CHAPTER 15
CLOSING REMARKS AND FUTURE WORK

15.1 Concluding Remarks

Two procedures for generation of anisotropic tetrahedral meshes were presented. The first is a procedure for generating boundary layer meshes for viscous flow simulations. The method, called the Generalized Advancing Layers Method is designed for reliable generation of valid, good quality meshes for arbitrarily complex non-manifold geometric model. It includes several technical advances to be able to handle complex domains that cannot be handled by other techniques. It also provides control and flexibility in the creation of meshes suitable for fluid flow simulations.

The technical contributions of the Generalized Advancing Layers Method are:

1. Ability to create valid meshes for general non-manifold models through the definition and use of mesh manifolds (Section 3.2.2 and Section 5.4).

2. Complete approach to controlling mesh quality and gradations in the boundary layer through the use of multiple growth curves (Section 5.5), multi-level transition elements (Section 7.8) and fixed and variable edge blends, (Section 7.9). Also, included in this approach are smoothing, shrinking and pruning for boundary layer mesh quality improvement and recursive adjustment of neighboring growth curves for improved mesh gradation (Sections 6.3, 6.4 and 6.5 respectively).

3. Comprehensive approach to shield the isotropic mesher from anisotropic faces using transition elements, blends and pruning of growth curves.

4. Definition and implementation of well defined set of checks for the creation of topologically and geometrically valid meshes particularly in the context of modification of the initial surface mesh to account for boundary layers (Section 5.6).
5. Several technical developments for the robustness of the procedure including development of new procedures for retriangulation of badly parameterized model faces based on recovery of edges in a surface mesh using local mesh modifications (Section 7.6 and [35]), alternate procedures to compensate for inability to modify the surface, assurance algorithms for prism validity (Section 7.7), and assurance algorithms to resolve self-intersections of boundary layers (Section 8.3).

6. Development of powerful but flexible methods for boundary layer specification and control (Section 5.8).

Results were presented to demonstrate the capability of the mesh generator to mesh complex non-manifold models while creating meshes with element sizes and gradations required to accurately capture the solution. Results of two classical problems in fluid mechanics were presented to demonstrate the suitability of the mesh for viscous flow simulations and its ability to capture the solution accurately. Also, the application of the mesh generator to create meshes suitable for simulations with free shear layers was demonstrated. The Generalized Advancing Layers Method has successfully generated meshes of the order of 3-4 million elements for other large complex geometric models and is currently being used for simulations on real automobile configurations in industry.

The second capability developed creates anisotropic meshes in models with thin sections using local mesh modifications. The procedures are designed to work in conjunction with any automatic isotropic mesh generator capable of providing an initial mesh. The method to create multiple elements through the thickness automatically identifies portions of the mesh that have less than the requested number of elements through the thickness and anisotropically refines those parts of the mesh using edge splits and swaps. The refinement algorithm can handle arbitrarily complex non-manifold models reliably.

Results were presented to demonstrate the capabilities of the procedures to create multiple elements through the thickness for various complex geometric models. Also, results of a heat transfer analysis were given to demonstrate the ability of the mesh to capture non-linear gradients through the thickness and to demonstrate
the savings in the number of elements that can be achieved using this mesh generator. The procedures were seen to identify deficiencies in the initial isotropic meshes well and refine them while controlling mesh quality.

The key technical contributions of the research on generation of tetrahedral meshes with multiple elements through the thickness are:

1. Automatic identification of thin sections in an initial mesh with insufficient number of elements through the thickness (Section 11.1).

2. Creation of multiple elements through thin sections by local mesh modification procedures followed by template based edge swapping (Section 12.1 and Section 12.2).

3. Qualification of constraints in wedge triangulations and techniques to overcome these constraints in the generation of multiple elements through thin section models (Section 12.3).

Results were presented to demonstrate the ability of the anisotropic refinement procedure of thin sections to handle complex domains and properly introduce the necessary number of elements through the thickness. This mesh generator has proven to be of considerable practical importance and has been used successfully to generate meshes for a wide range of applications including semiconductor device modeling, casting, injection molding, modeling of MEMS, electromagnetics, biomechanics, heat transfer analysis, coupled fluid-thermal simulations in intercoolers, chemical corrosion and structural analysis.

Both procedures presented here are being used within an overall framework for reliable automatic mesh generation of complex geometric domains for finite element simulations in a wide variety of engineering applications [62].

15.2 Future Work

There are number of ways the research presented in here can be further developed. Some of the necessary and desirable developments to boundary layer mesh generator to create better meshes for viscous flow simulations are:
1. Ability to create prism elements in the boundary layer.

2. Implementation of blend elements: This a key feature of the procedures necessary to shield the isotropic mesh generator from the anisotropic faces of the boundary layer mesh and is critical to the overall robustness of the meshing framework. In addition, the introduction of general blends with multiple growth curves is necessary for smooth mesh gradations.

3. Capability to generate boundary layer meshes with matching meshes on faces with periodic boundary conditions: This capability is of great practical importance as it can result in large savings in mesh sizes by taking advantage of symmetries in the solution. The central issue here is the matching of prism and blend diagonals on boundaries to be matched. As the reader may recall from discussion of boundary layer prism creation and prism templates in the generation of multiple elements through the thickness, there are constraints on how individual prisms and a set of connected prisms may be triangulated without refinement of the surface triangulation. These constraints must be respected and if necessary, a surface mesh refinement strategy devised to be able to match the boundary layer diagonals on two model faces.

4. Separation of growth curve from model boundaries: Recall that in this implementation, growth curves are constrained to be interior or boundary and only a specific type of partially boundary quad is dealt with. The ability to handle growth curves and quads with general classification is important to mesh quality.

5. General curvilinear shape for interior growth curves: This will allow better control over mesh quality.

6. Ability to partially unite or coalesce growth curves: While the current procedures allow the number of nodes to vary along a model face, they do not allow joining of two neighboring growth curves. This is an important capability that will allow the mesh generator to decrease the number of nodes and thereby automatically increase mesh size as the mesh proceeds towards the interior.
The key issue to be addressed for introducing this capability is the redefinition of adjacent growth curves.

7. Capability to adapt shear layers without redefining the geometric model: The current procedures require a model surface definition to be able to grow a boundary layer forcing the introduction of an artificial surface in the geometric model to represent shear layers or wake surfaces behind bluff bodies. It is more desirable to adapt the shear layer mesh independent of the shear or wake surface definition.

8. Parallel boundary layer mesh generation: The generation of large meshes for turbulent flow simulations, particularly Large Eddy Simulations, makes it necessary to parallelize the creation of boundary layer meshes and raises a number of open issues.

Future work in the development of the research on tetrahedral mesh generation with multiple elements through the thickness must primarily address the direct creation of layers of prisms between matching sets of mesh faces on opposite model faces. As per the discussion in Section 12.3, a surface refinement strategy must be incorporated into the procedures that will introduce the least number of points while maintaining mesh quality. In addition, general refinement procedures to eliminating remaining deficient paths must also be incorporated.

In conclusion, two robust automatic procedures for the generation of anisotropic meshes for complex non-manifold geometric models were presented as components in an overall framework for anisotropic mesh generation. The two works of research described addressed many key issues in the reliable generation of good quality anisotropic meshes for specific classes of problems. They were demonstrated to reliably generate quality meshes with suitable mesh sizing and gradation for capturing the solution in various problems accurately.