Hexahedral Meshing of complex and invalid CAD Geometries

Torsten Sadowski[1] and Robert Liebich[2]

[1] Berlin Institute of Technology torsten.sadowski@tu-berlin.de
[2] Berlin Institute of Technology robert.liebich@tu-berlin.de

Summary. The primary requirement for a mesh generator used in an automated tool is robustness. Surface based meshing algorithms fail very often especially with invalid boundary representation geometries. With generic boundary representation formats like STEP or IGES, invalid geometries are very common due to the loss of information and precision in CAD Data Exchange. This paper presents an approach to a robust hexahedral mesh generator that is insensitive to invalid geometries and produces meshes which can be used for stiffness calculations.

1 Motivation

A special preprocessor for the multibody system simulation of crankshafts (CADSimShaft [SL07]) is under development by the Chair for Engineering Design and Product Reliability at Berlin Institute of Technology. An important part of the preprocessing is the stiffness calculation of crankshaft parts. Stiffness calculation is a common task in mechanical engineering and easily done using the finite element method. But first of all a model preparation is needed that includes the most important part, the mesh generation.

CADSimShaft uses OpenCASCADE [OPE08] as its geometry kernel. The CAD models of the crankshafts are imported using generic CAD data exchange formats like STEP and IGES resulting in invalid geometries sometimes. But even if the geometry is valid the surface based mesh algorithms are not always successful. Of 44 different CAD crankweb models only 9 could be meshed using the available algorithms in the Salome [OPE06] project. Common cause for the failed meshes was a failure to create a consistent and closed surface mesh in order to initialize the volume meshing algorithm.

Robustness of the mesh generation process is an absolute necessity for the CADSimShaft software, even with geometrically invalid boundary representation models. All failures are surface related, therefore a new volume based mesh generator is being developed. Hexahedral meshes are preferred over tetrahedral meshes because of usually better computational results [BPM+95].

2 Volume based Hexahedral Meshing

Volume meshes can be build from a mesh of the surface of the model or directly without an existing surface mesh. The volume meshing algorithms presented in [Owe98] can be classified into both groups. The algorithms working directly with the surface or a surface mesh are: Boundary Constrained Triangulation, Advancing Front, Medial Surface, Plastering and Whisker Weaving.

Volume oriented algorithms do not require a surface mesh and cope better with dirty geometries[WS02][LLG+06]. They can be used as long as it is possible to check if a point is inside or outside of a volume. This can be successfully determined using the CAD kernel even if the surface representation is not completely valid. The Octree-based and Grid-based algorithms can be used for tetrahedral and for hexahedral meshing. An interesting variation of the octree for hexahedral meshes, the 27-tree, is presented in [SSW96].

3 CAD Model Preparation

Complete CAD models are unnecessarily complex for mesh generation. A reduction of their complexity is possible with the CAD software used to design the model. It is quite easy to export the design before all fillets and chamfers are applied if the full design model and not just a generic exchange file is available. A different approach is using feature recognition [Tau01] to remove needless detail. Much research effort is spent on the closely related automatic decomposition [Bla96][LG96][LGT99][LGT01]. Automatic decomposition is difficult to implement for complex shapes where fillets on other fillets might have erased the basic geometry.

Two more simple approaches do exist. Either the many small faces are combined to fewer but larger approximations [Mez08] or the individual faces are ignored and used to support a mesh node only if necessary.

Boundary Representations (BRep) of solid parts are constructed from six different topological entities: Vertex, Edge, Wire, Face, Shell and Solid [OPE07]. Three of these (Wire, Shell, Solid) carry organizational information only, the other three (Vertex, Edge, Face) have geometrical information as well.

Most of the edges result from fillet patches. These patches can be very small or narrow and have edges connecting tangent surfaces. They are detrimental to the mesh because of the small face they define. In order to maintain the shape it is necessary to identify those topological faces, edges and vertices which are important for the model.

Automatic classification can be based on entities carrying geometric information only. Possible classifications for faces are tangency at face boundaries, surface area and aspect ratio. Edges can be classified by tangency of connecting faces and length.

