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Volume mesh generation by rotational sweep

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Abstract

Sweeping is a powerful tool for generating good quality meshes in volumes that can be characterized as 2.5D. There exist robust algorithms for mesh generation by extrusion of a source surface mesh along a curvilinear path, with varying cross section, to the target surface. A characteristic of the sweeping algorithm is that the guide surfaces connecting the source and target are fitted with a structured quad mesh. This paper presents a generalization of sweeping algorithm to include cases where the swept volume is generated by rotation of the source surface(s) to the target surface(s), where source/target surfaces share edges or vertices. Setting up the sweep parameters on the guide surfaces and meshing the guide surfaces with a quad dominant mesh containing a strip of triangular faces at the axis of rotation is the crux of the new algorithm. We have used the rotational sweep algorithm described in this paper for meshing cut sections of components having rotational symmetry such as nozzles, injectors, and pipes.

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Keywords: Mesh generation; sweeping; 2.5D; rotational sweep

1. Introduction

A 2.5D volume is one which is generated by extrusion of a surface along a third dimension. The curvilinear path along which the surface is extruded or swept is known as the sweep axis. No restriction is placed on the shape and size of the cross-section at any location along the sweep axis, however, the cross-section must be topologically invariant through the sweep. Each surface bounding the volume plays one of the following roles: *source surface* where a topologically 2D mesh is generated before sweeping, *target surface* where the sweep ends and *guide surface* along which the source surface is swept to the target surface.

In thermo-fluid simulation, we often encounter components with rotational symmetry such as pipes, nozzles, injectors etc. In such cases, we can utilize the property of rotational symmetry to reduce computation time by modelling a cut-section of the geometry between symmetry planes with suitable boundary conditions. From the meshing perspective, sweeping is the preferred approach since it produces a mesh that can be aligned with geometric features and has relatively good quality compared to a completely unstructured mesh and it is the workhorse algorithm for producing all-hexahedral mesh, by sweeping all-quadrilateral surface mesh. Models with rotational symmetry have traditionally

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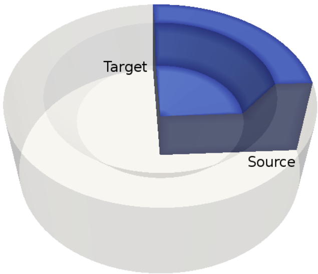


Fig. 1. Modelling a cut-section of a geometry with rotational symmetry

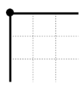
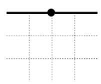
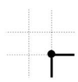
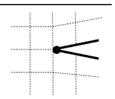
been swept by decompising the model into a “core”, which is swept along the axis of rotation, and an outer region, which is swept rotationally. In this paper, we describe a sweeping algorithm which can mesh such models in a single operation. As seen in Fig. 1 the volume of interest is swept around an axis of rotational, using source and target surfaces that share the axis of rotation and edges and vertices on that axis.

The discussion in this paper is limited to one to one sweep but the ideas discussed here may be extended to many to one and many to many sweeps. The rest of the paper is structured as follows: in section 2 we describe the terminology used in the sweeping algorithm. In section 3 we give a detailed explanation of how the sweeping algorithm can be modified to handle rotational sweep and in section 4 we discuss some improvements that can be incorporated in the rotational sweep algorithm.

2. Background

We assume that the volume to be meshed is represented as boundary representation (BREP) model where the surfaces are correctly oriented and the source and target surfaces have been identified. In order to understand the modification to support rotational sweep we will first review the sweep parameters defined in [1] that capture the geometric and topological characteristics of the volume. These parameters determine whether the volume is sweepable and if so facilitate the generation of a structured mesh on the guide surfaces and in the interior of the volume. In 2D, a structured mesh is one in which each non-boundary mesh vertex is connected to four other mesh vertices and is shared by four faces and in 3D each non-boundary mesh vertex is connected to six other vertices and is shared by eight cells.

Table 1. Vertex types

	END	*SIDE*	*CORNER*	*REVERSAL*
				
# faces connected to vertex	1	2	3	4
Ideal angle in degrees	90	180	270	360
Empirical numeric value	1	0	-1	-2

The *vertex type* of a vertex on a surface parametrizes the number of mesh faces connected to that vertex. Table 1 indicates the different vertex types available in curvilinear sweeping. If V is a set of all boundary vertices on a surface, then a structured mesh can be generated on the surface if the following condition is satisfied

$$\sum_{v_i \in V} VertexType(v_i) = 4 \qquad (1)$$

All guide surfaces satisfying Eq. 1 can be represented in a parametric space having two parameters i and k with + or - directions whereby each edge on a guide surface is assigned a signed edge parameter. The direction of traversal of edges is determined by the orientation of the surfaces and the assignment of signed i and k parameters is done according to the rules in Table 2. For sweep meshes, Ref. [1] proves that all guide surfaces fit into a globally consistent *i k* parametric space. A non-SIDE vertex on a guide surface induces a change in edge parameter. We define a *logical side* as contiguous edges that have the same signed edge parameter.

