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Time consistent fluid structure interaction on collocated grids for incompressible flow

T. Gillebaart*, D.S. Blom, A.H. van Zuijlen, H. Bijl

Faculty of Aerospace Engineering, Delft University of Technology, P.O. Box 5058, 2600GB Delft, The Netherlands

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Highlights

- Time consistent FSI on collocated grids for incompressible flow is demonstrated.
- A detailed analysis of time consistency for moving collocated grids is given.
- Generalized BDF time integration on moving grid is given for the PISO method.
- First, second and third order BDF time integration schemes are demonstrated.
- Efficiency increases with higher order time integration for FSI cases analyzed.

Abstract

Consistent time integration on collocated grids for incompressible flow has been studied for static grids using the PISO method, in which the dependencies on time-step size and under-relaxation has been studied in detail. However, for moving grids a detailed description is still missing. Therefore, a step by step analysis of a time consistent fluid–structure interaction (FSI) method for incompressible flow on collocated grids is presented. The method consist of: face normal and area correction for moving grids, treatment of velocity boundary conditions for no-slip walls, time integration of structure equations and fluid force interpolation to structure. The basis of the method is the PISO method of the incompressible Navier–Stokes equations. Time consistency on static grids is shown first, after which time consistency on moving grids is described and analyzed. For moving grids consistent time integration is described in two ways: (1) constructing the face velocities from a normal and tangential component, and (2) correcting the face flux with a face normal and face area correction. For both descriptions the general formulation for the backward differencing schemes (BDF) are given and the correct behavior of the first, second and third order schemes is demonstrated by means of an academic test case (circular cavity flow). Additionally, the (force) coupling from the fluid to the structure is discussed in detail for combining a fourth order explicit Runge Kutta scheme for the structure with a BDF scheme for the fluid. Three interpolations for the fluid forces are shown, which result in either a first order or second order FSI scheme. Third order FSI is demonstrated when the third order BDF scheme is applied on both the structure and fluid equations. Also, under-relaxation for the fluid equations is considered and it is demonstrated that the order of the three BDF schemes are independent of the under-relaxation factor. Finally, the proposed method of time consistent FSI on collocated grids for incompressible flows is demonstrated

* Corresponding author. Tel.: +31 15 27 87527.
E-mail address: T.Gillebaart@tudelft.nl (T. Gillebaart).

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by applying it to a three-dimensional flow over an elastic structure in a channel and the cylinder flap FSI benchmark case of Turek and Hron.

Keywords: Fluid–structure interaction; Consistent time integration; Collocated grids; Incompressible flow; Moving grids; PISO

1. Introduction

The application of high fidelity models for aero-elastic analysis has been growing over the past years. A good example is the paradigm shift in the Wind Energy world, where high fidelity models are starting to gain interest for fluid–structure-interaction (FSI) analysis of (extreme scale) wind turbines [1]. In many cases partitioned Computational Fluid Dynamics (CFD)—Computational Structural Dynamics (CSD) coupling is used. Even though computer power continues to increase, efficient FSI methods are required to increase the applicability of high fidelity models. One of the main contributors to the cost of a FSI computation is the unsteady nature of the physics, resulting in a time resolved simulation. The solution to limit the number of time steps is to use time consistent (higher order) methods. Time consistency ensures that for a decreasing time step the error decreases with the order of the discretization scheme used. Potentially this leads to the use of a larger time step combined with a higher order scheme, resulting in a reduction of the computational time.

For flow simulations on moving grids, it has been shown that the Discrete Geometric Conservation Law (DGCL) needs to be satisfied to prevent errors in the form of artificial mass sources and to preserve the non-linear stability properties of the temporal discretization scheme [2,3]. The DGCL ensures that a uniform flow remains uniform when the grid is moving/deforming. Farhat and Geuzaine also showed that only satisfying the DGCL does not ensure consistent order behavior [3]. Depending on the chosen model and discretization technique additional effort is needed for time consistency on moving grids (and for FSI). For compressible flows time consistent FSI has been shown for second order schemes [4,5]. More recently, higher order FSI by using implicit/explicit Runge–Kutta (IMEX) time integration schemes has been shown [6,7]. However, to our knowledge time consistent FSI on collocated grids for incompressible flow has not yet been presented, mainly due to the difficulties of time consistency on moving grids for collocated (unstructured) grids.

In the current study the widely applied finite volume formulation of the incompressible Navier–Stokes are used. A collocated grid approach is chosen, because of its flexibility of applying it to both structured and unstructured grids. To solve the Navier–Stokes equations an iterative Pressure Implicit with Splitting of Operators (PISO) algorithm is used [8], which requires a momentum interpolation scheme, on which many studies have been performed [9–11]. The original interpolation from Rhie and Chow (see [12]) did not ensure time consistent behavior due to pressure oscillation for smaller time steps as shown by Shen et al. in 2001 [9]. Additionally, Yu et al. showed that some of the proposed interpolation schemes are still time-step dependent and/or under-relaxation factor dependent [10]. They proposed a new set of momentum interpolation schemes, ensuring the solution to be independent of under-relaxation and time step (for steady state). Recently, a study has shown time consistency for unsteady aerodynamics on static grids for collocated grids using different momentum interpolation algorithms [13]. Higher order ESDIRK schemes have been applied to this discretization method on static grids by Kazemi-Kamyab et al. [14]. However, time consistency on moving grids for incompressible flows on collocated grids has only been shown by Tuković and Jasak [15]. They have shown time consistency for unsteady aerodynamic on moving collocated grids [15] by using Yu et al. [10] their approach, although they did not consider solid moving boundaries, which are required for FSI applications. Additionally, a clear and detailed description, and demonstration of time consistent FSI for incompressible flows on collocated grids is missing.

The goal of this paper is to describe and show consistent time-order behavior for a FSI solver for collocated grids using the segregated (momentum interpolation) approach for the incompressible Navier–Stokes equations. The main focus is on time consistency on moving collocated grids for incompressible flow, while consistent time integration for the used structural models is considered to be well known. For the Navier–Stokes equations the backward differencing (BDF) schemes are considered for time integration. First, second and third order methods are used. The key ingredient of ensuring consistent order behavior is to have the correct face velocities used for the pressure equation. To ensure a