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Closed loop geometry based optimization by integrating subdivision, reanalysis and metaheuristic searching techniques

Guanxin Huang [a,b], Hu Wang [a,b,*], Guoping Wang [c,d], Guangyao Li [a,b]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, China
[b] Joint Center for Intelligent New Energy Vehicle, China
[c] Graphics & Interaction Laboratory, EECS Department, Peking University, China
[d] Beijing Engineering Technology Center of Virtual Simulation and Visualization, China

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ABSTRACT

A closed loop geometry based optimization method is developed in this work by integrating subdivision, reanalysis and metaheuristic searching techniques. For that purpose, subdivision surfaces using triangle meshes are simultaneously applied to CAD (computer aided design) modeling and CAE (computer aided engineering) analysis. In this framework, feature objects are defined by the subdivision model, so that the subdivision models can be controlled by geometric parameters. Global optimization with metaheuristic algorithms is then performed, and an independent coefficients (IC) reanalysis method is introduced to enhance the efficiency of optimization. In order to improve the accuracy of triangular meshes, the ES-FEM (edge-based smoothed finite element method) technique is employed for analysis work. The proposed approach is successfully tested in three real engineering geometry optimization problems.

1. Introduction

In conventional structural design, two kinds of models are used: CAD (computer aided design) and CAE (computer aided engineering) models. The CAE model is derived from the CAD model by meshing. Sequentially, when the simulation results based on the CAD model are obtained, designers should adjust the CAD model according to the analysis results. Finally, the modified CAD model should be re-meshed. Obviously, it is impossible to develop a closed loop geometry optimization system based on such framework. In this study, to overcome this defect, a subdivision based CAD/CAE optimization method is developed. Due to this characteristic, a closed loop optimization can be performed. In other words, geometric parameters can be optimized automatically without artificial interference. To further improve the efficiency of optimization, reanalysis methods are introduced. Thus, objective function and corresponding constraints can be evaluated efficiently.

The first important issue is to integrate the CAD and CAE models seamlessly. B-rep (Boundary representation) [1] is a widely used model representation in computer geometry design. Under the framework of B-rep, there are two different popular methods for geometric modeling: Non-Uniform Rational B-Spline (NURBS) and subdivision. For some historical reasons [2], NURBS are popular for CAD, and subdivision for animation and entertainment. Hughes proposed a CAD/CAE integration method based on NURBS, which is known as IsoGeometric Analysis (IGA) [3], and it has been well developed [4]. In the IGA, the shape function is chosen as the basis functions of NURBS. It not only integrates CAD and CAE seamlessly, but also creates a feasible way for structural optimization, because NURBS control points can be used as design variables. However, IGA based on NURBS is not perfect due to the quality of NURBS [5]. For example, (1) because basis functions do not satisfy the orthogonality condition, mistakes and overlap may exist in IGA meshes; (2) in some complex models, surfaces may be discontinuous among different patches. Compared with NURBS, subdivision has its own characteristics and advantages. NURBS are usually generated on the grid with a well-defined topology. Each node of the grid is a control point of NURBS. The continuity of these patches needs to be carefully handled by designers, especially at the intersection points of several patches. Conversely, subdivision can be generated on any polygon meshes without topological constraints. Therefore, subdivision can represent freeform surfaces without stitching patches. As subdivision level increases, mesh converges to a specific spline surface except for some extraordinary vertices. A detailed description of subdivision can be found in Ref. [6]. Recently, some scholars paid attention to the field of NURBS-compatible subdivision surfaces [2]. Many operations on NURBS have their counterpart on subdivision, which ensures that

* Corresponding author at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, China.

E-mail address: wanghu@hnu.edu.cn (H. Wang).

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the subdivision technology is suitable for CAD applications [7]. For example, trimming is an important and difficult operation in the NURBS based CAD system, and a bunch of methods have been developed for NURBS – symbolic, numerical or hybrid [8–10]. Trimming for subdivision surfaces is much simpler than for NURBS. The only concern is to constraint the boundary of the exact trim curve [11]. There are also methods for converting the trimmed NURBS surface to the Catmull-Clark subdivision surfaces [12].

More importantly, subdivision surfaces are usually based on simple polygons such as triangle (Loop subdivision [13], $\sqrt{3}$ subdivision [14]) and quadrangle (Doo-Sabin subdivision [15], Catmull-Clark subdivision [16]). Therefore, the CAE model can be discretized by the subdivision easily. Such idea of integrating CAD/CAE by using subdivision has also been developed recently [17,18]. However, triangle mesh (the simplest polygon) is not suitable for structural analysis. Hence, several methods were developed in order to improve the accuracy of triangle mesh, such as assumed natural strain (ANS) [19], discrete shear gap (DSG) [20] and edge-based smoothed finite element method (ES-FEM) [21]. Among them, the ES-FEM technique is used in this study to make triangle mesh more feasible.

