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博士の専攻分野の名称 博士（情報科学） 氏名 前濱 宏樹

学 位 論 文 題 名

Dimension-Driven Deformation and Adaptation of Finite Element Meshes for Efficient Computer Aided Engineering

（効率的 CAE のための有限要素解析用メッシュの寸法駆動変形とメッシュ適合）

Currently, digital engineering becomes widely used for efficient product design. Especially, Computer Aided Design (CAD) is used for cost reduction of product shape design such as auto mobiles and air planes. In addition, Computer Aided Engineering (CAE) becomes absolutely imperative because it can reduce costs of building prototypes and development work periods of products. In CAD and CAE systems, “solid models” and “mesh models” are used for representing product shapes. Solid models enable us to define volumetric shapes of products and edit them easily, can represent curved surfaces easily and precisely, and can be easily transformed to drawing data. Therefore, solid models are widely used in CAD systems. On the other hand, mesh models generated from the solid models are often used in Finite Element Analysis (FEA) which is needed to evaluate performance of products in CAE. In FEA, accuracy and calculation time of analyses are strongly affected by several factors of mesh models, and they have to be setting appropriately according to the purpose of the analysis.

In product shape design and analysis process using CAD/CAE, geometric operations for the products, e.g. changing dimension of the parts and object’s positions and orientation in the assembly, and evaluation of product shapes by FEA are repeated until a product shape with the desired performance is obtained. In current process, geometric operations are performed using solid models and FEA is performed using the mesh models. In general, in order to obtain the mesh models, meshing is applied to solid models. However, for complex shapes, meshing process is time consuming tasks and mesh models generated by meshing may needs to be modified manually in order to satisfy required quality. Moreover, in current process, because meshing is also repeated, it means that current process is inefficient. On the other hand, direct geometric operations for mesh models while keeping mesh properties can reduce the frequency of meshing. Therefore, methods for direct geometric operations of mesh models are required in order to realize an efficient product shape design process.

The purpose of this thesis is to develop certain geometric operations of finite element mesh models for efficient CAE process. To achieve this goal, a dimension-driven tetrahedral mesh deformation method is first proposed for efficient parameter survey. Second, a mesh adaptation method of tetrahedral meshes is proposed for efficient analysis of assembly models. Finally, the applicability of these two proposed methods to hexahedral mesh editing by a conversion method between tetrahedral meshes and hexahedral meshes is described.

This thesis mainly includes the following topics:

(1) Dimension-driven tetrahedral mesh deformation for parameter survey: dimension-driven mesh deformation is effective for finding optimal shape parameters because it can directly change the parameters of form features of product meshes. In this thesis, a new dimension-driven deformation method for tetrahedral meshes is proposed. The method consists of a mesh segmentation, dimension-driven shape deformation, and quality improvement. First, a surface segmentation method for tetrahedral meshes is proposed in order to extract dimensions of the input tetrahedral mesh. In the segmentation method, planar, cylindrical, conical, spherical, and torus surfaces with C0 or C1 boundaries are sequentially extracted. For extracting each surface segment, region-growing based on principal directions, normal vectors, and surface fittings are performed. Secondly, a dimension-driven shape deformation method for tetrahedral meshes is proposed. In this method, vertices of tetrahedral meshes are moved using a space embedding method and surface information obtained by the segmentation. The proposed de-

formation method enables us to change several feature parameters of mesh models such as not only height of a boss and radius of a cylindrical hole, but also radius of a fillet, angle of a chamfer, and so on, which cannot be handled by existing methods [Takano 2010, Onodera 2008, Xian 2009]. Finally, we propose a quality improvement method based on Optimal Delaunay Triangulation (ODT) [Chen 2011], which improves element shape qualities, mesh densities, and shape approximation accuracy from the boundary to the inside of the tetrahedral mesh. Through some experiments, it is shown that the dimension-driven tetrahedral mesh deformation method enables us to change parameters of the form features of tetrahedral meshes, such as the fillet radius and chamfer angle, while preserving mesh qualities such as the mesh density, shape approximation accuracy, and element shape quality.

(2) Tetrahedral mesh adaptation for efficient finite element analysis of assembly models: mesh adaptation can generate a conformal mesh from mesh models of multiple objects and space surrounding them (called object meshes and space meshes respectively in this thesis) by modifying the mesh connectivity and vertex positions on the contacting surfaces between the object meshes or the boundary surfaces of the object meshes and space meshes. Therefore, it is effective for some analysis of assembly models with movable parts such as structural analysis of assembly models and electro-magnetic field analysis of motors. However, the existing methods are inefficient because the mesh topology and geometry are globally adapted even if the differences in poses of the objects in motion are very small. In addition, the existing methods do not deal with contacts of the object meshes. In this thesis, a new efficient tetrahedral mesh adaptation method for moving objects with contact. In the proposed adaptation method, for efficient mesh adaptation, the mesh adaptation process is applied to only a set of space mesh elements around the moving object (deformed region). In addition, to keep mesh conformity on the contact regions between object meshes, the topology and geometry of surface triangular meshes of contacted object meshes are adapted by vertex repositioning and local topological operations. Moreover, in order to obtain high quality meshes, element shape qualities of the deformed region and the contact regions are improved by a quality improvement method based on ODT smoothing with local topological operations. By the tetrahedral mesh adaptation method, even if the object meshes contacted with each other, the conformal tetrahedral mesh of each motion step with moderate element shape qualities can be generated while avoiding drastic increase of elements on the contact region in at most 5s for conformal tetrahedral mesh including about 160k tetrahedra in an experiment.

(3) Validation of Deformation and Adaptation of Hexahedral Meshes based on Tet-Hex Conversion: hexahedral meshes are preferred over tetrahedral meshes because accurate FEA can be performed with the small number of elements by using hexahedral meshes. However, it is difficult to generate high quality hexahedral meshes for complex product shapes automatically. In addition, editing of hexahedral meshes such as deformation and quality improvement is difficult because local topological operations of hexahedral meshes are not established. Therefore, some conversion methods between tetrahedral meshes and hexahedral meshes have been proposed. In this thesis, in order to realize certain geometric operations of hexahedral meshes, the mesh deformation and adaptation methods developed in this research are combined with a conversion method between tetrahedral meshes and hexahedral meshes [Meshkat 2000], and the applicability of the proposed methods to hexahedral mesh editing are investigated. Although it is difficult to obtain all-hex meshes from deformed or adapted tetrahedral meshes by only performing the conversion method between tetrahedral meshes and hexahedral meshes, hex-dominant meshes after deformation and object motion can be generated by the combination of the proposed methods with the conversion method.