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Extending slide-slip mesh update method to finite volume method

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A B S T R A C T

For simulations of flows around rotating bodies, usually sliding mesh method or overset grid method is used. But both of them have to perform inter-mesh interpolation which introduces much numerical error and usually violates conservation. Shear-slip mesh update method (SSMUM) is another method for such flows. In each time step of SSMUM, a mesh slipping step follows a mesh deforming step to undo the deformation and results in a new mesh of good quality. Each vertex on the slipping interface can only move from one node to the next node in the circumference, which makes the interface always conformal and no need for inter-mesh interpolation. However, SSMUM didn't get enough attention in the community of finite volume method. In this paper, SSMUM is extended to cell center finite volume method. To guarantee conservation and obtain high order accuracy on a slipping interface, a remapping procedure is needed to transfer flow field from an old mesh to a new mesh. This was achieved by solving a linear convective PDE with one or two explicit steps, thus only resulting in little extra computing cost. Oscillating NACA0012 airfoil was simulated with the improved SSMUM. The results showed excellent agreement with the data by rigid rotating mesh. And the flow field was always smooth. It suggests that this improved SSMUM has advantages in getting conservative, smooth and high accuracy solutions for rotating problems.

1. Introduction

For CFD simulations of flows over rotating bodies, such as wind turbines or helicopter blades [1–3], an interface between a fixed domain and a rotating domain has to be handled properly. Two popular methods to handle an interfaces are sliding mesh method and overset grid method. In the sliding mesh method, an interface is a moving non-conformal interface. At each time step, the flow variables in each ghost cell outside of an interface are obtained by interpolating in the opposite mesh which provides donor cells for interpolating. Usually, this interpolation can not guarantee the conservation of flux across the interface. To fix this problem, Sutherland–Hodgman algorithm [4] was applied to obtain all polygons resulted from intersection of the two surface meshes [5]. And then by computing flux across each polygon, the conservation can be satisfied. But this approach was much more complicated. Another problem is that it is cumbersome to apply high order and non-oscillating interpolation across a non-conformal interface. Zhang and Chen et al. developed a high order conservative remapping method for static non-conformal interfaces [6]. The 2nd or 3rd order ENO/WENO [7,8] method was used for reconstruction and then areas of all the polygons resulted from intersection were used to rebuild the flow variables in the ghost cells. Extending this approach to sliding mesh is feasible but very complicated. So in many practical applications, usually a simple interpolation, such as bilinear or trilinear interpolation, is adopted, which products good results only when the interface is located in smooth region. Beside the problems of lack of conservation and accuracy, discontinuous isolines or contour levels cross an interface is another problem in visualization. The method of overset grid also has these disadvantages.

For harmonic balance simulations of full periodic flows in rotor–stator problems, an unsteady flow are decomposed into both temporal and spatial modes. And spatial modes are defined in stator zones and rotor zones respectively, but they are matched on interfaces [9,10]. In this approach, the flow field on an interface can be presented as a Fourier series. Thus intersection across the interface can be avoided. But for non-periodic flows, pure unsteady algorithms have to be used.

The difficulties of sliding mesh and overset grid are resulted from the non-conformal interface between a moving mesh and a fixed mesh. If a conformal interface can be constructed, these difficulties can be overcome. Shear-slip mesh update method (SSMUM) proposed by Tezduyar et al. [11–13] is such a method. SSMUM was developed for Deformable-Spatial-Domain/Stabilized

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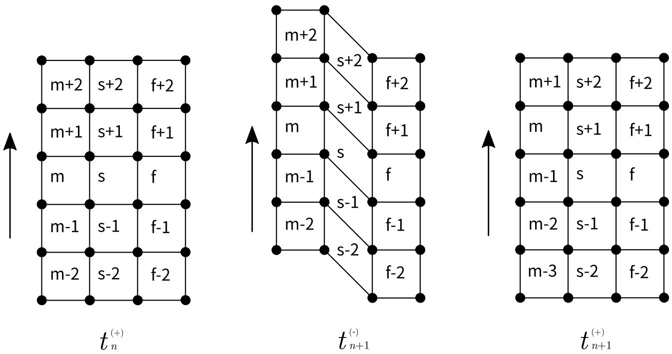

Fig. 1. Schematics of SSMUM at t_n^+, t_{n+1}^- and t_{n+1}^+.

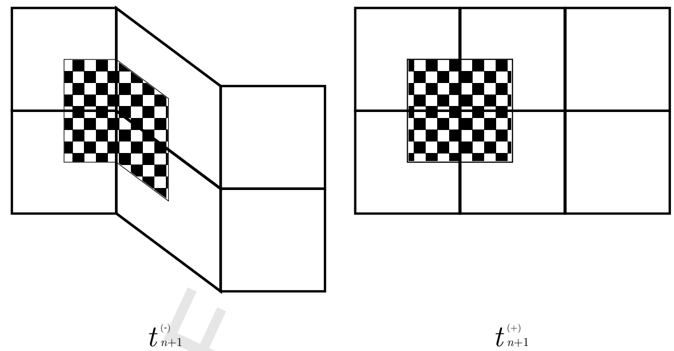

Fig. 2. Domain changing of a dual control volume (the tessellated region) from $t_{n+1}^{(-)}$ to $t_{n+1}^{(+)}$.

