Zipper layer method for linking two dissimilar structured meshes

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ABSTRACT

A novel meshing method named the zipper layer method is presented, which links two topologically different multi-block structured meshes together without overlapping or hanging nodes. It can either locally or globally connect two dissimilar structured meshes with a small number of tetrahedra and pyramids on either side of the interface to form a conformal mesh. To test the method, the results using a zipper layer mesh and a fully structured mesh are compared regarding solution accuracy and convergence. This method has been demonstrated for several applications of turbomachinery interest, where quality multi-block structured meshes are connected and the numerical flow solutions on these zipper layer meshes are also shown.

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1. Introduction

Quality meshing for complicated geometries is still one of the main bottlenecks for engineering design. Neither the structured nor the unstructured mesh techniques can satisfy the industrial needs. Generally, a body-fitted structured mesh gives higher accuracy for CFD simulations; however, it is very labour intensive to generate a quality multi-block structured mesh for complicated geometries. To address this problem, some recent effort can be found to automate the multi-blocking topology generation process. For example, Tam and Armstrong [1] used the medial axis technique to subdivide the 2D geometry into meshable subregions/blocks. Price and Armstrong [2,3] further extended the method to 3D geometry by employing the medial surface method, which requires a series of templates for subdivision. However, it is difficult for the templates to cover all the geometries, thus limiting its application.

More recently, aiming for quality hexahedral meshes, unstructured hexahedral meshing [4–6] or hex/quad dominated meshing have gained some attention. Tautges and Blacker [7] first developed the Whisker Weaving method which generates the unstructured hexahedral meshes by employing the spatial twist continuum (STC) [8], but wrong connectivity may sometimes result. The H-morph method developed by Owen [9,10], creates hex-dominated meshes by combining the tetrahedra into hexahedron from a fully unstructured tetrahedral mesh, hence the quality of resultant mesh relies on the original tetrahedral mesh.

Hybridizing structured and unstructured meshing techniques to retain their advantages has been studied for potential solution to high quality automatic meshing. One method is to generate high quality structured meshes for different parts, and then link them together to form the final mesh. The patched grid method for finite difference methods was developed by Rai [11] and extended to finite volume methods by Walters et al. [12]. In this method, the non-conformal interface needs special treatments when solving the governing equations. Rai used a piecewise-constant reconstruction at the interface to
achieve a first order accurate and global conservative scheme. However, a stair-like effect was observed when interpolating from a coarse mesh to a fine mesh. Biedron and Thomas [13] proposed a second order accurate patched grid method to overcome the problem. Lerat and Wu [14] developed a conservative and unconditionally stable algorithm for dissipative difference schemes. Recently, Zhang et al. [15] proposed a conservative remapping method, in which Essentially Nonoscillatory ENO [16] and weighted ENO [17] were applied to select or combine the stencils for the patched mesh. Almgren
Fig. 4. The dual fast march method (solid line: Mesh A; dashed line: Mesh B).

Fig. 5. Node movement.

Fig. 6. Triangulation of the polygon. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
et al. [18] applied patched grid method to design adaptive grid embedding algorithms for resolving near-wall regions in direct numerical simulation and large eddy simulation [19,20] of turbulent flows.

For patched meshing, if the interface is curved and has different grid point distributions on either side of the interface, gaps and overlaps (as shown in Fig. 1) are unavoidable, causing problems with the conservative properties of the interpolation [13]. In light of the study by Benek et al. [21], the solution accuracy is reduced due to the loss of the conservative property at the interface. Though aforementioned patched grid methods claim the conservative property at the interface, it only holds if the interface is planar or two meshes match exactly to each other on the interface. This restraint of the patched grid method greatly limits the application of patched grid to arbitrary complicated geometries.

Another popular approach is to allow for overlapping of meshes around different components, such as the Chimera Overset Grid [21]. Based on this, the DRAGON (direct replacement of arbitrary grid overlapping by nonstructured) mesh is developed by Kao and Liou [22,23] which generates structured meshes for different components and then is assembled
Recently, a novel method called the buffer layer method, developed by Qin et al. [24], has been developed combining unstructured cell layers to link topologically different structured meshes together to form a conformal mesh. It avoids the hanging nodes in the mesh by using pyramidal layers, prismatic layers and tetrahedral layers to bridge the two structured meshes. This method further enlarges the scope of the application of the generic hybrid mesh. Though the buffer layer method can link the structured meshes, it was found that the robustness is a problem in applications when the linkage is required in a very small gap.

