Oral presentation | Numerical methods

Numerical methods-IV

Wed. Jul 17, 2024 2:00 PM - 4:00 PM Room A

[8-A-03] On the Convolutional Immersed Boundary Method for Suppression of Spurious Force Oscillations

*Pao-Hsiung Chiu[1] (1. IHPC, Agency for Science, Technology and Research, Singapore)

Keywords: Direct forcing immersed boundary method, Spurious force oscillations, Convolutional kernel, Incompressible Navier-Stokes equation

On the Convolutional Immersed boundary method for suppression of Spurious Force Oscillations

Pao-Hsiung Chiu*
Corresponding author: chiuph@ihpc.a-star.edu.sg
* IHPC, Agency for Science, Technology and Research, Singapore

1 Introduction

Due to fundamental idea of employing a fixed grid to solve time-varying geometries, the immersed boundary methods have received increasing attention as flow-structure-interaction (FSI) solver. Despite the potential in applications direct forcing immersed boundary (DFIB) method, accurately evaluate drag/lift forces of time-varying geometries by DFIB method still remains a challenge. From the previous studies, it is well known that spurious force oscillations (SFO) will appear when the geometry conservation is not fully-satisfied, which is the case in general for the DFIB method. To alleviate the SFO, you may employ the method of inclusion the mass source/sink term into continuity equation[1], employ the cut-cell method[2], or employ the continuity constrained least-squares interpolation[3]. Nevertheless, the efficiency of the abovementioned approaches drops dramatically when we employ small time step size, due to the fact that the SFO for these methods is proportional to $O(\Delta x^2)$ and $O(1/\Delta t)$, where Δx and Δt are spatial and temporal step size. The smaller time step size tends to increase the SFO in practice for these methods, result in spoil the simulated results when solving the FSI problems.
In this study, we propose the convolutional DFIB (cDFIB) method for solving the fluid flow with time-varying geometries [4]. The fundamental idea is to employ of convolutional kernel for the direct forcing source terms, to better model the forcing terms to mimic the solid bodies. The SFO produced by the current approach is then reduced and changed to be proportional to $O(\Delta x)$ and $O(\Delta t)$, so that the accurate solutions can be obtained for both moderate and small time step size. The proposed method robustly provides accurate solutions in small time step size where conventional DFIB will produce unphysical spikes into drag/lift forces, while still maintaining good accuracy in moderate time step size.

2 Problem Statement

To demonstrate the efficiency and accuracy of cDFIB method, we first investigated Seo and Mittal oscillation cylinder problem in 2D. From Figure 1-2, it clearly revealed that current method can efficiently alleviate the SFO, and most importantly the temporal convergence rate is proportional $O(\Delta t)$. The 3D Seo and Mittal oscillation cylinder and the flow past sphere problem also been investigated to further demonstrate the applicability of cDFIB method for 3D problems. From Figure 3-6, it again shows the proposed cDFIB method alleviate the SFO efficiently for moving boundary problem with the $O(\Delta x)$ and $O(\Delta t)$ converge rate, while the drag coefficient can be accurately predicted [1,5].

To further validate the applicability and efficacy of the present cDFIB method for more real-world complex geometries, we also applied the current framework to the modelling of incompressible flow past fish-like wavy foil problem at $Re = 5000$, similar to other previous work [6]. From Figure 7, it again reveals that the current cDFIB method can efficiently alleviate the SFO, while the vortex features behind the foil can be accurately resolved and the drag and lift coefficients have good agreements with the reference in [6], as shown in Figure 8-9.

References

[1] J. Kim, D. Kim and H. Choi. An Immersed-Boundary Finite-Volume Method for Simulations of Flow in Complex Geometries. J. Comput. Phys. (2001) 171:132-150

[2] J.H. Seo and R. Mittal. A sharp-interface immersed boundary method with improved mass **conservation** and reduced spurious pressure oscillations. J. Comput. Phys. (2011) 230:7347-7363.

[3] D.M.C. Martins, D.M.S. Albuquerque and J.C.F. Pereira. Continuity constrained least-squares interpolation for SFO suppression in immersed boundary methods. J. Comput. Phys. (2017) 336:608-626

[4] P.H Chiu. cDFIB: A convolutional direct forcing immersed boundary method for solving incompressible flows with time-varying geometries J. Comput. Phys. (2023) 487, 112178

[5] T. A. Johnson and V. C. Patel. Flow past a sphere up to a Reynolds number of 300. J. Fluid Mech. (1999) 378:19-70.

