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Non-intrusive reduced order modelling of fluid–structure interactions

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Highlights

- First non-intrusive reduced order model for fluid–structure interactions.
- First implementation of such NIROM to a combined fluid (FLUIDTY) and solid (Y2D) models.
- The POD–RBF NIROM does not require any change/knowledge of original code.
- First demonstration of NIROM in one and two way fluid and solid coupling cases.
- A large reduction in the CPU computation cost (by 5–6 orders of magnitude) while the accuracy of the solutions is maintained.

Abstract

A novel non-intrusive reduced order model (NIROM) for fluid–structure interaction (FSI) has been developed. The model is based on proper orthogonal decomposition (POD) and radial basis function (RBF) interpolation method. The method is independent of the governing equations, therefore, it does not require modifications to the source code. This is the first time that a NIROM was constructed for FSI phenomena using POD and RBF interpolation method. Another novelty of this work is the first implementation of the FSI NIROM under the framework of an unstructured mesh finite element multi-phase model (Fluidity) and a combined finite-discrete element method based solid model (Y2D).

The capability of this new NIROM for FSI is numerically illustrated in three coupling simulations: a one-way coupling case (flow past a cylinder), a two-way coupling case (a free-falling cylinder in water) and a vortex-induced vibration of an elastic beam test case. It is shown that the FSI NIROM results in a large CPU time reduction by several orders of magnitude while the dominant details of the high fidelity model are captured.

Keywords: RBF; POD; Fluid–structure interaction; Non-intrusive; Coupling

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1. Introduction

Fluid–structure interaction is an interaction phenomena between deformable or movable solid structures with a surrounding or internal fluid flow [1]. The FSI problem plays an important role in many scientific and engineering areas such as aerospace wings design, biology, turbomachinery and blood flow in veins and arteries. However, the computational cost for simulating the FSI problem is intensive. In this paper a new reduced order modelling method is presented to resolve complex FSI problems at a low computational cost.

Over the past decades, the reduced order modelling method has proven to be a powerful tool of reducing the dimension of large dynamic systems. Among model reduction techniques, the proper orthogonal decomposition (POD) is the most widely used method. POD is capable of representing large systems using a few number of optimal basis functions and it has been applied successfully to various research and engineering fields such as ocean models [2], air pollution [3], mesh optimization [4], shape optimization problems [5], porous media [6,7], shallow water [8–10], aerospace design [11] and neutron/photon transport problems [12].

In POD reduced order modelling, Galerkin projection methods are usually used to generate a reduced order model (ROM) by projecting the governing equations onto POD bases [13]. However, the main issues in reduced order modelling are stability and non-linear inefficiency [14–17]. Various stabilization methods have been proposed such as Petrov–Galerkin method [2,18], calibration [19,20], regularization [21] and Fourier expansion [22]. A number of non-linearity treatment methods have also been presented, including empirical interpolation method (EIM) [23], discrete empirical interpolation method (DEIM) [17], residual DEIM (RDEIM) [24], Petrov–Galerkin projection method [19], Gauss–Newton with approximated tensors method (GNAT) [25] and the quadratic expansion method [26,27].

Recently, the reduced order modelling method has been applied to fluid–structure interaction problem [28–33]. However, those methods are dependent on the governing equations, that is, they are intrusive ROMs. The disadvantage of intrusive ROMs is that the source code describing the physical system has to be modified in order to construct the ROM. The modifications could be complex or may be impossible if the source code is unavailable (*e.g.* in commercial software) [34]. To overcome this disadvantage, various non-intrusive reduced order modelling (NIROM) methods have been proposed. Xiao et al. proposed a non-intrusive ROM for the Navier–Stokes equations using the POD and Smolyak sparse grid interpolation methods [35]. This method constructs a hyper surface that replaces the equations of reduced system. Chen et al. proposed a non-intrusive ROM based on black-box stencil interpolation method [34]. Walton et al. proposed one for unsteady fluid flow using radial basis function (RBF) interpolation and POD [36]. Audouze et al. proposed a two-level non-intrusive reduced order modelling approach for nonlinear parametrized time-dependent PDEs using RBF and POD [37,38]. Xiao et al. also presented a non-intrusive reduced order method for Navier–Stokes equations using POD and RBF interpolation [39].

This paper uses, for the first time, the non-intrusive method to derive a reduced order model for fluid–structure interaction problems using the POD and RBF methods. This has been implemented under the framework of an unstructured mesh finite element model (Fluidity) and a combined finite-discrete element solid model (Y2D). The novelty of this work lies in the use of non-intrusive method to represent solutions of fluid–structure interaction problems on reduced spaces.

In this approach, the solutions to the high fidelity model are recorded as a sequence of snapshots and a number of POD bases are generated through these snapshots that optimally represent the fluid–structure interaction problem. The RBF multi-dimensional interpolation method is then used to construct a hyper-surface that represents the FSI ROM. After obtaining the hyper-surface, the solution of the new FSI ROM at the current time levels can be calculated through inputting POD coefficients at earlier time levels into this hyper-surface. The capability of the new fluid–structure interaction reduced order model (FSI NIROM) has been assessed through three coupling test cases: a one-way coupling test case—flow past a cylinder, a two-way coupling test case—a free-falling cylinder in water and the case—vortex-induced vibration of an elastic beam. Comparisons between the high fidelity full model and the proposed FSI NIROM are made to validate the accuracy of the new FSI NIROM.

The structure of the paper is as follows: Section 2 presents the governing equations of fluid–structure interaction problems; Section 3 derives the methods of constructing a non-intrusive reduced order model for fluid–structure interaction problems using the FSI NIROM method; Section 4 demonstrates the capability of the derived methodology by three numerical examples: a one-way coupling test case (flow past a cylinder), a two-way coupling test case (a free-falling cylinder in water) and a vortex-induced vibration of an elastic beam test case; Finally in Section 5, summary and conclusions are presented.