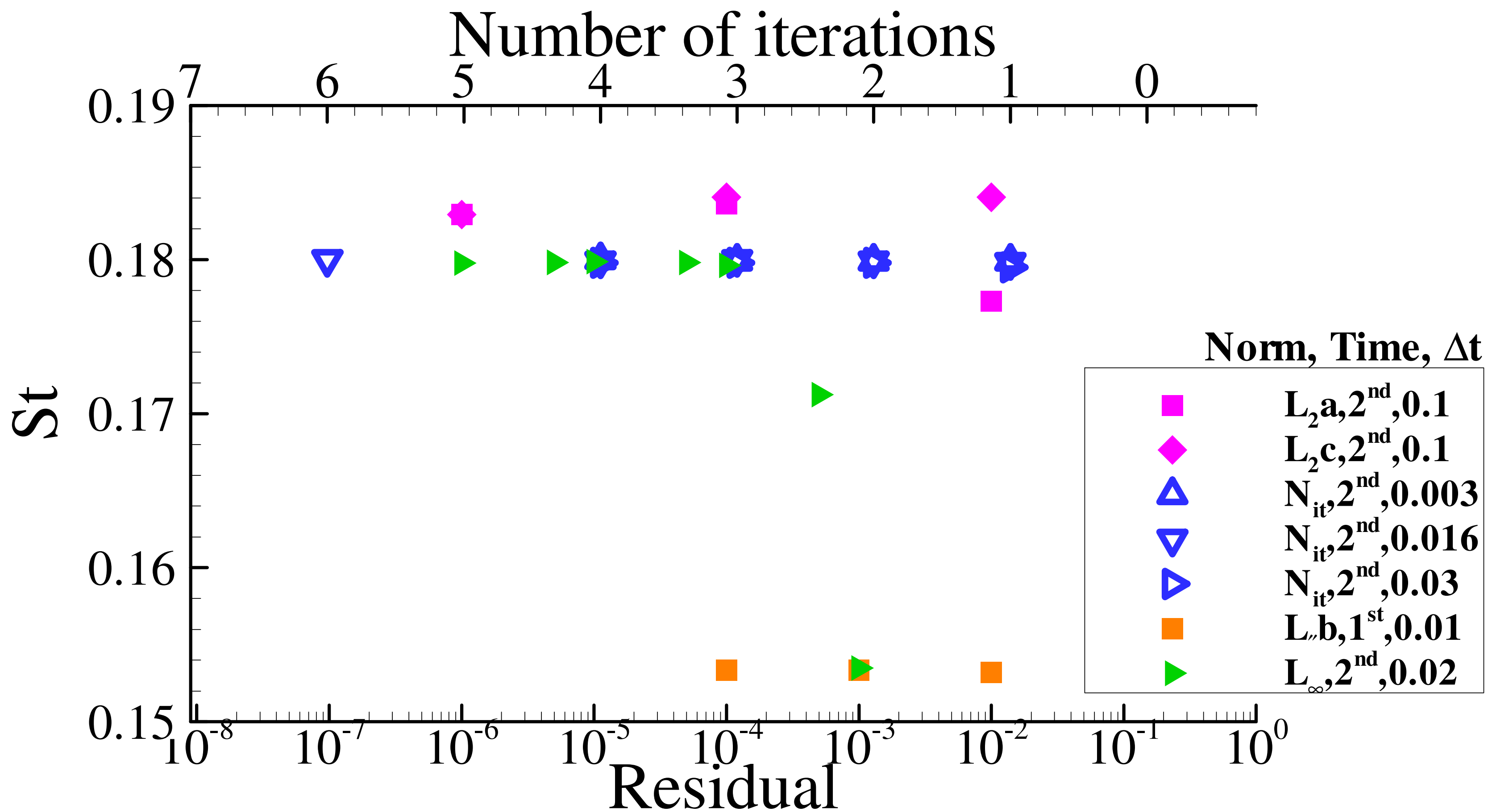
- Re=150, Grid 1



Standard deviation lift coefficient

Submitted Results

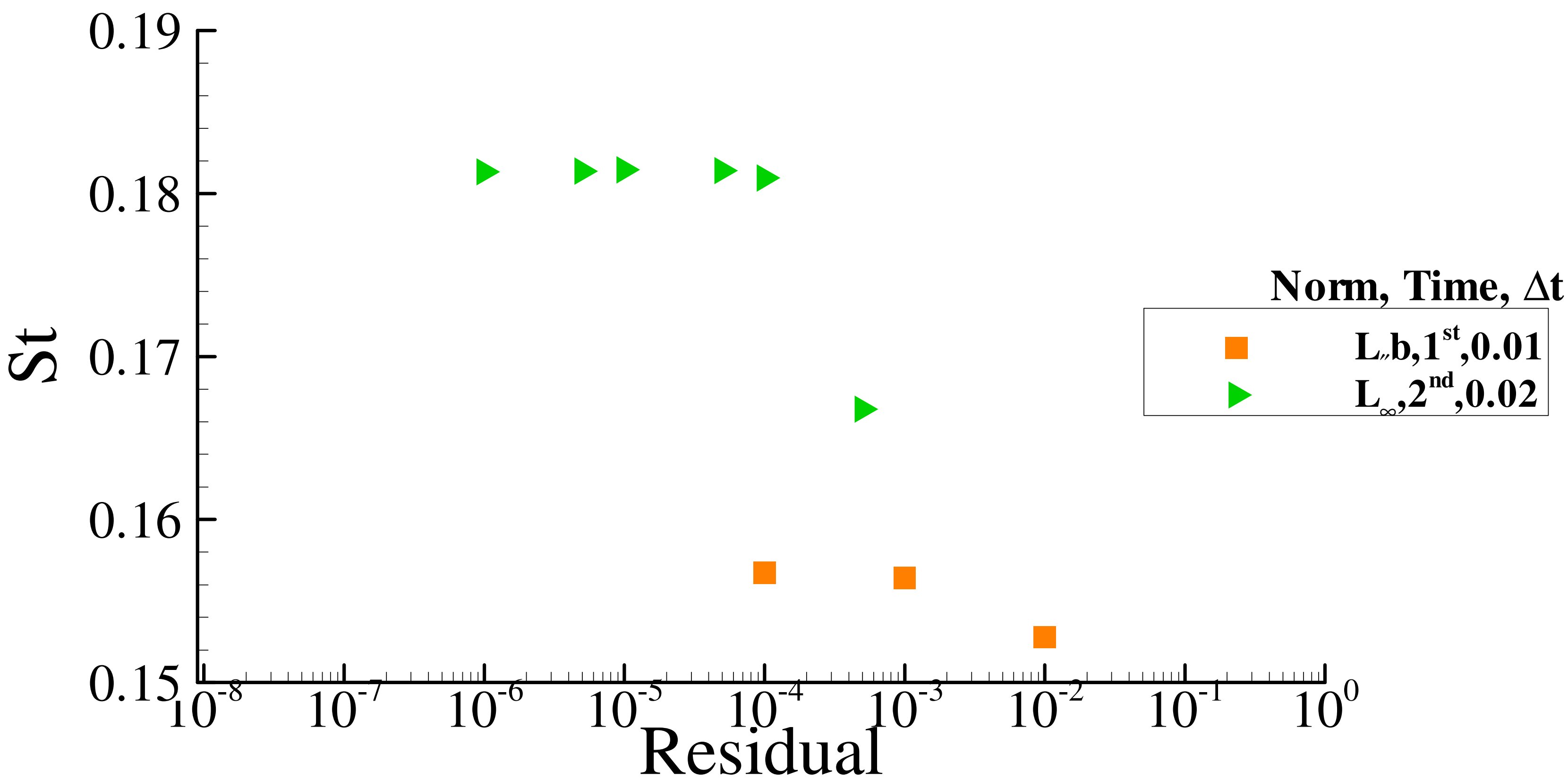
- Re=150, Grid 4



Strouhal number

Submitted Results

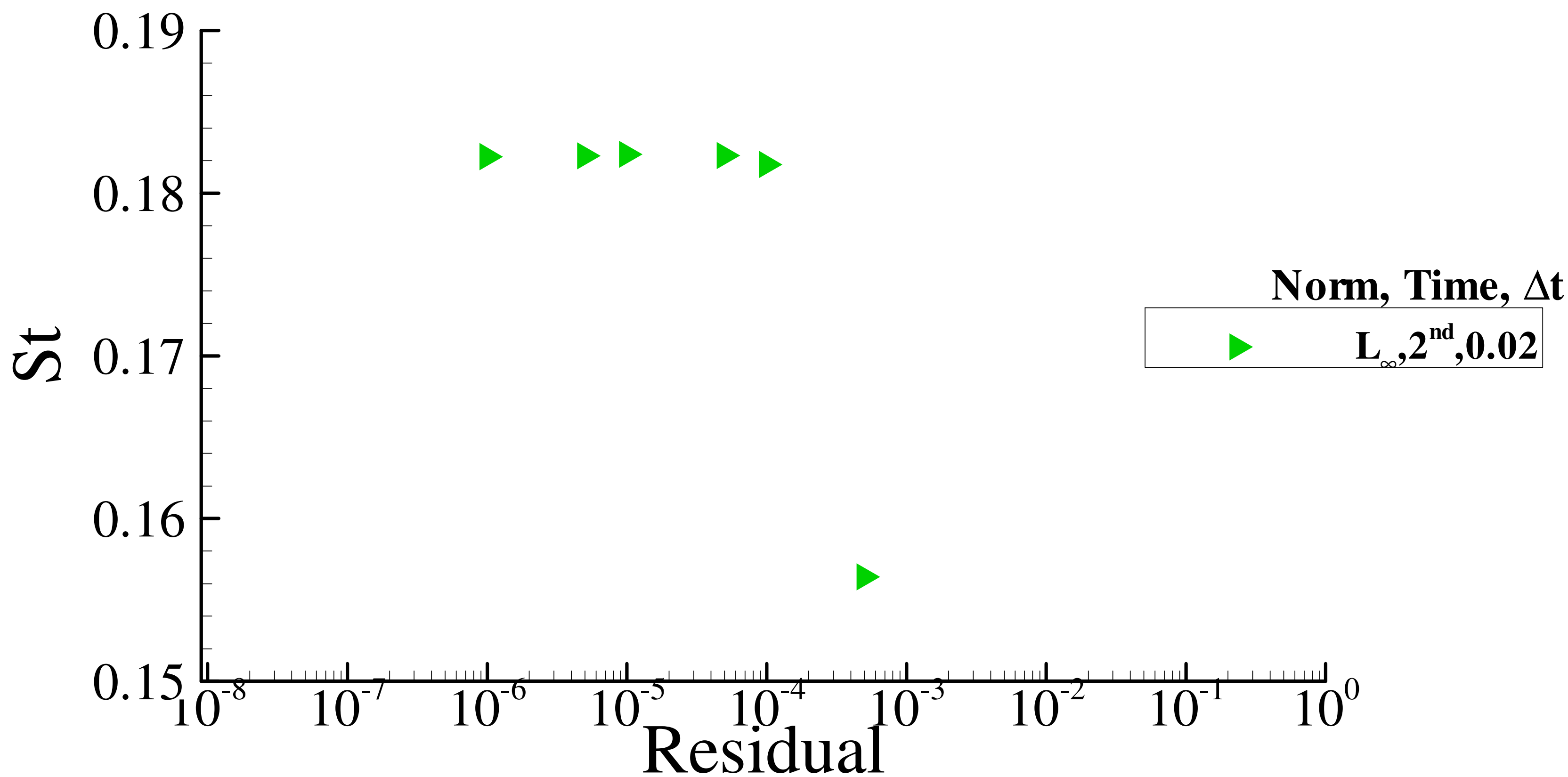
- Re=150, Grid 3



Strouhal number

Submitted Results

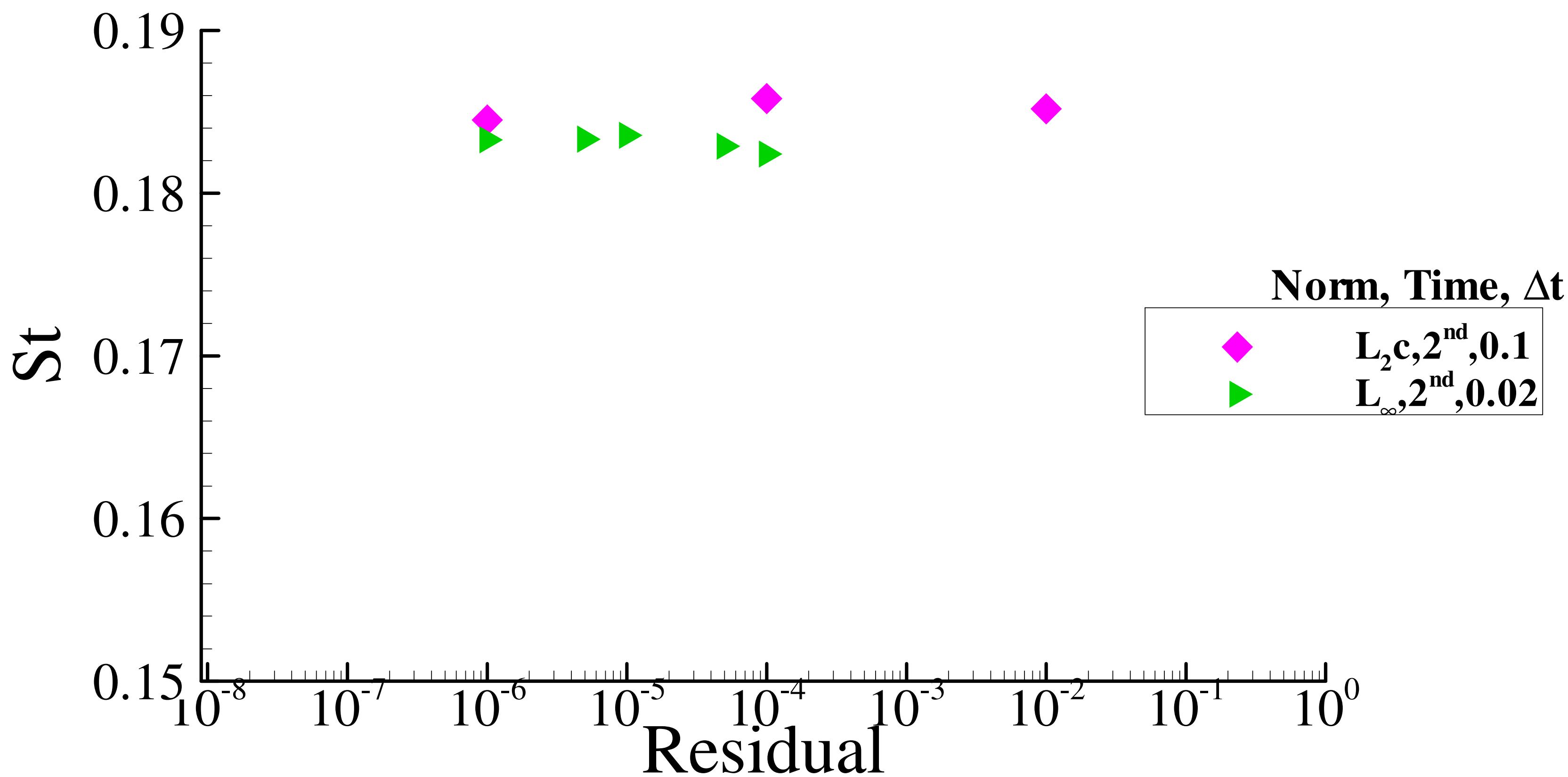
- Re=150, Grid 2



Strouhal number

Submitted Results