[6] G.-J. Dong, X.-Y. Lu. Characteristics of flow over traveling wavy foils in a side-by-side arrangement, Phys. Fluids 19 (2007) 057107.

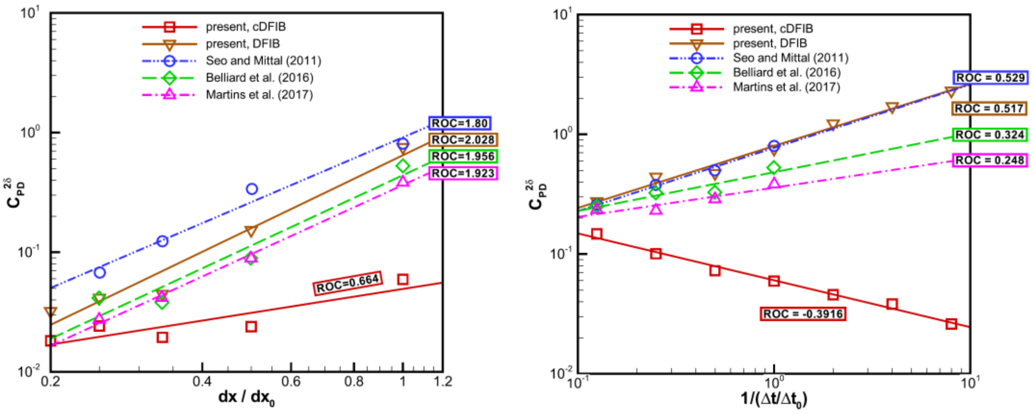

Figure 1: comparisons of drag coefficient by conventional DFIB and cDFIB method with reference solutions for the 2D Seo and Mittal oscillation cylinder problem.

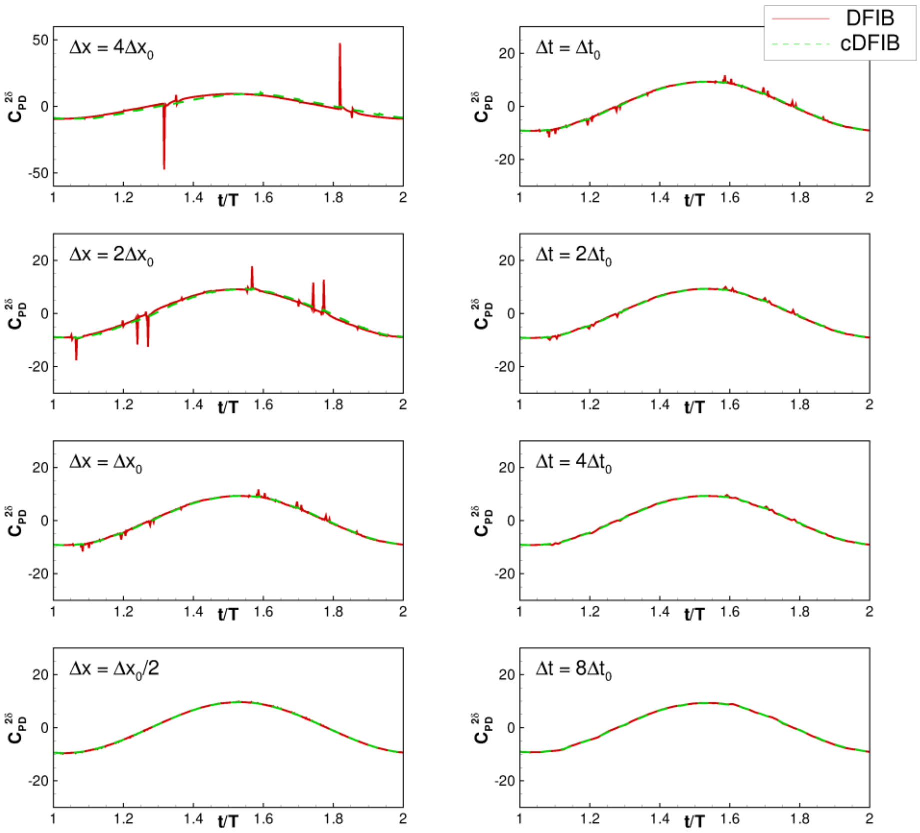

Figure 2: comparisons of drag coefficient by conventional DFIB and cDFIB method with different mesh sizes and time steps for the Seo and Mittal oscillation cylinder problem.

