Grid deformation based on macro-element and partitioning techniques for flapping mechanism

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Abstract

The grid deformation algorithms can be classified into linear algebra methods, elasticity-based approaches, and their hybrid forms. The methods in the first category have advantages in efficiency, but do not normally produce grids of sufficient quality. A spring analogy in the second category is known to cause grid irregularity for the large moving boundary problem and methods for improving the robustness of the grid regularity are subsequently required. The finite element method in the same category provides better quality than simple interpolation schemes, but become too expensive for large grids. Hybrid method using the macro-finite elements and interpolation reduced not only computational cost for finite element solution over entire grid, but also the disparity of mesh size, which causes bad effect on the grid quality.

However, the hybrid scheme is still needed to be improved for the flapping mechanism, which has the large deformation and motion. The failure during the grid deforming is mainly occurred near the moving object, namely the flapper. So the improvement should be focused on this region. Therefore, in this work, partitioning into body-fitted grid and other is enhanced on top of the hybrid scheme using the macro-element technique. In a little detail, the grid deformations are firstly computed in the body-fitted grid region because the highest performance is required. The deformations along the interface between the two regions are used as the boundary condition for the other domain. The hybrid scheme is then applied to the other region. The proposed grid deformation shows the better performance as compared to a conventional hybrid scheme in terms of grid orthogonality and its volume change in applications of flapping mechanisms.

Keywords: Grid deformation, Macro-element, Partitioning techniques, Flapping mechanism

Introduction

In modern computational fluid dynamics, the moving boundary problem receives a great deal of attention, as it is mandatory in free surface flows, forced vibration problems, optimization, and fluid-solid interaction. A crucial part of this computation is the grid deformation at every step during the numerical time integration of the fluid analysis.

The finite macro-element based method for structured grids, which consists of fluid grids, computes the grid deformation along with interpolation scheme (Bartels, 2005). This reduced not only computational cost for finite element solution over entire mesh, but also the disparity of element size which causes bad effect on the grid quality.

Recently, as an interesting type inspired by nature, flapping hydrofoil power generator from tidal stream have been developed in the UK: Stingray of Engineering Business Ltd and the newer Pulse stream 100 designed by Pulse Generation Ltd. in conjunction with IT Power Ltd. These system are known as echo-friendly systems (Glynn, 2006) compared to typical rotary turbines. Power extraction using the flapping mechanism requires large heave and pitch motion as well as structural deformation. Thus, higher performance in grid deformation is necessary.

Therefore, improvement methods were introduced such as the Jacobian option (Stein, Tezduyar and Benney, 2003) and partitioning method in which the verifications of the grid quality based on volume change and orthogonal change were adopted. In this paper, the performance of the finite macro-element based grid deformation is explored for large pitch and span flexure of a typical airfoil. The efficiency of power extraction is obtained by the approach.

Methods

A. Volume grid deformation (VGD)

To consider deformed shape effects, VGD(Volume Grid Deformation) code is developed in the overset grid Navier-Stokes solver as a mesh deformation code. The VGD code is developed based on the Ref. (Ko, 2010). The mesh deformation is divided into two main steps. First step is computing deformation from a finite macro-element model generated by fluid grid. The second step is transfinite interpolation that translates from the deformation of the macro-elements to whole fluid grids.

