Journal of Computational Physics 321 (2016) 997–1025

Contents lists available at ScienceDirect

Journal of Computational Physics

www.elsevier.com/locate/jcp

Adaptive radial basis function mesh deformation using data reduction

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

ARTICLE INFO

Article history:
Received 6 October 2015
Received in revised form 9 March 2016
Accepted 17 May 2016
Available online 6 June 2016

Keywords:
Radial basis function mesh deformation
Fluid–structure interaction
Greedy selection
Boundary correction
Adaptive selection

ABSTRACT

Radial Basis Function (RBF) mesh deformation is one of the most robust mesh deformation methods available. Using the greedy (data reduction) method in combination with an explicit boundary correction, results in an efficient method as shown in literature. However, to ensure the method remains robust, two issues are addressed: 1) how to ensure that the set of control points remains an accurate representation of the geometry in time and 2) how to use/automate the explicit boundary correction, while ensuring a high mesh quality. In this paper, we propose an adaptive RBF mesh deformation method, which ensures the set of control points always represents the geometry/displacement up to a certain (user-specified) criteria, by keeping track of the boundary error throughout the simulation and re-selecting when needed. Opposed to the unit displacement and prescribed displacement selection methods, the adaptive method is more robust, user-independent and efficient, for the cases considered. Secondly, the analysis of a single high aspect ratio cell is used to formulate an equation for the correction radius needed, depending on the characteristics of the correction function used, maximum aspect ratio, minimum first cell height and boundary error. Based on the analysis two new radial basis correction functions are derived and proposed. This proposed automated procedure is verified while varying the correction function, Reynolds number (and thus first cell height and aspect ratio) and boundary error. Finally, the parallel efficiency is studied for the two adaptive methods, unit displacement and prescribed displacement for both the CPU as well as the memory formulation with a 2D oscillating and translating airfoil with oscillating flap, a 3D flexible locally deforming tube and deforming wind turbine blade. Generally, the memory formulation requires less work (due to the large amount of work required for evaluating RBF's), but the parallel efficiency reduces due to the limited bandwidth available between CPU and memory. In terms of parallel efficiency/scaling the different studied methods perform similarly, with the greedy algorithm being the bottleneck. In terms of absolute computational work the adaptive methods are better for the cases studied due to their more efficient selection of the control points. By automating most of the RBF mesh deformation, a robust, efficient and almost user-independent mesh deformation method is presented.

---

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

http://dx.doi.org/10.1016/j.jcp.2016.05.036

1. Introduction

High-fidelity models for aero-elastic analysis are gaining interest due to the increase of computing power and the always present desire to obtain accurate results. Generally CFD–CSD models are coupled to obtain a high fidelity aero-elastic model (i.e. fluid–structure-interaction (FSI) model). These coupled models are applied in several areas: for example for (large scale) wind turbines [1], micro-aerial vehicles (MAV) [2], cardiovascular systems [3] and aerospace [4]. When the FSI model is based on the Arbitrary Eulerian Lagrangian (ALE) formulation of the fluid equations, both the fluid and structure mesh need to be deformed from their initial state. For the structural mesh (and its equations) this is often straightforward due to its Lagrangian formulation, while for the fluid mesh this can be a challenge in terms of accuracy, efficiency and stability.

To assess the performance of the mesh deformation algorithm, four criteria are generally considered: resulting mesh quality, robustness, efficiency and user dependency/input required. Mesh quality is of key importance for accuracy and convergence of the system of fluid equations solved. Robustness is considered to be important to ensure that a single algorithm can be used for a wide variation of applications. Thirdly, since FSI calculations are expensive by nature, the mesh deformation algorithm should add the least possible extra computational time to the complete FSI simulation. Finally, an often forgotten performance criteria is user dependency. The more expert knowledge is needed for proper use of the method, the less robust such a method will be. In literature several options have been discussed for deforming a fluid mesh. The spring analogy [5], Laplacian [6] or Bi-Harmonic smoothing [7] and linear elasticity approach [8] are all grid connectivity based algorithms, which are considered to be relatively expensive since they solve a system of equation equal to the mesh size. Transfinite interpolation [9] is a robust and simple method, but only applicable on structured meshes. Radial basis functions (RBF) [10] results in high quality meshes (thus robust and accurate), while being applicable to both structured, unstructured and hybrid meshes (due its point-to-point nature). Therefore, Radial Basis Function mesh deformation has been gaining interest [11–15].