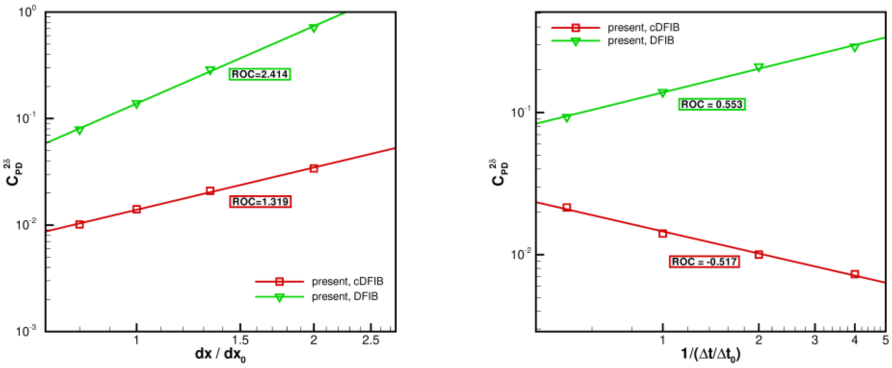

Figure 3: comparisons of drag coefficient by conventional DFIB and cDFIB method with reference solutions for the 2D Seo and Mittal oscillation cylinder problem.

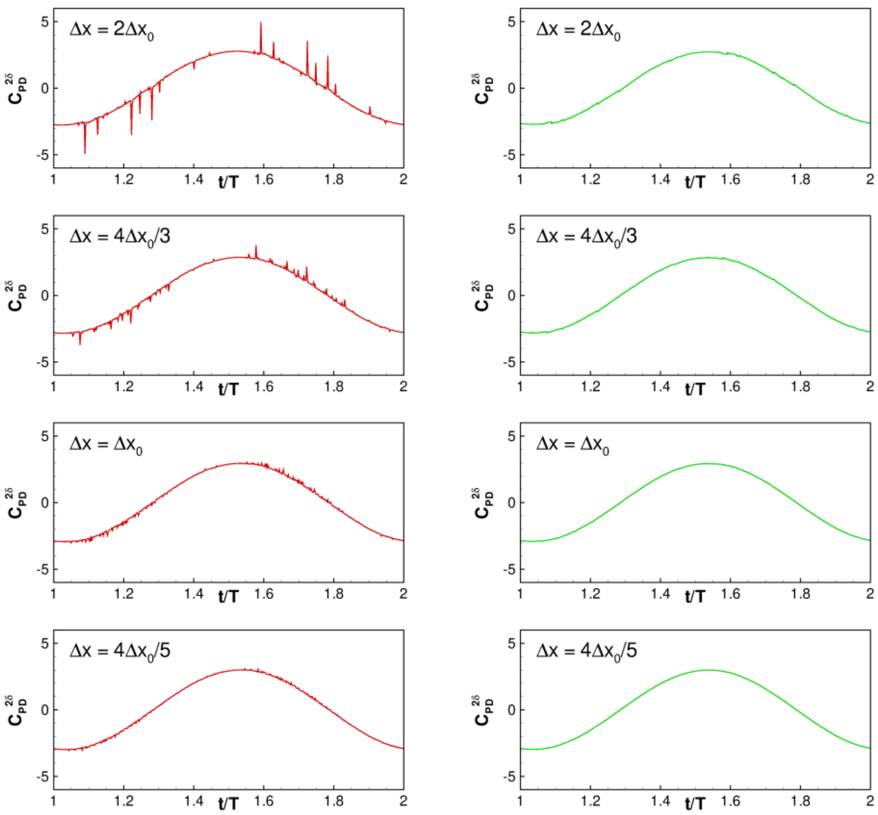

Figure 4: comparisons of drag coefficient by conventional DFIB and cDFIB method with different mesh sizes for the 3D Seo and Mittal oscillation cylinder problem.