To overcome this problem, a novel method, named the zipper layer method, is proposed in this paper. The zipper layer method introduces unstructured meshes at the interface to link two structured meshes without any hanging nodes or non-conformal mesh vertices. Therefore the conservative property is maintained without any special treatment even on curved interfaces. In this way, joining the two topologically different multi-block meshes negates the need of interpolation at the interface. In addition, by using the zipper layer method, the multi-grid convergence efficiency can also be maintained as shown later. This method provides design engineers with an automated high quality mesh generator, which can be easily integrated in the design process. High quality meshes can be ensured by linking multi-block structured meshes around various product components, such as rotor blades, casing treatment and cooling holes.
Fig. 11. Zipper layer mesh.

(a) Zipper layer mesh    (b) Transparent view of zipper layer mesh

(c) Tetrahedra in the zipper layer mesh    (d) Pyramids in the zipper layer mesh

Fig. 12. Local zipper layer mesh for NASA Rotor 37 without groove.
2. Zipper layer method

The essence of the zipper layer method is to generate an interface mesh as a media (a zipper) to link two different structured meshes which share the same interface. The interface mesh contains all the nodes and edges of the two meshes at the interface and the two structured meshes can be linked together by splitting some hexahedra on either side of the interface. Being able to generate a valid linkage even in a tiny gap, this interface mesh offers more robustness, since only some existing hexahedra are split when it is necessary, so that the minimum linkage cells are generated at the interface.

The whole process can be divided into the following steps:

(1) Identify the node positions at the interface of the two multi-block structured meshes by using the dual fast march method which will be detailed in the next section, Fig. 2(a);

(2) find intersecting points and polygons formed by edges from the two meshes at the interface, and merge the nodes or project the nodes to the edge when it is necessary, Fig. 2(b);
(3) generate an unstructured surface mesh (triangles and quadrilaterals) by triangulate the polygons generated in step (2), Fig. 2(c);
(4) insert nodes at the geometric centres of the hexahedra which need to be split on either sides of the interface, and then generate unstructured volume cells on both sides of the interface, including tetrahedra, pyramids and hexahedra, Fig. 3.

2.1. Dual fast march method and node movement

In order to correctly split the cells and move the nodes, the connectivity between the two meshes must be established first. A method called the dual fast march method is developed to locate the surface cell position in Mesh B for the nodes in Mesh A on the interface. Based on the essence of the fast march method [25] applied on a single mesh, the dual fast march method is applied on the two different meshes simultaneously. As this method only searches the nearby cells, it can significantly decrease the search time than the brutal force search. The steps below outline the process of the dual fast march method:
Fig. 17. Entropy comparison along a line across the tip gap. (a) Position; (b) distributions.

(a) Starting from Seed Node S1 (a corner node or a node along the boundary) in Mesh A, find Seed Cell, SC1, in Mesh B containing S1. This can be done efficiently to start the process (Fig. 4(a)).

(b) Set the adjacent nodes of S1 as Trial Nodes T1, . . . , T4 in Mesh A, and the adjacent cells of SC1 as Trial Cells TC1, . . . , TC4 in Mesh B (Fig. 4(b)).
Choose a trial node and check whether the trial node is in the seed cell (SC1) or the trial cells (TC1,...,TC4). If the node is in the seed cell or the trial cells, set this node as a new seed node, S2, and go to step (b), as shown in Fig. 4(c). If the node is not in the seed or trial cells, set the trial cell’s neighboring cells as new trial cells and extend the search.

(d) Stop the procedure when all the nodes in Mesh A have found their corresponding cells in Mesh B. The dual fast march method is then completed.