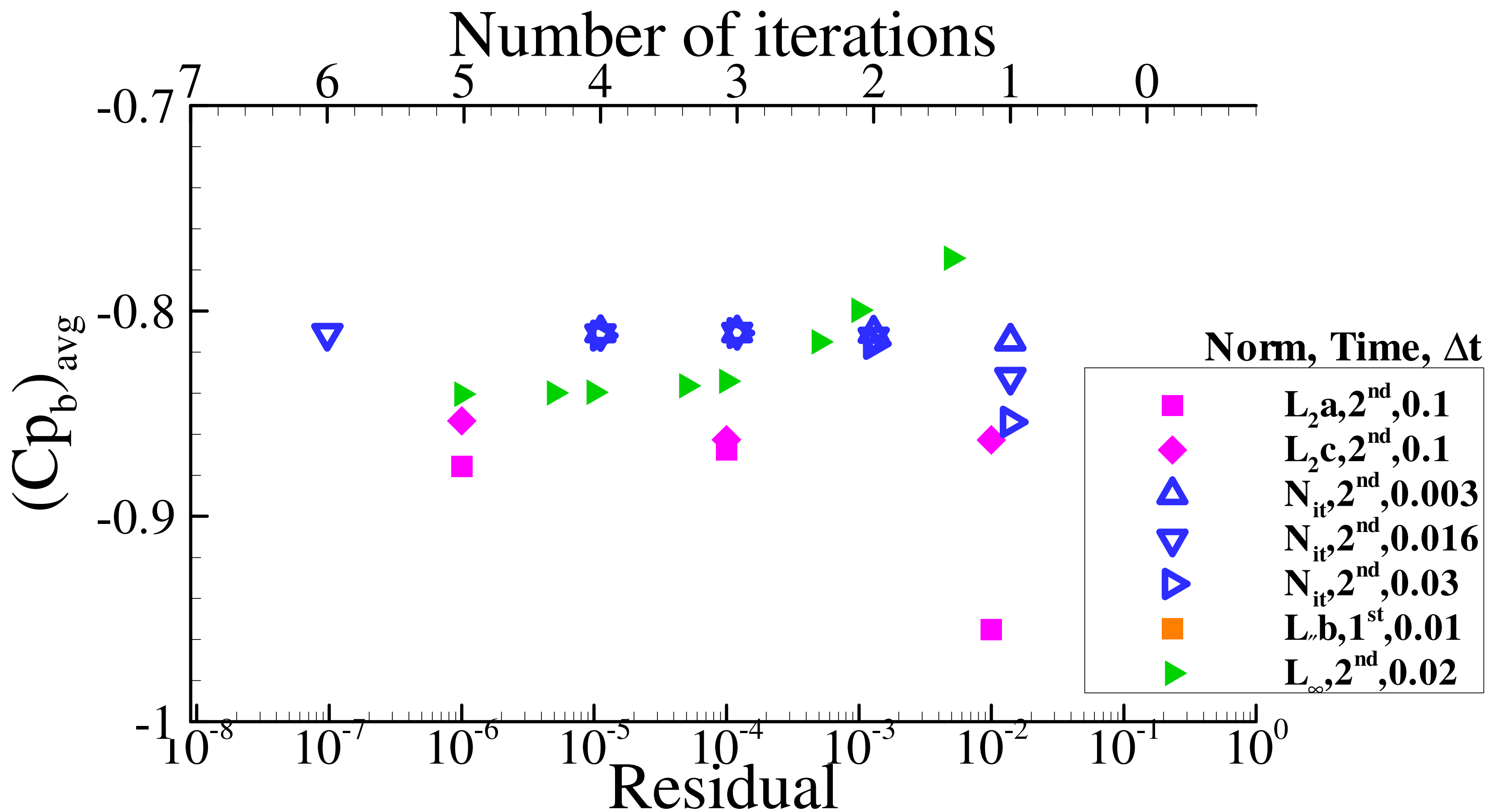
- Re=150, Grid 1



Strouhal number

Submitted Results

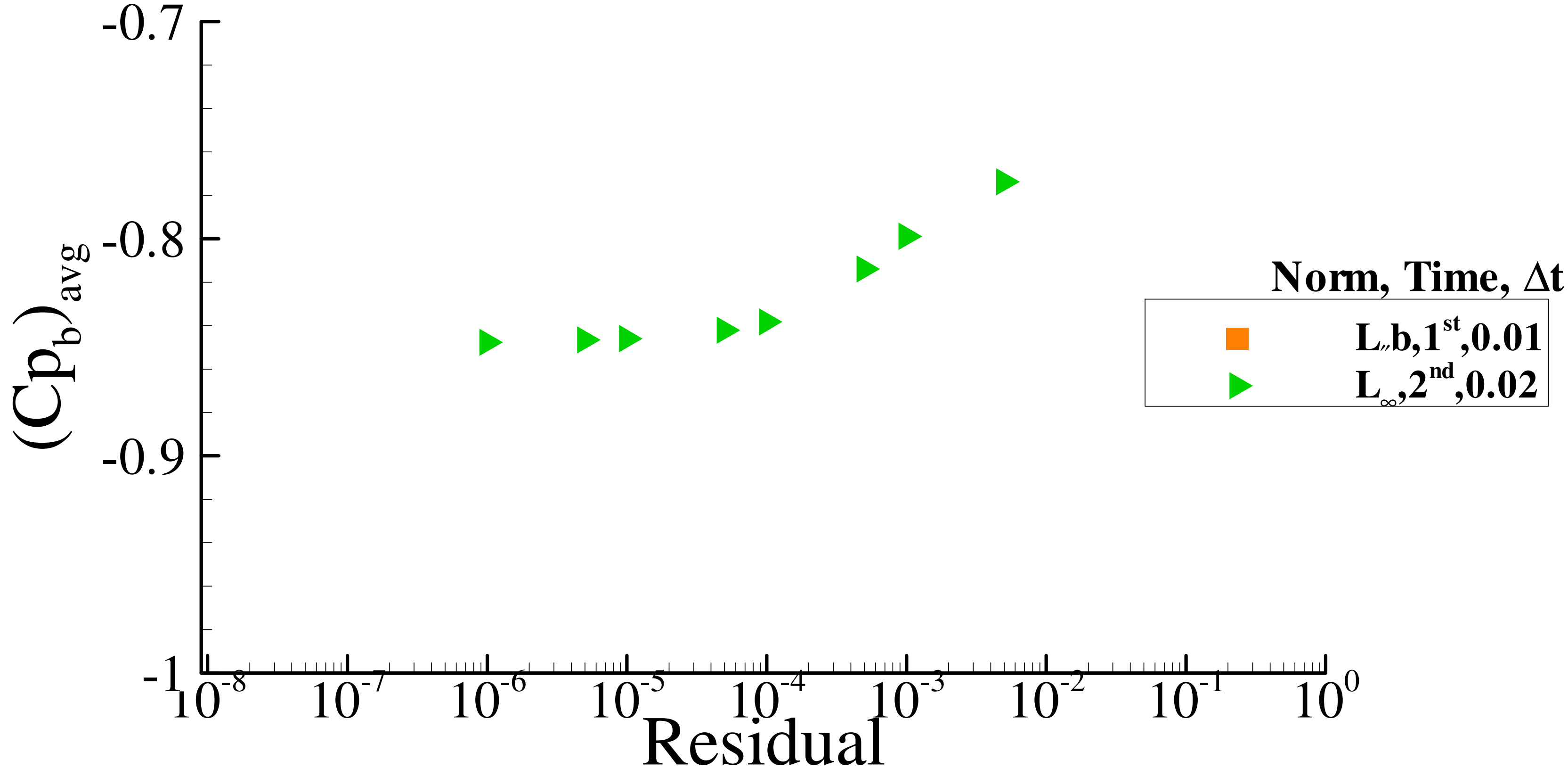
- Re=150, Grid 4



Time-averaged base pressure coefficient

Submitted Results

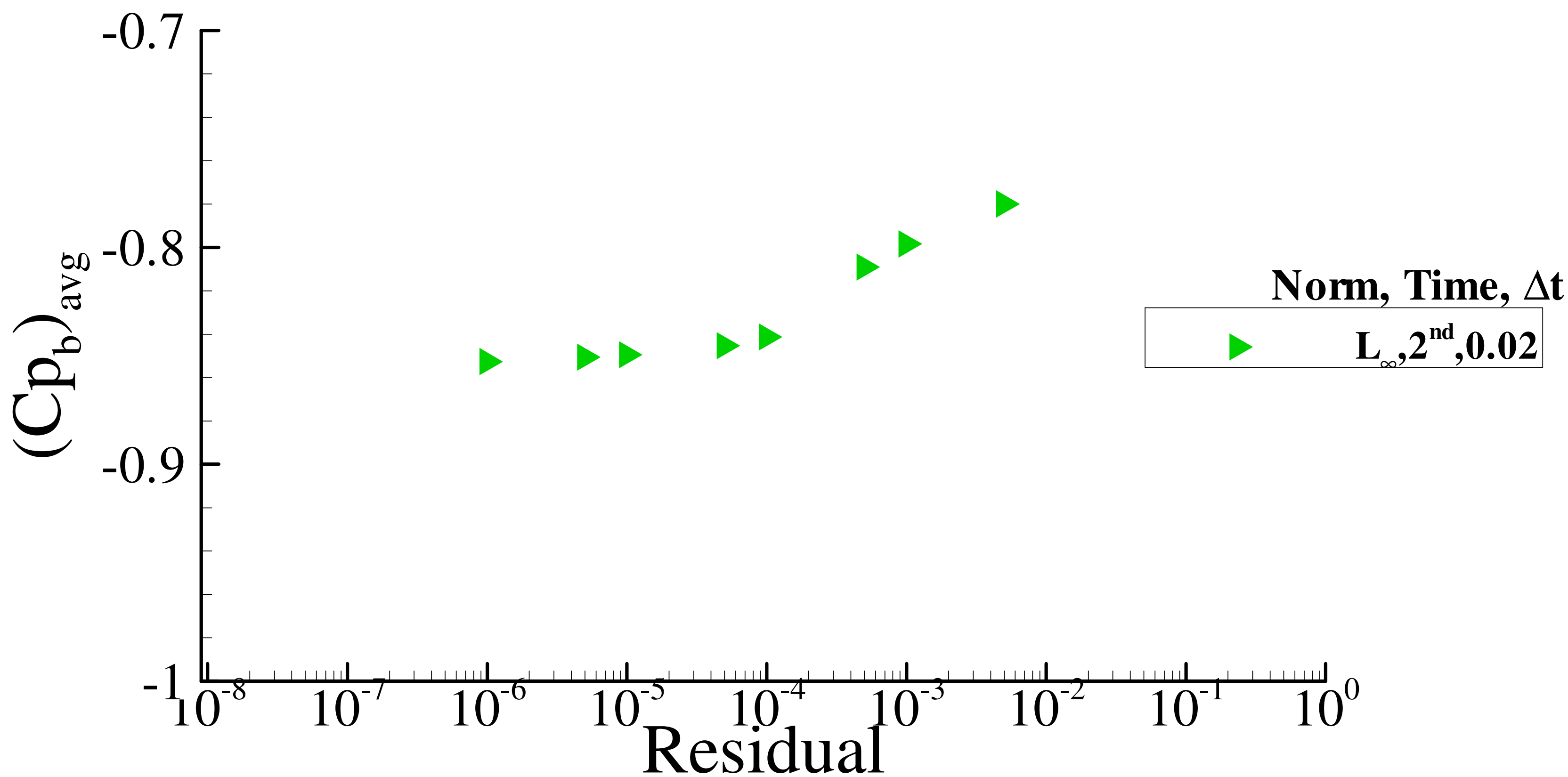
- Re=150, Grid 3



Time-averaged base pressure coefficient

Submitted Results

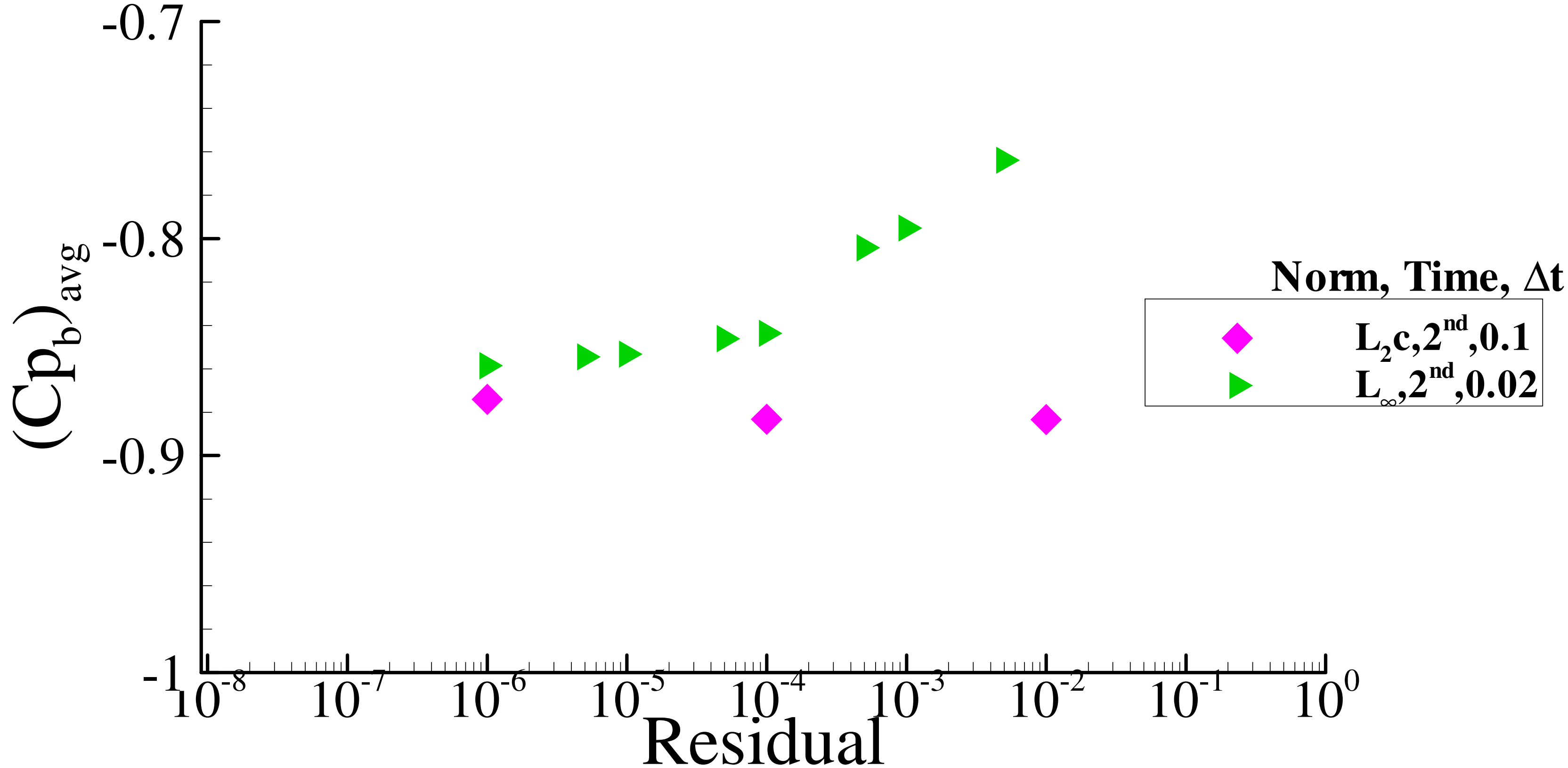
- Re=150, Grid 2