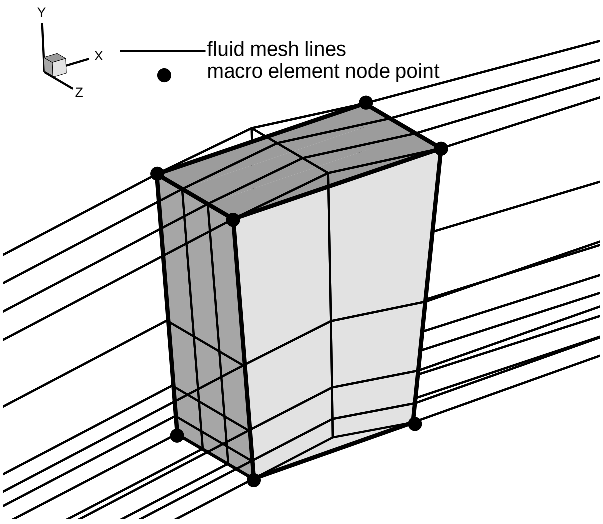

Figure 1. Constitution of a macro-element

B. Generation and deformation of macro-finite element

Finite element based grid (or mesh) deformation approaches typically uses entire fluid grids in constituting the finite macro-elements as depicted in Fig. 1. How the fluid grids are included in a macro-element is important for the preservation of the grid regularity. Here, we use the condition that satisfies minimum distance and minimum gird index number of each edge line of the macro-element.

C. Grid deformation by transfinite interpolation

Once the node displacements of the macro-elements are obtained from the finite element system, a transfinite interpolation is performed by using a blending function. The results are known to be a continuity of displacements at all macro-element boundaries, even if continuity of the derivative of the displacement is not ensured (Ko, 2010). A blending function in public domain, BLEND is employed. BLEND is coded by C and FORTRAN languages and is released in the function that interpolates corresponding fluid grids from a macro-element by using the deformations of the edge points. However, the moving boundary is composed of surfaces in three-dimension; thus we need to modify the original code for translating the fluid grids from given displacements over the surface of the macro element.

Through the two separate procedures, the large motions over the moving boundary successfully translate to the whole fluid grids. The grid deformation is developed only for three dimensional structured grids and is referred to as volume grid deformation (VGD).

The Jacobian option was implemented by accounting for the Jacobian of the transformation from the mesh domain to the physical domain

$$\int_{\Xi}[\ldots]^{e} J^{e} d\Xi = \int_{\Xi}[\ldots]^{e} J^{e}\left(\frac{J^{0}}{J^{e}}\right)^{\chi} d\Xi \tag{1}$$

As another scheme for improving grid quality near wall, the partitioning method is adopted. The whole grid is separated into two subdomains. The first subdomain including the object is solved first and the second subdomain is solved with the boundary conditions computed from the first solution.

D. Computational fluid dynamic code and interface

As mentioned previously, numerical simulation for obtaining aerodynamic forces will be done by a computational fluid dynamics code. KFLOW, which we adopt, is an in-house code for the three-dimensional compressible, preconditioned Navier-Stokes analysis. Multi-block structured grid and automated interpolation point generation algorithm are implemented (Park 2003). Spatial discretization is done by finite volume method where discretization schemes with second and fourth order accuracy and WENO (Weighted Essentially Non-Oscillatory) scheme with fifth order accuracy are implemented. Spalart Allmaras, k-ω Wilcox, k-ω Wilcox Durbin (WD+), k-ω SST (Shear Stress Transport), and k-ε

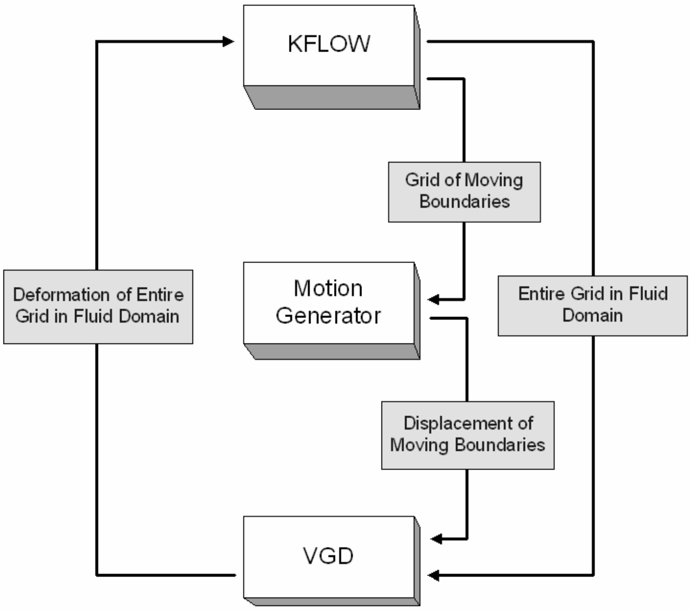

Figure 2. Modules and data flow when VGD interfaces with KFLOW.