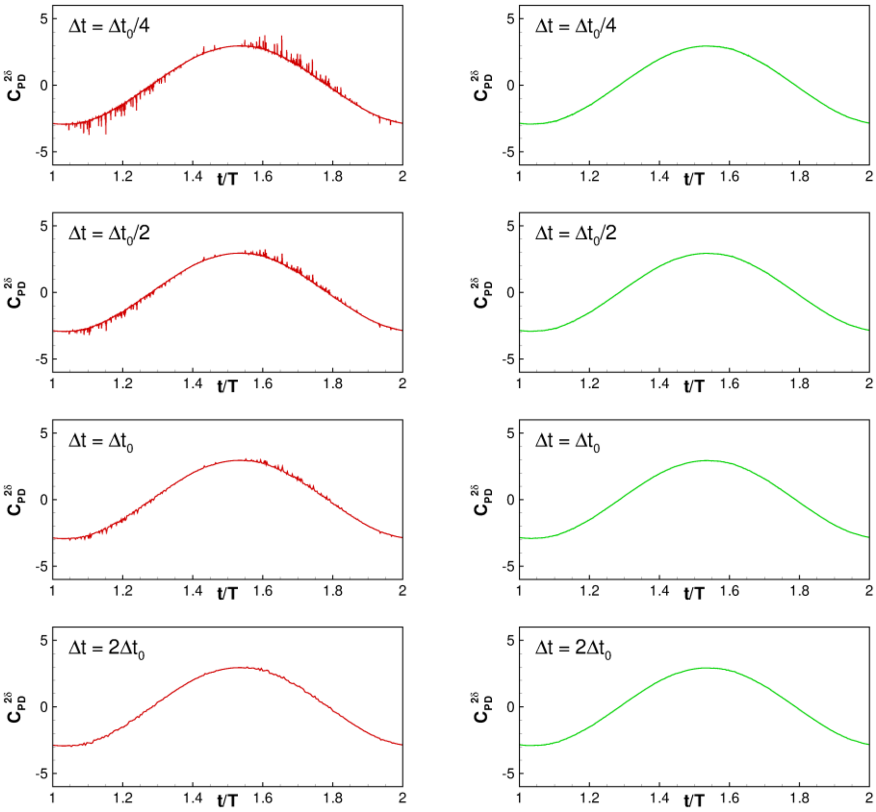

Figure 5: comparisons of drag coefficient by conventional DFIB and cDFIB method with different time steps for the 3D Seo and Mittal oscillation cylinder problem.

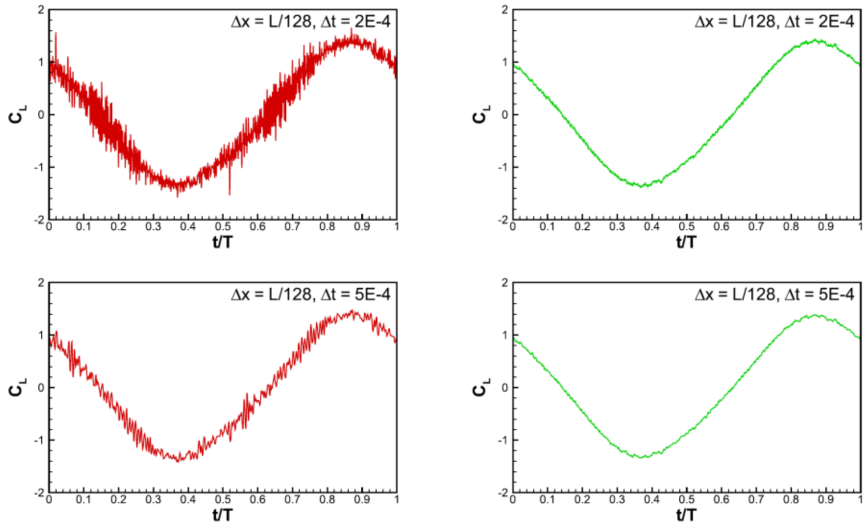

Figure 6: comparison lift coefficient with conventional DFIB (left) and cDFIB (right) method for the flow past fish-like wavy foil problem.