Before triangulation of the interface surface mesh, to eliminate the sliver cells, node movement is adopted. Once the node position is located, some nodes are then moved or projected to the edge based on their locations. As shown in Fig. 5, Node B is near Edge CD, so Edge CD becomes CBD to eliminate the small triangle which will be generated in the next procedure, while Node A is very close to Node E, hence these two nodes can be merged together.
2.2. Generation of interface mesh and volume mesh

In order to generate the unstructured meshes on the interface, some of the edges on both sides of the meshes are split by the intersection nodes. As shown in Fig. 6, the cell’s four edges (the red edges in Fig. 6) are split by the intersection with another mesh (in green in Fig. 6). The interface mesh is formed by the newly generated edges and the original edges which have not been split. In Fig. 6, the triangulation method is as follows:

1. Find the polygon which has more than four sides;
2. Insert a point into the geometric centre of the polygon;
3. Link the point with the two end nodes of each edge of the polygon to form triangles.

Fig. 7 illustrates how a 2D interface mesh is generated. Figs. 7(a) and 7(b) are two topologically different structured meshes, whereas Fig. 7(c) is the interface mesh, and Fig. 7(d) is the magnified view of Fig. 7(c). It is clear that the majority of the cells remain unchanged, only a few cells are split, which is a great advantage of the zipper layer method.
The volume mesh is created by splitting the hexahedra which contain the split edges. First insert a point into the geometric centre of the hexahedron, and then link the end points of the edges to form tetrahedra or pyramids. Hence there are three types of cells in the zipper layer mesh, namely tetrahedron, pyramid and hexahedron, as shown in Fig. 8.
3. Examples and numerical applications

Before diving into the complicated geometry, a simple geometry is demonstrated to illustrate the basic view of the zipper layer mesh and its capability. In Fig. 9(a), a uniformly distributed structured mesh is on the top of a non-uniformly distributed mesh. The red surface highlights the interface surface where an interface mesh will be generated to link the top and bottom meshes, as shown in Fig. 9(b). With the nodes on the interface surface and the intersection nodes, an interface mesh is then generated, as shown in Fig. 10. Since the bottom mesh is smaller than the top one, all the top cells are split while some of the cells at the bottom remain unchanged because they are ‘contained’ in the cells on the top. In order to form the volume mesh, the hexahedral cells are then split based on the interface mesh. In Fig. 11(a) and (b), the zipper layer mesh is shown, while (c) and (d) show the tetrahedral and pyramidal elements in the zipper layer mesh.

3.1. NASA Rotor 37 case

The NASA Rotor 37 case is used here as the test case to verify the method. It is an isolated axial-flow compressor rotor designed and studied experimentally at NASA’s Lewis Research Center (now NASA Glenn Research Center). The geometry of the blade can be found in the AGARD report [26]. In rotor design, a tip clearance which is usually larger than aerodynamically desirable is necessary. The tip clearance is made as small as possible to account for the change in blade position at different operating conditions and for manufacturing limitations/tolerance. However, tip clearance effects can reduce the operating range, pressure ratio and efficiency of a transonic axial compressor. Thus, casing treatment such as a stepped tip gap or “grooves” is used to alleviate the blockage and extend the operating range of the rotor. Nevertheless, the topology changes dramatically from the blade tip to the grooved casing wall in a short distance (tip gap), which is difficult to mesh using pure multi-block structured mesh.
3.1.1. Local zipper layer mesh

The zipper layer can be created locally at the interfaces of multi-block mesh components, named the local zipper layer mesh, or globally for the whole interface across the computational boundaries. In this section, the local zipper layer method is tested by locally linking a single groove mesh to the casing mesh. Two different geometries (with/without groove) were tested. The former is for comparison and verification of the zipper layer method with the original multi-block structured mesh, where it is applicable.

Fig. 12 shows the local zipper layer mesh. As can be seen from the picture, the zipper layer mesh is introduced directly on the casing near the middle chord, and then the groove part is removed for the numerical comparison with the structured mesh. The same HYDRA [27] solver (Rolls Royce’s in-house flow solver) is used with both meshes with 4 levels of multi-grid with a CFL = 2. The wall function and the Spalart–Allmaras turbulence model were used. All the solid walls were treated as non-slip adiabatic. A subsonic inflow condition was specified at the inlet where the total pressure and temperature profile were set according to the data from the AGARD report [26]. A radial equilibrium subsonic boundary was used at the exit, which allowed for a single pressure to be specified at a given radial point from which the exit pressure was calculated.