Time-averaged base pressure coefficient

Submitted Results

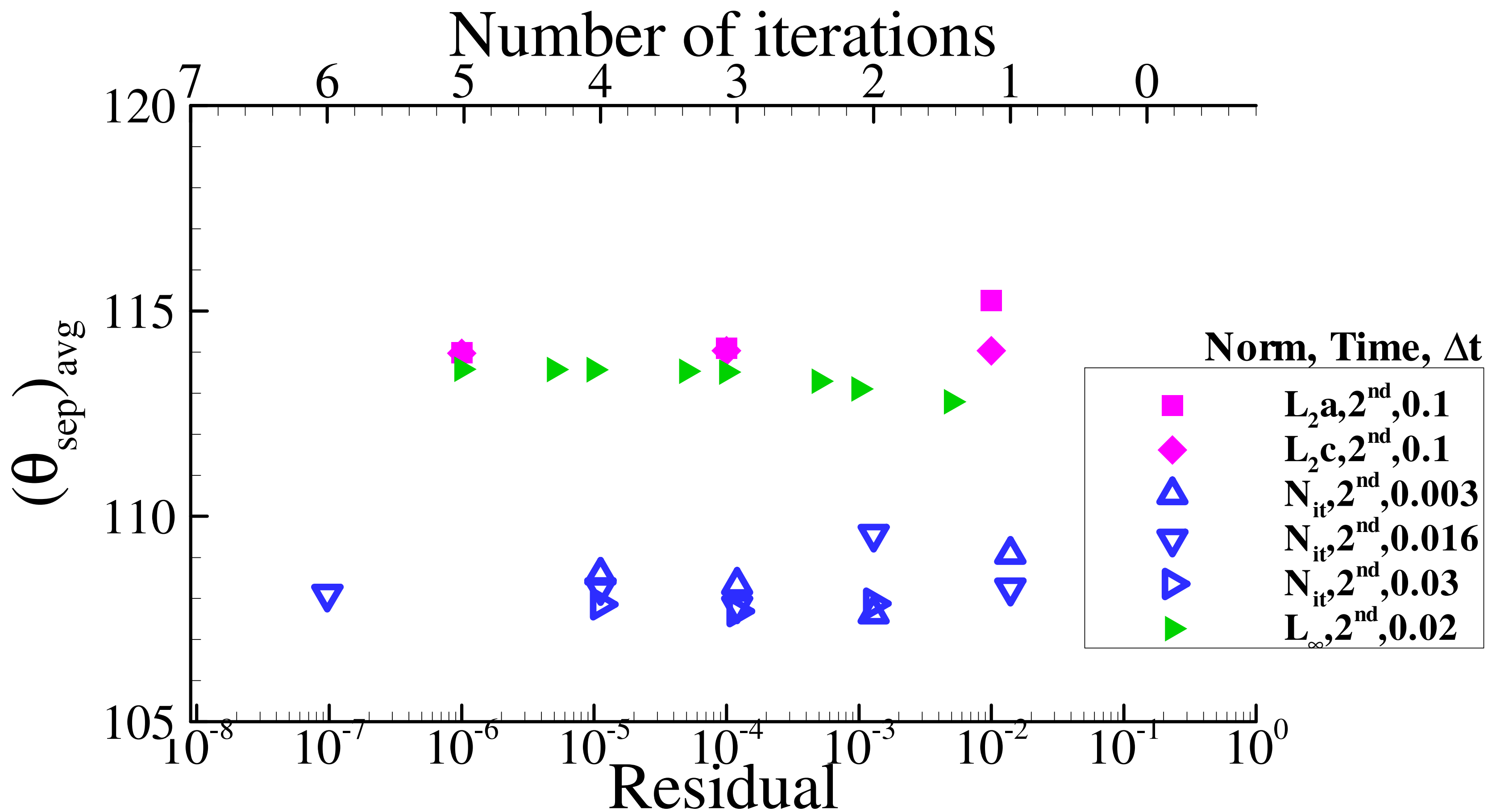
- Re=150, Grid 1



Time-averaged base pressure coefficient

Submitted Results

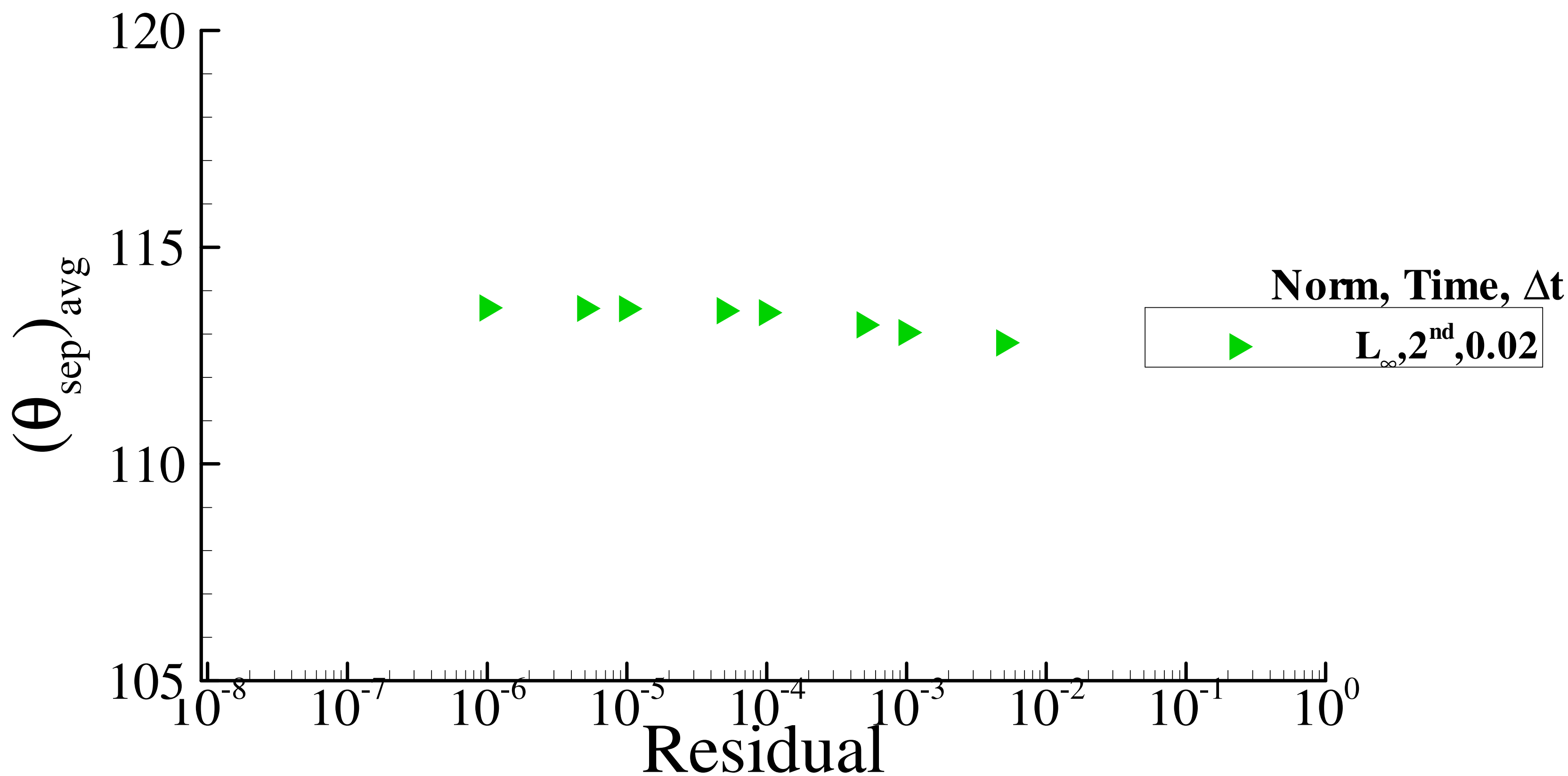
- Re=150, Grid 4



Time-averaged separation point

Submitted Results

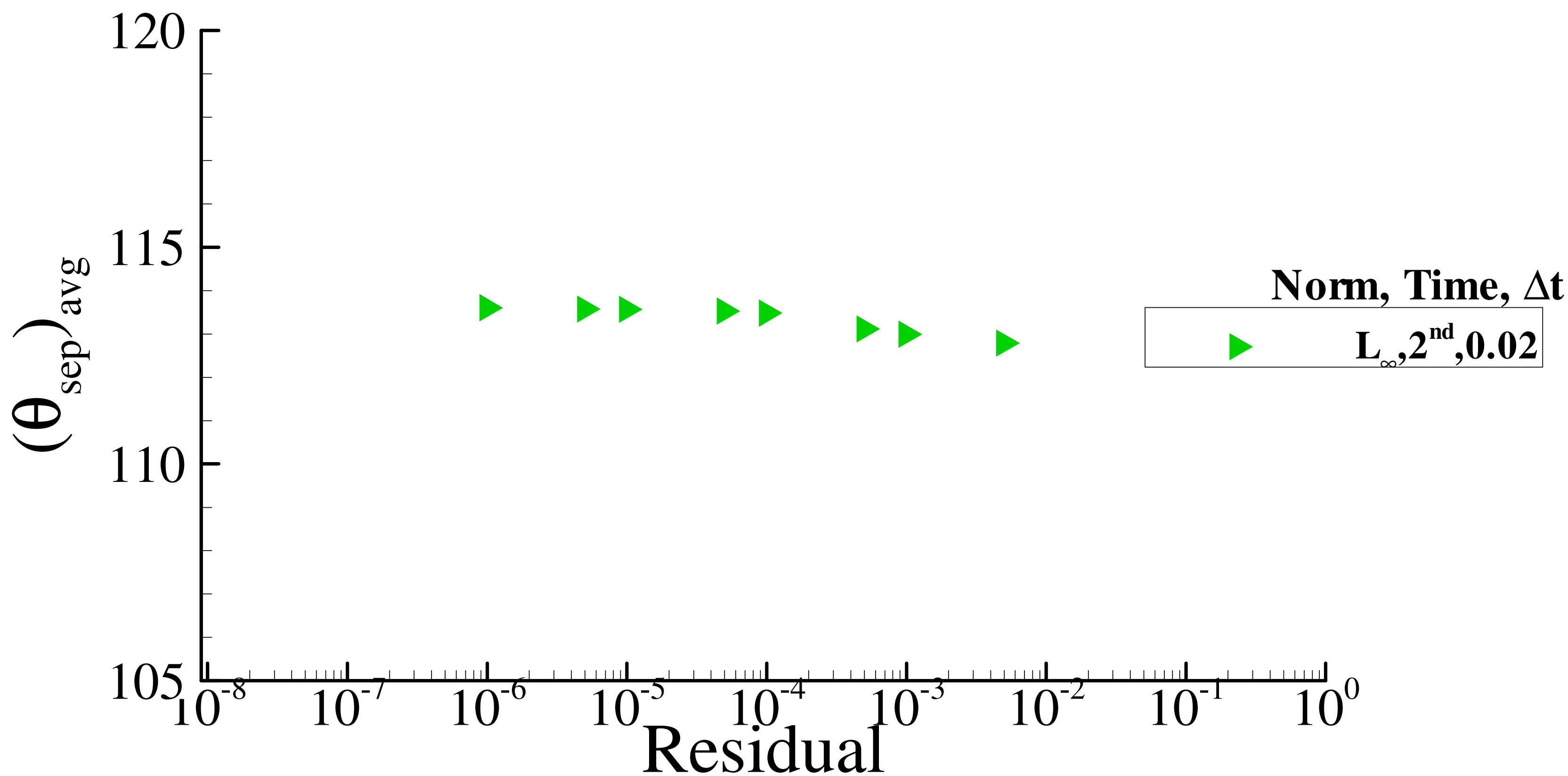
- Re=150, Grid 3



Time-averaged separation point

Submitted Results

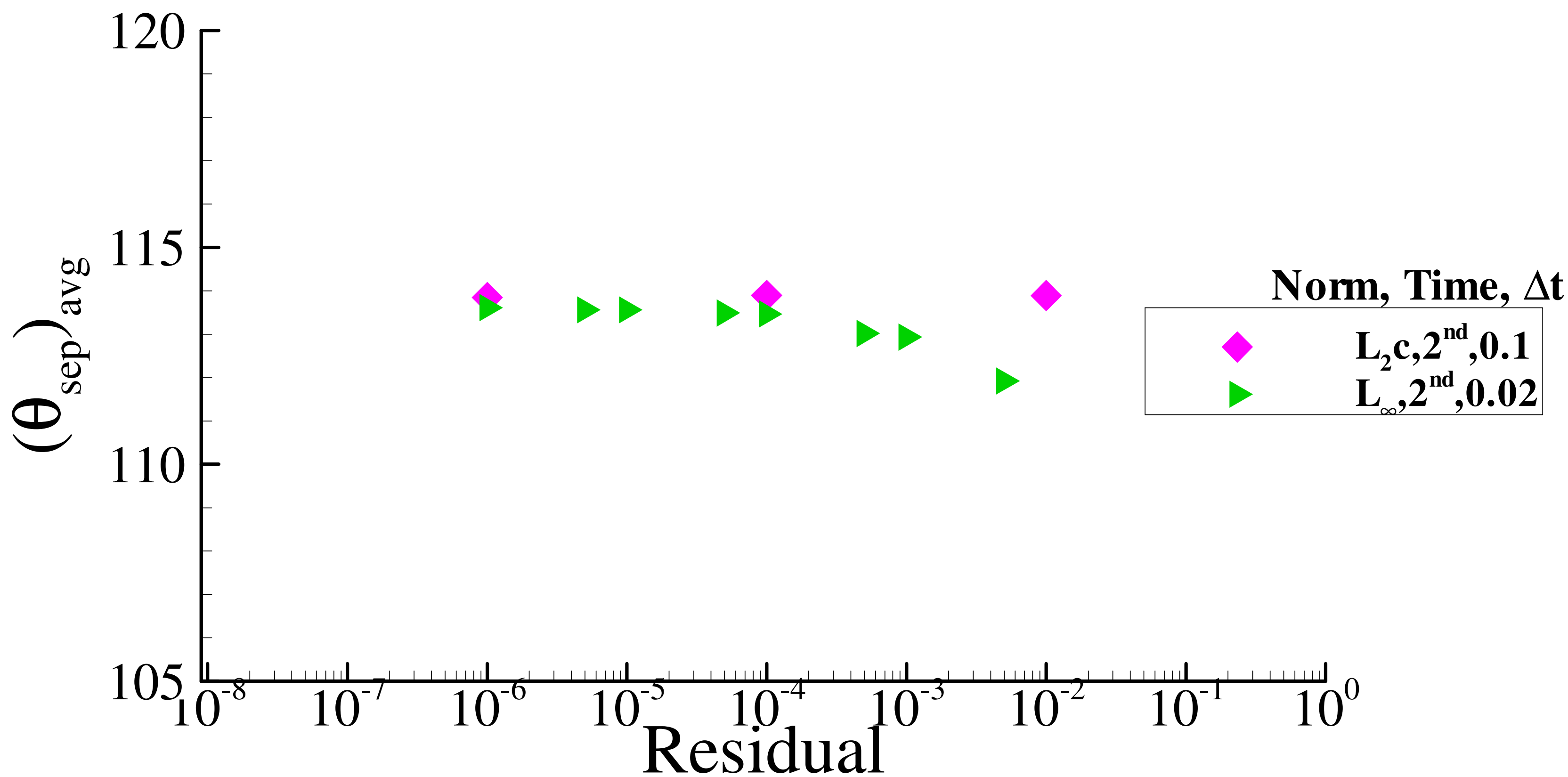