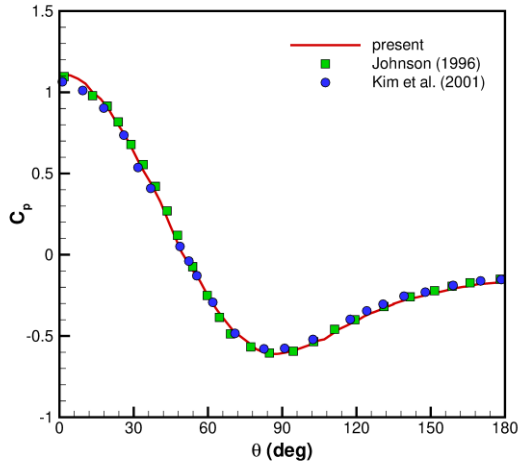

Figure 7: comparison drag coefficient with reference results for the flow past sphere problem.

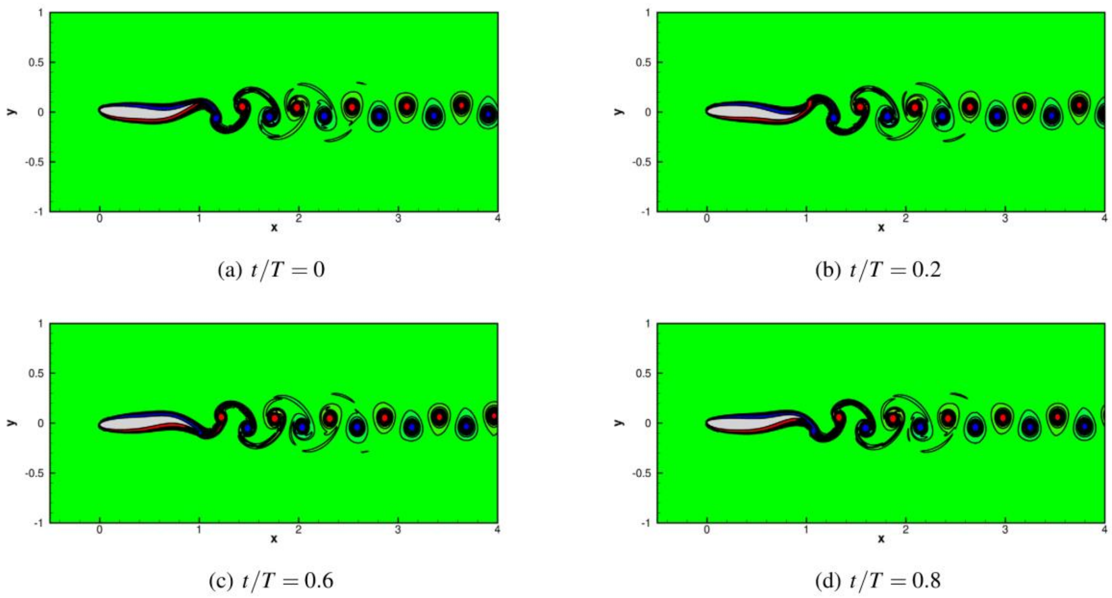

Figure 8: predicted vorticity contours at different time instances for the flow past fish-like wavy foil problem.

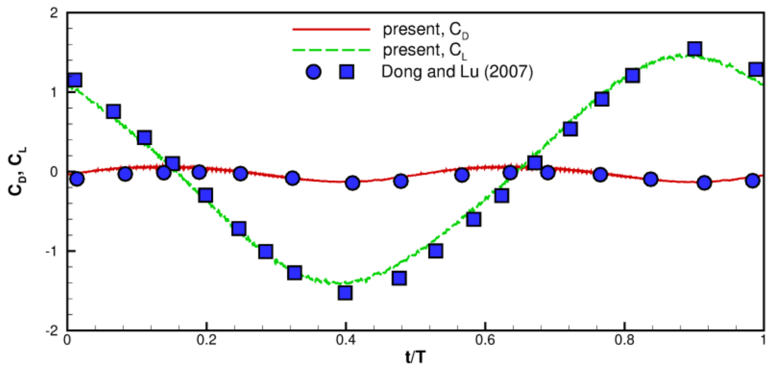

Figure 9: The plot of comparisons of the predicted drag(C_D) and lift(C_L) coefficient for the flow past fish-like wavy foil problem

.