Available online at www.sciencedirect.com
SciVerse ScienceDirect
Mathematics and Computers in Simulation 106 (2014) 26–43
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Original article

Unstructured meshes for large body motion using mapping operators

Sina Arabi, Ricardo Camarero, François Guibault *

École Polytechnique de Montréal, 2900 boul. Édouard-Montpetit, Campus de l'Université de Montréal, 2500 chemin de Polytechnique, Montréal (Québec), Canada H3T 1J4

Received 7 June 2011; received in revised form 28 March 2012; accepted 7 May 2012
Available online 1 June 2012

Abstract

This paper addresses the problem of generating unstructured meshes with fixed connectivity for large rigid body motion. The proposed approach consists in generating a mesh in computational space for a generic configuration of the moving body. The management of body and mesh motion is carried out in computational space using a sliding mesh paradigm. The mesh in physical space is obtained through PDE mapping operators. Two mapping operators and two discretization techniques are implemented, validated and compared. The overall methodology is applied to complex geometric configurations representative of engineering applications.

Keywords: Mesh mapping; Unstructured mesh; Fixed mesh topology; Large motion; Mesh smoothing

1. Introduction

To perform unsteady flow simulations in domains with moving boundaries that incorporate the complete details of geometry as well as flow features, numerical algorithms with great fidelity are needed. Such unsteady phenomena are encountered in many engineering problems such as turbomachinery, oscillating airfoils, propellers and fluid–structure interactions, and have led to the development of algorithms for simulating fluid physics, where dynamic grid generation for both viscous and inviscid regions play a significant role. While several applications to complex 3D configurations have been presented in the literature [11,4], these remain involved both from the numerical cost resulting from interpolation and from the mesh management point of view. Specifically, the problem becomes even more difficult for large motion of bodies in close proximity or in contact.

Despite the considerable efforts addressed at this type of problems, efficiency and robustness remain critical issues. Chimera schemes simplify the mesh management by superposition of the static and moving parts of the grids at the expense of the cost of interpolation. Some mesh management strategies using local mesh adaptation have successfully avoided interpolation by the use of edge swapping in both 2D [19,10] and 3D [20]. However, these approaches remain complex to implement, especially in 3D, and even more so for meshes comprising more than one type of element.

To overcome these drawbacks, a new approach [2] has been presented based on a flow analogy where the grid cells are advected past the moving boundaries by a fictitious potential-like fluid flow. In this approach, the mesh motion is managed in physical space, and requires special treatment of grid cells on the boundaries, especially for bluff bodies.

* Corresponding author. Tel.: +1 514 340 4711x4876; fax: +1 514 340 3240.
E-mail addresses: sina.arabi@polymtl.ca (S. Arabi), ricardo.camarero@polymtl.ca (R. Camarero), francois.guibault@polymtl.ca (F. Guibault).

0378-4754/$36.00
http://dx.doi.org/10.1016/j.matcom.2012.05.004

In the present paper, these difficulties are addressed by managing grid motion in computational space instead, and mapping the grid to physical space using PDE operators. Performing the cell motion in computational space reduces constraints which arise from the handling of mesh clustering in high curvature parts of the physical boundaries and considerably simplifies the algorithm for moving bodies.

Minimizing or avoiding grid modifications preserves the mesh topology and validity during boundary motion and increases the robustness of the mesh generation procedure. In addition, this approach simplifies the application of Arbitrary Eulerian–Lagrangian (ALE) methods and the satisfaction of geometric conservation laws (GCL).

2. Mesh movement

Mesh motion strategies for time evolving domains presented in the literature can be divided in two major categories: methods based on changing topology and methods which maintain the mesh connectivity.

Mesh changing topology approaches use different techniques such as local remeshing [11,12], mesh coarsening and enrichment [3] swapping and merging [2,10]. However, there remain a number of critical issues relating to accuracy and efficiency due to the interpolation schemes between consecutive time steps.

Amongst the mesh motion strategies in physical space which are based on preserving the mesh connectivity, the most straightforward approach is the spring-analogy type of algorithm. These have been improved in [8] by adding torsional springs for controlling the arbitrary motion of grid points. The difference between vertex and segment springs to calculate the equilibrium edge lengths is presented in [5] and the segment spring method based on the modified stiffness has been applied for a pitching airfoil where the original spring analogy methods had failed. However, a disadvantage of this approach is that the grid smoothness and regularity are lost when the grid is subjected to large motion.

Another promising method is based on the radial basis functions presented in [21] which can be used for mesh motion while preserving the cells connectivity. An interpolation technique is used to propagate the displacement of boundary nodes onto the interior nodes. The method can be compared with PDE-based approaches in terms of mesh quality and efficiency for motions where the surface deformations are smooth as in fluid–structure interaction problems. However, it is not able to deal with contact and separating boundaries.

PDE operators such as Laplace and Poisson equations have been used as a mechanism to generate and smooth meshes. One such method is based on the linear elasticity theory. Yang and Mavriplis [27] showed how linear-elastic smoothing can be used to perform very large deformations for inviscid and viscous meshes. One advantage of this approach is that it uses a variable elastic stiffness, inversely proportional to the cell volume, in order to preserve the mesh quality in viscous layers. This method has been found very robust for several engineering applications but gives invalid cells in some large periodic motions.

The methods described so far, all share one major characteristic which is that the mesh motion is carried out in physical space. This treatment, as described in [1], presents difficulties regarding the management of grid valence as required for local element splitting at separation and reattachment points. Another difficulty is the nodal velocity propagation inside the domain to avoid tangled meshes. Consequently, in the present paper, these difficulties are addressed by managing grid motion in computational space, and then, mapping the grid to physical space using a system of PDE operators. Managing cell movement in computational space decreases difficulties in handling physical domain features, especially in regions where boundary curvature varies rapidly. The major goal of this approach is to preserve the mesh topology as time evolves, making it well suited for Arbitrary Lagrangian–Eulerian (ALE) flow solvers and allowing for the rigorous application of geometric conservation laws (GCL). It is known that the ALE approach combines both, the Lagrangian and Eulerian reference frames and allows for a flexible, moving grid. This is helpful in problems with large deformation of boundaries where the grid tracks the fluid or boundary. In addition, an often overlooked issue in moving grids is the discretization of the GCL. These consist in two equations that state that cell volumes must be bounded by their surfaces (surface conservation law, SCL) and that a volumetric increment of a moving cell must be equal to the sum of changes along the surfaces that enclose the volume (volume conservation law, VCL). Imposing these requirements for time dependent meshes in a finite volume method have been presented in [28,24] and are greatly simplified in the present approach as the grid connectivity is fixed.

The proposed procedure for this method consists in three major steps. First, an unstructured mesh is generated in computational space around a generic body. Then, the generic boundary is made to slide through the cells according to the defined trajectory for the physical boundary, and finally, the mesh is mapped on the physical domain. The mapping