The general shape of CAD models is preserved good enough for most applications if all sharp edges and vertices at corners are represented in the mesh. Only a single parameter, the “sharpness” of an edge is necessary for an automatic complexity reduction of the CAD model. The required information is given by the standard exchange formats STEP and IGES. Tangency is therefore the most important classification possibility and can either be checked for each edge or for each face. Edge based classification is easier to implement because every edge is connected to exactly 2 faces whereas faces are bounded by n edges connecting them to n more faces. This is similar to [Mez08] but individual faces are not used to rebuild a new surface in the present approach.

Edge tangency checking is done by calculating the angle between the surface normals on the faces at several points along the connecting edge. If an angle is larger than a given threshold the edge must be considered in the mesh. The result is a number of master edges of the shape. Vertices at non tangent master edge connections are master vertices. Approximately one third of the topological edges and one eighth of the topological vertices are master edges and master vertices for all tested crankwebs.

Figures 1 and 2 give an impression of the reduction in complexity for a crankweb using an threshold angle of 6°. Only a fraction of the topological edges shown in fig. 1 is selected as master edges. The few master vertices are shown in fig. 2 as small crosses.

4 Implementation

The mesh can be created with an octree based algorithm or with a grid based algorithm. The grid based approach is easier to implement for a BRep model and results in a regular mesh for the first step. The grid is created with the help of the spatial twist continuum (STC) [MBBM]. The STC of a regular hexahedral grid is a regular hexahedral grid as well. Hence, the additional effort seems unjustified. On the other hand it is easier to manipulate hexahedral meshes using their dual STC [BMT$^+$97][TK03][HBO04]. Only one input parameter is used, the average element edge length.

The mesh generation is done in six steps: creation of the STC as a regular grid using ray-casting, deformation of the STC to fit the surface (similar in effect to [Dho99]), construction of the primal mesh, projection of primal mesh surface nodes on the model surface, paving of identified master wires, moving mesh nodes on master vertices.

5 Results and Conclusion

The robust meshing of the crankwebs as the most important target could be achieved. All crankwebs could be meshed into hexahedra like the example Fig. 3. First tests for stiffness calculations with hexahedral meshes showed good results. Because the true stiffness is not known, the results can only be checked against results from other FEM calculations which are currently used for the multibody dynamic simulation.

The meshes presented in this work are useful for stiffness calculations but not yet for stress analysis. But the mesh and its STC is a useful base for improvements using sheet insertion [HBO04]. The current study showed some elements along the master wires being deformed into concave shapes. Although this has not been a challenge for the method so far, sheet insertion to be used in the future would solve this[MT95][ZHB08][MESB08][PBSB08].

Fig. 1. Crankweb with all topological edges

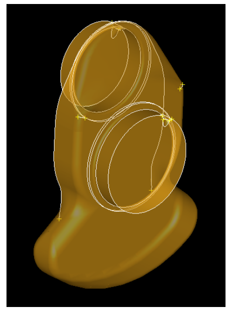

Fig. 2. Crankweb showing only master (sharp) edges

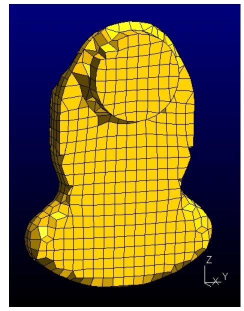

Fig. 3. Finished Mesh

References

[Bla96] Ted Blacker. The cooper tool. In *5th International Meshing Roundtable*, pages pp.13–30. Sandia National Laboratories, October 1996.

[BMT+97] T.D. Blacker, S.A. Mitchell, T.J. Tautges, P. Murdock, and S.E. Benzley. Forming and resolving wedges in whisker weaving and the spatial twist continuum. *Engineering with Computers*, 13:pp. 35–47, 1997.

[BPM+95] Steven E. Benzley, Ernest Perry, Karl Merkley, Brett Clark, and Greg Sjaardema. A comparison of all-hexahedral and all-tetrahedral finite element meshes for elastic and elasto-plastic analysis. In *Proceedings, 4th International Meshing Roundtable*, pages pp.179–191. Sandia National Laboratories, October 1995.

[Dho99] Guido D. Dhondt. Unstructured 20-node brick element meshing. In *Proceedings, 8th International Meshing Roundtable*, pages pp.369–376, South Lake Tahoe, CA, U.S.A., October 1999.

[HBO04] Nathan J. Harris, Steven E. Benzley, and Steven J. Owen. Conformal refinement of all-hexahedral element meshes based on multiple twist plane insertion. In *Proceedings, 13th International Meshing Roundtable*, volume SAND #2004-3765C, pages pp.157–168, Williamsburg, VA, September 19-22 2004. Sandia National Laboratories.