- Re=150, Grid 2



Time-averaged separation point

Submitted Results

- Re=150, Grid 1



Time-averaged separation point

Observations

- Convergence criteria applied at each time step of flow solvers that use implicit time integration may have a significant influence on the numerical accuracy of the solution.

- Obtaining statistical convergence (periodic solution) and observed orders of grid/time convergence matching the formal order of the discretization does not guarantee that the iterative error is negligible.

Observations

- Results submitted to the Workshop use several different convergence criteria at each time step, distinct accuracies of time discretization and/or various strategies to define the time step. Therefore, comparison between different data of different codes is troublesome.

- However, submitted data suggest that convergence criteria that guarantee a negligible influence of the iterative error depend on the grid refinement, time step (Courant number) and accuracy of the time integration technique.

Future Work

- A second edition of the Workshop will be proposed for the V&V Symposium of 2018. Test case (and grids) remain identical, but simulations will be performed only at Re=100.
- Quantities of interest remain the same and the number of levels of the iterative convergence criteria at each time step should be preferably larger or equal than 3, discarding conditions that lead to solutions without vortex shedding or with an unreasonable value of the Strouhal number.
- Three different time steps (or maximum Courant numbers) will be prescribed.

Future Work

- Participants will be requested to report the following information:

  - Average and maximum values of the residuals at each time step;

  - Average and maximum number of iterations performed at each time step;

  - Procedure adopted to normalize the residuals;

  - Number of cycles used to obtain the quantities of interest and maximum changes obtained in these cycles.

Acknowledgement

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