Another important issue is to find the global optimum efficiently. In engineering optimization, objective functions and constraints are usually evaluated by large-scale simulations, such as FE (finite element) and CFD (computational fluid dynamics) analysis. With the increase of complexity of problems, computational cost of such a simulation based problem becomes more expensive. The popular strategy to overcome this bottleneck is to use a surrogate model instead of the exact function evaluation. However, error on predicted response value cannot be estimated and is difficult to be controlled. Surrogate assisted optimization (SAO) may miss the real global optimum and find a local optimum or even wrong results. Therefore, reanalysis methods are employed to improve the efficiency of optimization in this work. Predicted response values are more accurate than surrogate models and much closer to exact function evaluations. For these reasons, reanalysis can be directly integrated with some evolutionary global optimization methods such as genetic algorithm (GA). Reanalysis methods can be mainly divided into two categories: direct methods (DMs) and approximate methods. The DMs are usually suitable for low-rank or local modifications. They can obtain an exact solution of the modified structures. As stated by Tuckerman [22], any DM that solves a system by modification of an original model is an explicit or implicit application of the Sherman-Morrison-Woodbury (SMW) formula [23–25]. Cheikh and Loredo presented a DM based on a Moore Penrose generalized inverse for static reanalysis of structures [26]. Huang et al. developed the independent coefficients (IC) method for large-scale problems [27]. Song et al. proposed a direct reanalysis algorithm by updating the triangular factorization in sparse matrix solution [28]. Compared with DMs, approximate methods usually do not obtain an exact solution. However, high-rank or global modifications can usually be well disposed by these algorithms. Combined approximation (CA) [29–31] might be the most popular approximate reanalysis approach. The CA method was originally developed for linear static problems [32], and then extended to multidisciplinary problems. Kirsch and Papalambros presented a reanalysis approach for geometric changes in structural systems based on the CA method [33]. Rong et al. extended Kirsch's method to a new effective modal reanalysis method for topological modification [34]. Kirsch et al. used the CA method to overcome the difficulty of repeating eigenproblem solutions for nonlinear dynamic reanalysis [35]. Chen et al. suggested a universal iterative combined approximation (ICA) approach for all types of topological modifications [36]. Gao et al. proposed an adaptive time-based global reanalysis (ATGR) for dynamic problems based on CA method [37]. Zhang et al. applied the CA method to probabilistic analysis and reliability-based design optimization of large-scale structures [38]. Other approximate reanalysis methods were developed in recent years. Epsilon-algorithm was presented for both static problems [39] and dynamic problems [40]. Preconditioned conjugate gradient (PCG) method is a classical iterative algorithm. Kirsch et al. introduced this method for structural reanalysis [41], and Wu et al. developed PCG method for both removal of degrees of freedoms (DOFs) and added DOFs [42–44]. A matrix perturbation method was used by Yang et al. for structural modal reanalysis [45,46]. Wu et al. also developed a reanalysis method based on rational approximation for very large changes in design variables [47]. Zuo et al. suggested some alternative CA methods for static structural analysis [48,49]. Recently, Wang et al. developed a fast analysis platform called "Seen is Solution" for complex product design [50]. Reanalysis can be applied to structural optimization efficiently.

The major advantage of reanalysis methods is to predict the response of the modified structure instead of the complete analysis. However, the application of reanalysis methods in optimization is still not as popular as expected due to the gap between CAD and CAE models. The present reanalysis methods concern more about the non-geometric optimization problem. For example, Kirsch used the CA method to optimize cross-section of truss structures [51]. Huang et al. suggested to use the IC method to accelerate the process of topological optimization [27]. Cai et al. enhanced the efficiency of compliance optimization of a continuum with bimodulus material under multiple load cases [52].

In view of the above mentioned issues, the purpose of this study is to develop a closed loop geometry optimization procedure based on subdivision and reanalysis. The new method is tested in three benchmark problems. The rest of this paper is organized as follows. In Section 2, subdivision technology is briefly introduced and is applied in CAD/CAE integration. In Section 3, a reanalysis based geometry optimization approach is described. Section 4 describes the test problems and discusses optimization results. Conclusions are summarized in Section 5.

2. Subdivision in integration of CAD/CAE

2.1. B-rep based subdivision

The basic idea of B-rep is to use boundaries to represent CAD models. Particularly, an entity can be represented by its surfaces, a surface by its edges, an edge by vertices, and a vertex can be defined by coordinates. The information of surfaces, edges and vertices are recorded according to their levels. The connections between different levels form a tree data structure. An illustration of B-rep model and its data structure is shown in Fig. 1.

The edges and surfaces in a B-rep model can be represented using subdivision. Subdivision is a discrete modeling theory. The idea of subdivision is to refine the mesh in an iterative way, and to obtain smooth curves or surfaces at the limiting condition (Fig. 2). Nowadays, many outstanding subdivision algorithms have been developed for different purposes. For example, Chaikin algorithm [53] is used to generate subdivision curves; Loop subdivision and Cutmall-Clark subdivision [16] can be used to represent surfaces. As being employed in this study, the Loop subdivision and $\sqrt{3}$ subdivision are introduced in this section.

Assume that the vertex of initial mesh is $\mathbf{p}_i^0,\ (i = 1, 2, \ldots, n_0)$. After subdivision for k times, the vertex becomes $\mathbf{p}_i^k,\ (i = 1, 2, \ldots, n_k)$, where n_k indicates the number of vertices on the rank-k subdivision mesh (k = 0 indicates the initial mesh). On the rank-k subdivision mesh, assume that there are n vertices $\mathbf{q}_{i,j}^k,\ (j = 1, 2, \ldots, n)$ connected to vertex $\mathbf{p}_i^k$.