3. Rotational sweep algorithm

In a rotational volume, at least one guide surface has fewer than 4 logical sides. Adhering to the sweep parameters defined for curvilinear sweep will render the volume un-sweepable because Eq. 1 cannot be satisfied on the side deficient guide surface(s) and the edge parameters cannot be assigned without violating the rules of vertex traversal. Secondly, we cannot generate a pure quadrilateral structured mesh on a guide surface with fewer than 4 logical sides. The first problem is addressed by adding a new *vertex type* and corresponding rules of vertex traversal. The second problem is addressed by relaxing the requirement for a pure quadrilateral mesh on the side deficient guide surfaces and allowing triangular mesh faces on such surfaces.

3.1. Vertex types and transitions in rotational sweep

We introduce a new vertex type called *ROTATION*. A vertex on a guide surface that is shared by at least one source and at least one target is designated as *ROTATION* and a guide surface that has one or more *ROTATION* vertices is called a rotational guide surface. There is no ideal angle for this vertex type. In contrast to the other vertex types, the assignment of type *ROTATION* is based purely on topology and as such a vertex designated as *ROTATION* cannot be re-assigned to any other type and vice versa. The *ROTATIONAL* vertex type is assigned a numeric value 2. The rationale is that the presence of a rotational vertex on a guide surface is an indication of a missing logical side so it may be interpreted as being equivalent to two *END* vertices. The criterion (Eq. 1) to check whether a structured mesh can be fitted on a guide surface remains the same. In order to incorporate the new vertex type in edge parametrization, we must define additional set of rules for vertex traversal associated with the new vertex type as done in Table 2.

Table 2. Rules for traversal over vertex types encountered in rotational sweep

Current edge parameter	Next edge parameter after traversal over vertex of type				
	END	*SIDE*	*CORNER*	*REVERSAL*	***ROTATION***
+i	*+k*	*+i*	*-k*	*-i*	***-i***
+k	*-i*	*+k*	*+i*	*-k*	***-k***
-i	*-k*	*-i*	*+k*	*+i*	***+i***
-k	*+i*	*-k*	*-i*	*+k*	***+k***

3.2. Structured mesh on rotational guide surfaces

The transfer of mesh from the *i* edges on the source boundary to the corresponding *i* edges on the target boundary and the distribution of layers on the *k* edges of guide surfaces is the same as in the curvilinear sweep case. In this section we will concentrate on the use of the Transfinite Interpolation (TFI) algorithm for computing the position of internal vertices of a structured mesh on a guide surface. When the sweep is curvilinear, the TFI algorithm lends itself readily for computing the internal vertex positions on a four sided guide surface because the rectangular array of points fed into the TFI algorithm can be easily created from the mesh vertices on the four logical sides of the guide surface. On the other hand, a rotational guide surface has fewer than 4 logical sides, hence the construction of the rectangular array must be modified. A rotational vertex may be interpreted as a missing logical side on the rotational guide surface so the missing side in the rectangular array is created by repeating the mesh vertex associated to the rotational vertex of the guide surface. The number of times the vertex is repeated is equal to number of vertices on the opposite side. The structured mesh generated on the rotational guide surface will have a row of degenerate quad faces adjacent to the rotational vertex. The degenerate quad faces with repeated vertices are converted to triangular faces as shown in Fig. 2.

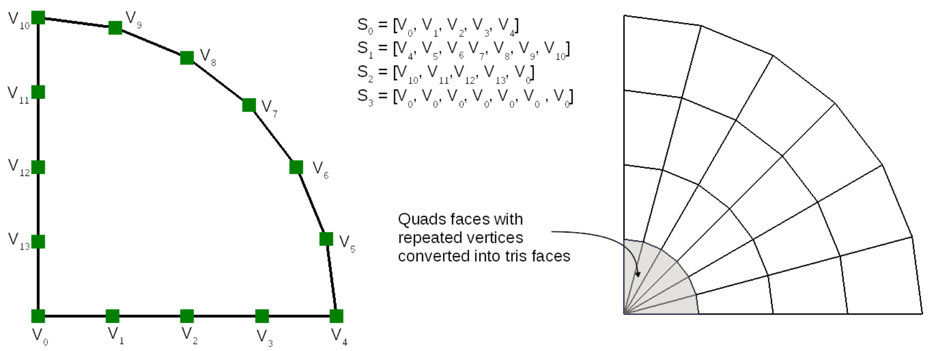


Fig. 2. Generating a quad dominant structured mesh on a rotational guide surface

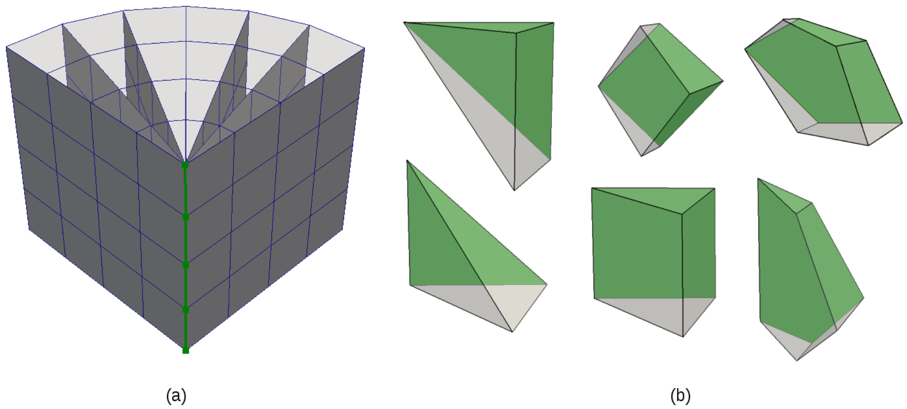


Fig. 3. Volume mesh generation a) Non-advance vertices and edges along axis of rotation b) Possible cell types generated along the axis of rotation