The convergence history of the case at peak efficiency condition is shown in Fig. 13. The results on both meshes are similar and both residuals converge more than six orders after 500 iterations with 4-level multi-grids. Since the two different meshes have almost the same number of mesh cells, both took about four hours on the same 8-core parallel computing
Fig. 29. Entropy contours.

Fig. 30. Global zipper layer for open rotor case.

system. In Fig. 14, the pressure ratios calculated on different meshes are compared. In order to verify that the local zipper layer mesh does not degrade the mesh quality, several zipper layer meshes are generated for comparison. The results from the local zipper layer mesh method show almost identical pressure ratios against inlet flow rates to those on the multi-block structured mesh, comparing well with the experimental data. Fig. 15 shows the comparison of the total pressure along the span. Both results on the zipper layer mesh and the multi-block structured mesh are comparable to the experimental data. In Fig. 16 the entropy contours on the local zipper layer mesh and the multi-block structured mesh are compared. Even in the zipper layer mesh region where the unstructured cells including tetrahedra and pyramids are introduced, the entropy contours show little difference from the solution on the fully structured multi-block mesh. To analyze the results within the crucial gap region, where the zipper layer is located, the entropy distributions from the two methods along a line in the gap starting from the blade tip to the casing wall are compared in Fig. 17. The maximum difference between the two distributions is less than 0.17%, which further proves that the local zipper layer mesh introduces very little extra numerical errors (entropies) in comparison with the multi-block structured mesh.

The zipper layer mesh of the NASA Rotor 37 case with a groove sits at the casing right above the leading edge of the blade is shown in Fig. 18. From top to bottom the first several layers are fully structured mesh (groove). The zipper layer mesh is in the tip gap, and the rest of the mesh is the original multi-block structured mesh. The tip gap is very small (0.356 mm) which makes the buffer layer mesh difficult to generate high quality meshes; while in this case the zipper layer
The total pressure ratios are compared in Fig. 19. In this case the single groove changes the total pressure of the NASA Rotor 37 at different flow conditions.

3.1.2. Global zipper layer mesh

Different from the previous local zipper layer mesh, which locally links the groove mesh to the casing, the global zipper layer mesh is more general and can be easily implemented, e.g. for multiple grooves. It is tested here by linking the whole new casing mesh with multiple grooves to the mesh from the blade side. As the global zipper layer creates more unstructured interface cells, it is therefore less efficient than the local zipper layer method. However, it makes the treatment of multiple components such as multiple grooves much more straightforward in design and optimization procedure.

To verify the global zipper layer mesh, the results on the multi-block structured mesh and the global zipper layer mesh are compared. Fig. 20 shows the multi-block structured mesh and the global zipper layer mesh. Being different from the buffer layer method, the zipper layer method only affects the two layer meshes which can be seen in Fig. 20. Each mesh shown was run from the choke to stall condition and compared to the clean annulus experimental data. HYDRA was run as a steady state calculation with a 4 level multi-grid approach with a CFL = 2.0.

Fig. 21 shows the comparison of the total pressure ratios calculated on the zipper layer meshes, the MB structured mesh, the patched mesh and the experimental data. The results on the zipper layer mesh matches well with those on the MB structured mesh and the experimental data. The results from the patched mesh show poor comparison with the other methods and the experimental data, due to the numerical errors introduced from the solution interpolation at the patching mesh successfully links the first layer of the casing to the groove mesh. The total pressure ratios are compared in Fig. 19. In this case the single groove changes the total pressure of the NASA Rotor 37 at different flow conditions.

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interface. Note that this interface is the same for the zipper layer and all the solution parameters are maintained for this comparison. In Fig. 22, the total pressure ratios along the span at the peak efficiency condition are compared. Though the result on the global zipper layer mesh shows a slight deviation from the structured mesh at 90%–95% span, the two results are almost identical in the rest of the region. The uniformly distributed structured mesh on the casing side for the zipper layer case may account for the mismatch, as it improves the flow resolution in this region. In Fig. 23, the convergence histories are compared, where the global zipper layer mesh shows again similar convergence to that from the MB structured mesh.