However, the original formulation can become expensive for large problems, hence acceleration techniques have been applied. Jakobsson and Amiognon [16] were the first to reduce the problem size by reducing the number of used boundary points. A similar approach has been taken by Rendall and Allen, who proposed a more efficient error-based selection method to reduce the problem size [11] (i.e. the greedy method), combined with an explicit correction to ensure the exact geometry is maintained [12]. More recently, a multi-level subspace RBF interpolation (based on a double-edge greedy method) has been designed to enhance the selection efficiency [17] and combining RBF with the Delaunay graph method shows promising results [18]. For the greedy based reduction methods a deformation of the boundary is required. As proposed by Rendall and Allen this can either be: a unit displacement (all boundary points have a unit displacement in all translational directions), predefined deformation (e.g. structural modes) or the actual deformation. Rendall and Allen suggested using the unit displacement, since this makes the selection independent of the actual deformation (at the cost of a reduction of accuracy of the boundary geometry and/or efficiency) [13]. Instead of using the same set of control points, for each direction the selection procedure could be executed separately, also known as sequential uni-variate adaptation [19]. Besides the reduction of boundary points, the parallelization of the method has been studied [14]. Here they did not consider any reduction algorithm and used the full set of boundary points. Rendall and Allen briefly discussed parallelization, but did not study or discuss it in depth [12], while Sheng and Allen discussed parallelization of the interpolation step [20]. Parallelization of the greedy selection method becomes more important when the selection process is repeated within the time loop. Otherwise it is only a one-off cost, which probably is of minor importance for parallelization considering the full unsteady calculation.

Even though a unit displacement as selection deformation has its benefits (only needed once and simple to implement), it potentially causes a reduction in accuracy or efficiency. Therefore, a more realistic prescribed deformation or the actual deformation could be used to select a set of boundary points. Here the prescribed deformation needs a priori knowledge (i.e. obtaining/creating a realistic deformation based on e.g. structural modes), which is undesirable, since it increases the user-dependency. Ideally, the actual deformation is used for selection, since it is already available and represents the structure deformation best. However, how to approach the changing deformations over time during a (FSI) simulation? And how does this influence the accuracy and efficiency of the RBF mesh deformation method? In addition, to have an efficient (parallel scalable) method, the number of control points should be limited or ideally mesh independent. However, this has not been shown yet, and is unknown until now. In addition, with a subset of boundary points as control points, a boundary error will exist. A simple explicit master-slave like correction [21] can be applied, as suggested by Rendall and Allen [12]. However, how does the correction influence the mesh quality and how to use radial basis functions efficiently for this: how to choose the function and its radius?

The goal of this paper is to present an adaptive radial basis function mesh deformation and show its (parallel) performance by analyzing the following criteria: (parallel) efficiency (cost of computation), mesh quality and user dependency. Secondly, a detailed analysis of the influence of the explicit boundary correction on the mesh quality is performed, after which we propose (and verify) an automated procedure for the explicit correction step. Additionally, a question/assumption for the (parallel) efficiency and robustness of the RBF method will be answered: is the number of control points mesh independent for a fixed selection criteria? With this new knowledge, the proposed adaptive method will be compared to the unit displacement and prescribed method to assess its robustness, efficiency and user dependency.

First, the radial basis function mesh deformation method is described for both a CPU intensive formulation and a memory intensive formulation. Here also the theoretical cost of the two formulations is discussed. After this, the greedy algorithm is shortly summarized. Based on the original greedy algorithm the adaptive method is described. Consequently, the boundary