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A parallel meshless dynamic cloud method on graphic processing units for unsteady compressible flows past moving boundaries

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Abstract

This paper presents an effort to implement a recently proposed meshless dynamic cloud method (Hong Wang et al., 2010) on modern high-performance graphic processing units (GPUs) with the compute unified device architecture (CUDA) programming model. Within the framework of the meshless method, clouds of points used as basic computational stencils are distributed in the whole flow domain. The spatial derivatives of the governing equations are discretised by the moving-least square scheme on every cloud of points. Roe's approximate Riemann solver is adopted to compute the convective flux. A dual-time stepping approach, which iterates in physical and pseudo temporal spaces, is employed to obtain the time-accurate solution. Simulation of steady compressible flows over a fixed aerofoil is firstly carried out to verify the GPU implementation of the method. Then it is extended to compute unsteady flows past oscillatory aerofoils. Numerical outcomes are compared with experimental and/or other reference results to validate the method. Significant performance speedup of more than an order of magnitude is verified by the numerical results. Systematic analysis shows that GPU is more energy efficient than CPU for solving aerodynamic problems. This demonstrates the potential of the proposed method to solve fluid–structure interaction problems.

Keywords: Aerodynamics; Oscillatory aerofoil; CUDA; Graph mapping

1. Introduction

Unsteady flows over moving boundaries are frequently encountered in many scientific fields such as aerodynamics, hydrodynamics and biological fluid dynamics. These complicated problems play an important role in fundamental research and industrial applications, however they have proved extremely challenging to theoretical, experimental and

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numerical investigations. When dealing with them by a computational fluid dynamics (CFD) method, the motion of boundaries need to be handled appropriately with a robust numerical algorithm. Meanwhile, the simulation itself is very time-consuming due to intensive computing. A persistent objective of CFD is to devise accurate and efficient numerical methods to solve these complicated flow problems.

During the past several decades, a new kind of numerical algorithm named meshless (or gridless, meshfree, particle) method has gradually attracted more and more attentions of researchers in CFD. A distinctive feature of meshless methods is that connectivities between points are not necessary to be considered, since they do not adopt traditional structured/unstructured mesh topologies but employs flexible clouds of points, which are basically composed of a centre point and several satellites, to discretise the flow domain. The derivatives of a mathematical function in a cloud of points can be computed by the least-square curve fit, radial basis function or other effective strategies. In the area of aerodynamics, meshless methods have been successfully applied to solve steady compressible flows [1–7]. Considering unsteady flows, Wang et al. [8] proposed a meshless dynamic cloud method to deal with moving boundaries. A very simple but effective algebraic mapping strategy was used in their work to adjust the distribution of meshless points. Solid boundary penetration induced by other numerical methods was avoided by the dynamic cloud method even for cases with relatively large displacements, such as a 30° pitch motion of an aerofoil (see Figs. 3 and 4 of [8]). This method has also been extended to drag reduction design for an aerofoil with active flow control [9].

Until now, these aforementioned research works of meshless methods for steady and unsteady flows past fixed solid bodies have mostly been carried out with serial computing on a single core of the CPU. On the other hand, Ortega et al. [10,11] paid attention to the parallelisation of the finite point method on multi-core CPUs with the OpenMP programming model. They observed unsatisfactory scalability problems and pointed out that attainable speedups on multi-core CPUs will drop once the number of processor cores is over 4 due to the high cache miss rate and limited memory bandwidth of CPU. Therefore, they suggested to use much higher-performance hardware platforms [11].

Nowadays, computer science is embracing a new and fast developing territorial namely GPU computing technology, in which the graphic hardware can deliver Tera-scale single- and double-precision floating-point operations per second in very recent years. This provides tremendous power to scientific computing and it is extremely attractive to the CFD community, in which high efficiency/performance is always a requirement of numerical methods for many complicated problems. For important GPU implementations of mesh methods, readers may refer to the works of Karatarakis et al. [12] and Papadrakakis et al. [13] for solid mechanics problems; Bard and Dorelli [14], Liang et al. [15], Corrigan et al. [16], Asouti et al. [17] and Kampolis et al. [18] for fluid mechanics problems. In these works, the strategies to utilise the GPU to solve complicated problems in solid or fluid mechanics are explained in detail. Specific techniques to prevent thread race conditions or to improve memory performance are also provided. All of them reported impressive speedups of the fundamental mesh based numerical solvers, this triggered off our intention to investigate the possibility of realising the meshless method for CFD on GPUs in the first place. Initial success of such kind of attempt to solve steady compressible flows with a meshless method on GPUs was reported in our recent work [19]. These inspiring works for flows over fixed objects encourage us to further develop GPU based numerical methods to solve more challenging unsteady compressible flows past moving boundaries. This study exhibits such kind of an effort to accelerate the meshless dynamic method, which enjoys the robustness to deal with rigid and/or flexible boundaries, on modern graphic hardware.

The rest of the paper is organised as follows. Key aspects of the numerical method including the governing equations, meshless discretisation, dual time stepping scheme and dynamic cloud technique are described in Section 2. The implementation of the meshless dynamic cloud method on the GPU is discussed in Section 3. Numerical examples of steady and unsteady flows are given in Section 4. The obtained results are compared to the experiment and/or other available reference solutions to verify the accuracy of the present method. Systematic performance benchmarks of the method on CPU and GPU with up to one million points are also carried out. Not only the running time costs are compared but also the energy consumptions are investigated.

The major contributions of the work may contain the following phases:

- To the best of our knowledge, we are the first to present a GPU based numerical method for simulating unsteady compressible flows past moving boundaries.
- The performance of meshless dynamic cloud method is successfully improved by more than an order of magnitude, and the GPU based computing method is more energy efficient than the CPU.
- This work demonstrates the potential of the present GPU based algorithm for solving more complicated fluid–structure interaction problems.