The modules and data flow of VGD coupled with KFLOW are depicted in Fig. 2. For the CFD analysis of a flapping foil, the CFD solver should consider the large deformation of moving boundaries. As aforementioned, VGD plays a role in computing the deformation of the entire fluid grids from the displacement of the moving boundaries, which is made by a motion generator in Fig. 2.

Results

A. Performance measures of grid quality

The orthognality change is calculated from the following equations with the edge vectors.

$$
\begin{aligned}
&\mathbf{v}_1 = \mathbf{x}_{i+1,j,k} - \mathbf{x}_{i,j,k} \\
&\mathbf{v}_2 = \mathbf{x}_{i,j+1,k} - \mathbf{x}_{i,j,k} \\
&\mathbf{v}_3 = \mathbf{x}_{i-1,j,k} - \mathbf{x}_{i,j,k} \\
&\mathbf{v}_4 = \mathbf{x}_{i,j-1,k} - \mathbf{x}_{i,j,k} \\
&q_k = \frac{1}{4}\left\{ \frac{(\mathbf{v}_1 \cdot \mathbf{v}_2)^2}{\mathbf{v}_1^2\mathbf{v}_2^2} + \frac{(\mathbf{v}_2 \cdot \mathbf{v}_3)^2}{\mathbf{v}_2^2\mathbf{v}_3^2} + \frac{(\mathbf{v}_3 \cdot \mathbf{v}_4)^2}{\mathbf{v}_3^2\mathbf{v}_4^2} + \frac{(\mathbf{v}_4 \cdot \mathbf{v}_1)^2}{\mathbf{v}_4^2\mathbf{v}_1^2} \right\} \\
&q_{i,j,k} = 1.0 - \frac{q_i + q_j + q_k}{3} \\
&q_{i,j,k}(t) - q_{i,j,k}(t=0))/\ q_{i,j,k}(t=0)
\end{aligned}
\tag{2}
$$

The volume change is simply calculated as follows:

$$
(V_{i,j,k}(t) - V_{i,j,k}(t=0))/\ V_{i,j,k}(t=0) \tag{3}
$$

B. Performance of grid quality

1) Large pitch angles

Pitch angles are changed by 45, 60, and 75 degrees. Fig. 3 shows volumes changes when the number of time steps increases. The Jacobian option updates the stiffness of the macro elements that plays roll in resisting the deformation. That is the reason why the volume change decreases as the number of time steps increases.

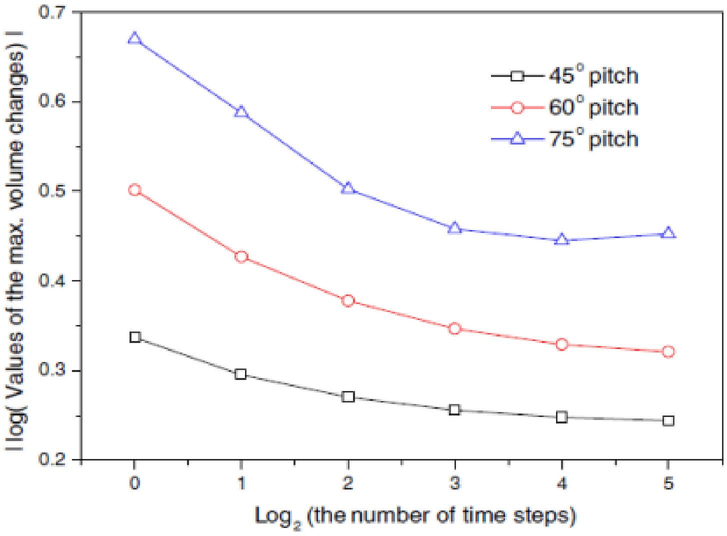

Figure 3 Volume change .vs. the number of time steps

2) Span flexure

Span flexure is given along the spanwise direction by a parabolic equation. The orthogonality and volume changes are depicted in Fig. 4. There are little orthogonality changes near the object while the some volume changes are existed. It is noted that the orthogonality change is more important than the volume change in order to obtain the accurate solution of the structured grid system.