3.3. Generation of volume mesh

A structured volume mesh is generated in two steps:

1. Duplicate the source surface mesh topology on each non-source layer and create volume cells after establishing 1-1 correspondences between vertices, edges and faces on successive layers.
2. Compute position of internal vertices on each non-source layer.

When the sweep is rotational, there is a column of mesh vertices and edges along the axis of rotation that is shared between all the layers. We will designate such vertices and edges as *non-advance* (see Fig 3.a). The only change in the first step is that while marching from the source layer to the target layer, we will re-use the *non-advance* vertices and edges from from the previous layer instead of creating entities. As in the curvilinear sweep case, the volume cells are prismatic except the column of cells adjacent to the axis of rotational which are of general polyhedral shape depending on the type of face (triangle, quadrilateral or polygonal) on the source surface and whether the face has an edge or only a vertex on the axis of rotation (see Fig. 3.b). Once the cells are generated, the algorithm for computing the position of internal mesh vertices on each layer (refer [3], [4], [5]) is not affected by the presence of non-advance vertices and edges. Fig. 4 illustrates volume meshes generated in models of varying complexity.

4. Conclusion

We have presented a generalization of the sweeping algorithm to include rotational sweep where source and target surfaces share edges or vertices. We have implemented the generalized sweep algorithm presented here in the

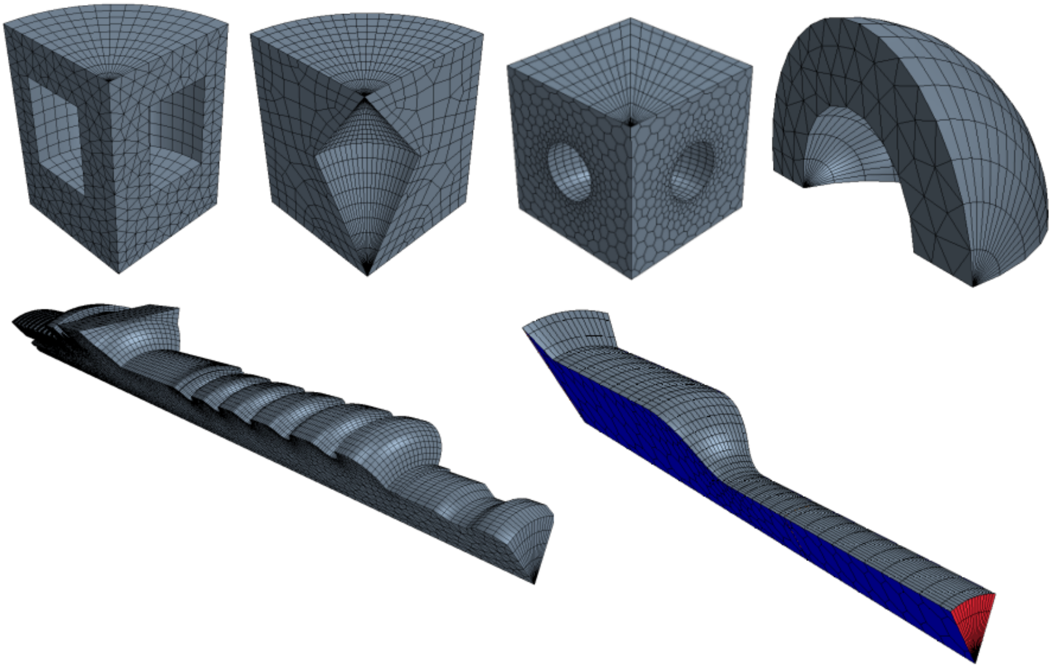


Fig. 4. Examples of volume meshes

Directed Mesh tool of *STAR-CCM+* software. We have tested our implementation on models of varying complexity and have found the algorithm to be robust. When a pure hexahedral or prismatic cell volume mesh is not a strict requirement, the rotational sweep algorithm is a robust option to mesh models having rotational symmetry. Starting from a good quality source mesh, the quality of the volume mesh is comparable to that produced by curvilinear sweep except in the neighbourhood of the axis of rotation. A limitation of the rotational sweep algorithm is the creation of poor quality cells along the axis of rotation when the user has specified a large number of layers. One way to overcome this drawback is to fuse adjacent cells near the axis of rotation axis thereby improving the aspect ratio of the cells. This method of cell quality improvement is under investigation.

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