Figs. 24 and 25 show the flow contours on the different meshes at 98% span. There is no obvious difference between the two meshes. In Fig. 26, the streamlines show the path of the tip leakage vortex which is critical to the stall. The results given by different meshes are similar to each other. The static pressure at 98% span is also compared in Fig. 27. The small mismatch is only observed at the leading edge, while most of the lines are identical.

Fig. 33. HP cavity.

After the verification and the validation of the global zipper layer method for the above case, a NASA Rotor 37 mesh with five grooves is generated using the aforementioned method. The five grooves have the same height, where the first groove starts from the place above leading edge. Fig. 28 shows the zipper layer mesh for this complicated configuration. The zipper layer method allows the connection of the high quality multi-block structured mesh around the rotor blade to the multi-block structured mesh in the grooves. As shown in Fig. 28, the zipper layer mesh is in the tip gap which links two different MB structured meshes together. So far these types of configurations are deemed to be hard to generate automatically by a pure multi-block structured mesh due to the complexity of combined geometry with grooves and blades. The most challenging part is that the tip gap is very small, and the two meshes change dramatically from one topology to the other. However, the zipper layer mesh method enables easy connection of the two meshes. In Fig. 29, the flow contours are sketched at near stall condition. By adopting this method, the groove mesh with the compressor blade can be generated automatically. A groove-casing optimization is conducted and an optimal configuration is obtained [28], which
proves the robustness of the method as the optimization process calls the zipper mesh generator many times due to the design changes.

3.2. Open rotor case

The zipper layer method can be applied to a wide range of flow problems, where conformal connection of quality mesh blocks is required. In this section, the global zipper layer mesh method is demonstrated for an open rotor case for aeroacoustic analysis. As can be seen from Fig. 30, the uniformly distributed farfield mesh for accurate acoustic calculation is smoothly linked to the clustered multi-block mesh around the rotor blade through the implementation of the zipper layer method. In Fig. 31, the convergence histories are compared. The zipper layer mesh converges at a faster rate than the pure multi-block structured mesh, because of the more uniformly distributed mesh in the farfield block. The entropy contours are compared in Fig. 32, showing no significant extra entropy generation across the zipper layer.

3.3. HP cavity case

The final test case is the solution of an HP (high pressure) turbine cavity with a non-axisymmetric pre-swirl cooling hole. It is a complicated geometry as shown in Fig. 33 and very difficult to generate a fully structured multi-block mesh. The cavity mesh is generated as a hybrid structured–unstructured type with structured hexahedral cells near the cavity wall for viscous resolution and the cooling hole mesh is a multi-block structured mesh (so-called butterfly topology), generated by PADRAM [29] (Rolls Royce’s in-house meshing software). The cavity mesh and the cooling hole mesh are connected easily and smoothly by the local zipper layer method, maintaining the quality of both meshes. The static temperature contours from the solution are shown in Fig. 34. The cooling air can be observed at the exit of the cooling hole with high temperature gradient.

4. Conclusion

A novel method for linking two topologically dissimilar structured meshes has been developed and presented. This method maintains the advantages of structured meshes in resolving viscous flow features near solid surfaces accurately while provides an effective means to connect these multi-block structured meshes with a zipper layer containing minimum unstructured mesh cells at the interface. Since the connection is conformal without overlapping cells or hanging nodes, solution interpolation is avoided. Solution efficiency is also maintained since the implementations of multi-grid acceleration and parallel computing are not affected.

Numerical tests show that the addition of the zipper layer mesh to a multi-blocked structured mesh maintains the solution quality and convergence of the flow solution for cases where pure multi-block structured meshes can be used. Linking the same multi-block meshes, the zipper layer method clearly outperforms the buffer layer method and the patched grid method in solution accuracy. The capability of the zipper layer method has been shown for a number of meshing problems of turbomachinery interest, including test cases for groove design optimization for compressor casing treatment, an open rotor mesh and a cooling hole mesh linkage to a turbine HP cavity.

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