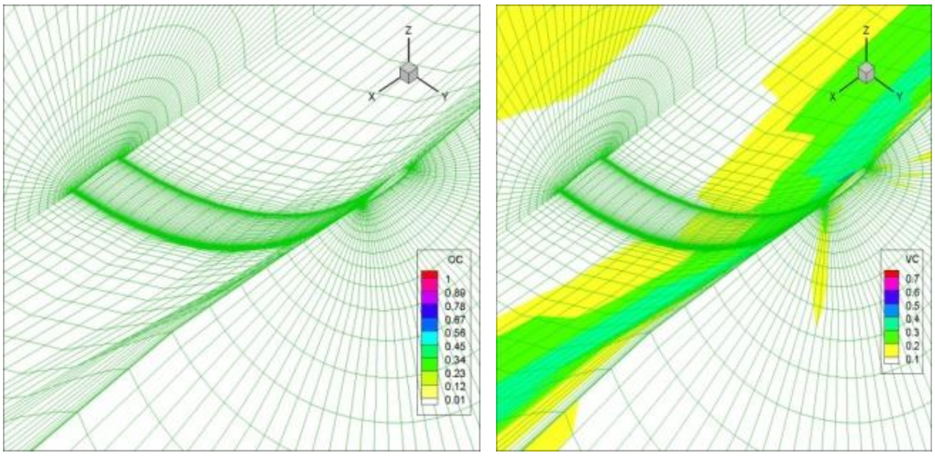

Figure 4 Orthogonality and volume change

Numerical experiment of the power extraction is conducted with the 50 pitch angle amplitude and 0.5c heave amplitude given. The force and moment coefficients are shown in Fig. 5. The power efficiency C_p is calculated by 24% from the results as compared to flow energy with 2m/s flow speed.

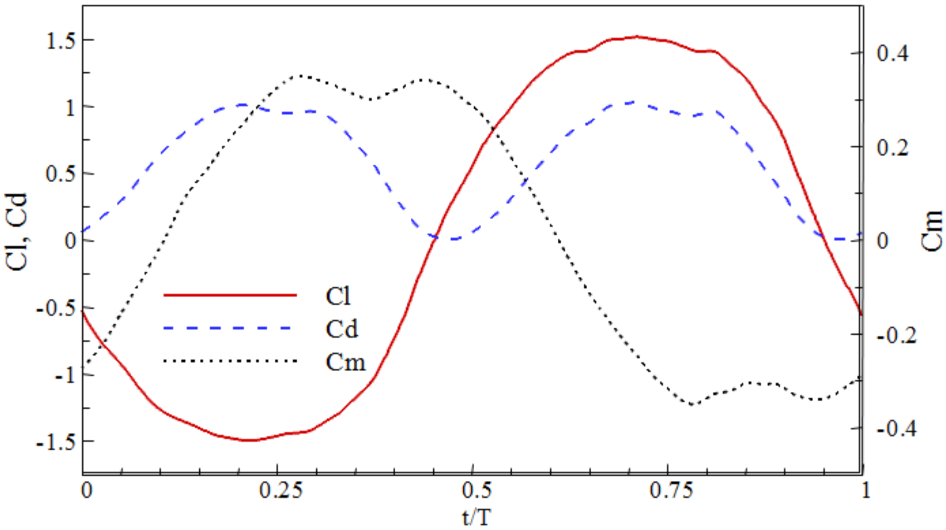

Figure 5 Force and moment coefficients versus time

Conclusion

Grid deformation based on macro element is able to preserve a good grid quality after a large deformation and rigid motion are given. Flapping mechanism for power extraction needs a much larger motion as well as structural deformation than that for propulsion applications. Hence, Jacobian option and partitioning schemes are enhanced. Here, the grid quality is measured by orthogonality and volume changes. Good grid quality is presented through validation for cases of large pitch and span flexure. Therefore, the grid deformation is usable for analyzing a flapping mechanism

Acknowledgement

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