Space–Time (DSD/SST) formulation, a special kind of finite element method. In SSMUM, mesh deforming and slipping are alternatively applied to handle the relative movement between meshes. And the most important advantage is that no interpolation is needed. However, SSMUM is not popular in the community of finite volume method (FVM). A possible reason is the gap between the community of FEM and that of FVM.

In this paper, SSMUM was extended to the frame of FVM. Our tasks were to keep conservation on a slipping interface and to apply high order discretization around a slipping interface, which are important to apply this SSMUM of FVM in simulations of compressible flows. These were achieved by solving an advective PDE with conservative high order scheme in course of mesh slipping. And the convective PDF describes how the flow variables vary in a moving mesh while the flow field is frozen. In the following sections, this SSMUM for FVM, as well as the relatively numerical methods, was described in detail. And then a simple but typical case was presented to test the improved SSMUM. At last, conclusion and feature work were given.

2. Methodology

2.1. Original SSMUM

In a simulation with SSMUM, between a moving mesh and a fixing mesh, there is not a sharp interface but a “shear-absorbing mesh”. This shear-absorbing mesh deforms and undergoes the shear strain. Usually it spans one layer of elements. Fig. 1 shows the three meshes. The left column is the moving mesh, the right column is the fixed mesh, and the middle column is the shear-absorbing mesh. The procedure of the original SSMUM can be described as following:

1. Initially, at the time $t_n^{(+)}$ (Fig. 1 left) there is no displacement and the elements in the shear-absorbing mesh do not deform.
2. Assume that the moving mesh shifts over one element each time step. So at the time step $t_{n+1}^{(-)}$ (Fig. 1 middle), the shear-absorbing mesh deforms with the movement. Notice its elements are stretched, while the elements in the other two meshes keep shape unchanged. Obviously, an ALE algorithm should be applied to the moving mesh and the shear-absorbing mesh to solve the flow field at $t_{n+1}^{(-)}$.
3. The elements in the shear-absorbing mesh slip back and form a new mesh with the same flow field. In Fig. 1 right, edges of Element s slip and align with Element $m-1$. But in this slipping step, we can see that all the vertexes do not move but are reconnected. Since all the flow variables are stored on vertexes, the flow field associated to vertexes are not changed. This means that there is no need for any manipulation such as projection, interpolation or remapping to transfer data from the old mesh at $t_{n+1}^{(-)}$ to the new mesh at $t_{n+1}^{(+)}$. After this slipping step, we obtain a new mesh system and its flow field (Fig. 1 right). This step is the most important in SSMUM.
4. The computation from $t_n^{(+)}$ to $t_{n+1}^{(+)}$ is completed. We can perform another deforming-slipping step to advance the flow field and the mesh-system.

SSMUM does circumvent the error of interpolation. However, the slipping step is not perfect. Because FEM CFD on linear elements is similar to the 2nd order FVM discretization on dual mesh [14], by checking carefully a dual control volume of a vertex in the shear-absorbing mesh, we can see that the domain of a dual control volume changes from $t_{n+1}^{(-)}$ to $t_{n+1}^{(+)}$ (Fig. 2). So the cell-average values certainly change unless the flow is uniform in the moving direction. Simply keeping the same cell average values does not satisfy conservation while introducing numerical error.

2.2. Extending SSMUM to cell-centered FVM

We prefer extend SSMUM into FVM since it can guarantee conservation naturally. This paper is focused on SSMUM for cell-centered FVM based on multiblock structured grids for its simplicity (So “mesh” and “grid” are used with the same meaning in this paper). At the same time, application of high order spatial discretization is relative easier in structured grids. But the idea can be extended to unstructured meshes.

For SSMUM procedure in Fig. 1, with cell-centered discretization, all the variables are stored in elements (control volumes). FVM with moving mesh is applied to advance the flow field from $t_n^{(+)}$ to $t_{n+1}^{(-)}$. From $t_{n+1}^{(-)}$ to $t_{n+1}^{(+)}$, for Element s in the shear-absorbing mesh, we can imagine that Element s slips down until it becomes a neighbor of Element $m-1$. In this course, the key problem is how to determine the variation of cell variables in Element s and its siblings without lost of accuracy and conservation. After that, a new mesh with conformal interface is constructed and FVM with moving mesh can be applied again without any difficulty.

The above slipping procedure is like the remapping in ALE: the flow field has to be remapped from an old mesh to a new mesh. Usually some kind of interpolation method is used. In order to keep conservation of mass, momentum and energy between the old and new meshes, the interpolation method would be very complicated, especially when high order spatial accuracy is required on 3D unstructured meshes. But for the slipping step in SSMUM, since the field is frozen and only mesh is moving without changing of its topology, those complicated remapping algorithms are not needed.

Observe Fig. 1, from $t_{n+1}^{(-)}$ to $t_{n+1}^{(+)}$, the flow field is frozen but the shear-absorbing mesh is moving. It is natural to find out that by integrating the flux across the moving faces in the course of

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