[LG96] Shang-Sheng Liu and Rajit Gadh. Basic logical bulk shapes (blobs) for finite element hexahedral mesh generation. In *5th International Meshing Roundtable*, pages pp.291–306. Sandia National Laboratories, October 1996.

[LGT99] Yong Lu, Rajit Gadh, and Timothy J. Tautges. Volume decomposition and feature recognition for hexahedral mesh generation. In *Proceedings, 8th International Meshing Roundtable*, pages pp.269–280, South Lake Tahoe, CA, U.S.A., October 1999.

[LGT01] Yong Lu, Rajit Gadh, and Timothy J. Tautges. Feature based hex meshing methodology: Feature recognition and volume decomposition. *Computer Aided Design*, 33:221–232, 2001.

[LLG+06] Y. K. Lee, Chin K. Lim, Hamid Ghazialam, Harsh Vardhan, and Erling Eklund. Surface mesh generation for dirty geometries by shrink wrapping using cartesian grid approach. In *Proceedings, 15th International Meshing Roundtable*, pages pp.325–338. Springer-Verlag, 2006.

[MBBM] P. Murdoch, S. Benzley, T. Blacker, and S. Mitchell. The spatial twist continuum captures the global connectivity of an all–hexahedral finite element mesh.

[MESB08] Karl Merkley, Corey Ernst, Jason F. Shepherd, and Michael J. Borden. Methods and applications of generalized sheet insertion for hexahedral meshing. In *Proceedings of the 16th International Meshing Roundtable*, pages pp.233–250. Springer-Verlag, 2008.

[Mez08] Andrey Mezentsev. An efficient geometrical model for meshing applications in heterogeneous environments. *Proceedings of the 16th International Meshing Roundtable*, pages 151–168, 2008.

[MT95] Scott A. Mitchell and Timmothy J. Tautges. Pillowing doublets: Refining a mesh to ensure that faces share at most one edge. In *Proceedings, 4th Internatinal Meshing Roundtable*, pages pp.231–240. Sandia National Laboratories, October 1995.

[OPE06] OPEN CASCADE SAS. Salome : The open source integration platform for numerical simulation. http://www.salome-platform.org, 2006.

[OPE07] OPEN CASCADE SAS. *Modeling Data User's Guide*, 2007.

[OPE08] OPEN CASCADE SAS. Open CASCADE Technology, 3d modeling & numerical simulation. http://www.opencascade.org, 2008.

[Owe98] Steven J. Owen. A survey of unstructured mesh generation technology. In *Proceedings, 7th International Meshing Roundtable*, pages pp.239–267. Sandia National Lab, October 1998.

[PBSB08] Michael Parrish, Michael Borden, Matthew Staten, and Steven Benzley. A selective approach to conformal refinement of unstructured hexahedral finite element meshes. In *Proceedings of the 16th International Meshing Roundtable*, pages pp.251–268. Springer-Verlag, 2008.

[SL07] Torsten Sadowski and Robert Liebich. Crankshaft slicing for multibody-system-simulation. In *SimDrive International User Meeting*, 2007.

[SSW96] R. Schneiders, R. Schindler, and F. Weiler. Octree-based generation of hexahedral element meshes. In *5th International Meshing Roundtable*, pages pp.205–216. Sandia National Laboratories, October 1996.

[Tau01] T. Tautges. Automatic detail reduction for mesh generation applications. In *Proceedings 10th International meshing roundtable*, pages pp 407–418, 2001.

[TK03] Timothy J. Tautges and Sarah E. Knoop. Topology modification of hexahedral meshes using atomic dual-based operations. In *Proceedings, 12th International Meshing Roundtable*, pages pp.415–423. Sandia National Laboratories, Sept. 2003.

[WS02] Z. J. Wang and Kumar Srinivasan. An adaptive cartesian grid generation method for 'dirty' geometry. *Int. J. Numer. Meth. Fluids*, 39:703–717, 2002.

[ZHB08] Yongjie Zhang, Thomas J.R. Hughes, and Chandrajit L. Bajaj. Automatic 3d mesh generation for a domain with multiple materials. In *Proceedings of the 16th International Meshing Roundtable*, pages pp.367–386. Springer-Verlag, 2008.