Computers & Industrial Engineering 57 (2009) 691–698

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Integration of CAD and boundary element analysis through subdivision methods

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ARTICLE INFO

Article history:
Received 1 June 2008
Received in revised form 13 January 2009
Accepted 14 January 2009
Available online 22 January 2009

Keywords:
Subdivision methods
Geometric design
Boundary element analysis
Mesh generation
Shape optimization

ABSTRACT

Subdivision methods have been mainly used in computer graphics. This paper extends their applications to mechanical design and boundary element analysis (BEA), and fulfills the seamless integration of CAD and BEA in the model and representation.

Traditionally, geometric design and BEA are treated as separate modules requiring different representations and models, which include continuous parametric models and discrete models. Due to the incompatibility of the involved representations and models, the post-processing in geometric design or the pre-processing in BEA is essential. The transition from geometric design to BEA requires substantial effort and errors are inevitably introduced during the transition. In this paper, a framework of realizing the integration of CAD and BEA was first presented based on subdivision methods. A common model or a unified representation for geometric design and BEA was created with subdivision surfaces. For general 3D structures, automatic mesh generation for geometric design and BEA was fulfilled through subdivision methods. The seamless integration improves the accuracy of numerical analysis and shortens the cycle of geometric design and BEA.

1. Introduction

Traditionally, geometric design and boundary element analysis are treated as separate modulus requiring different methods and representations, which include continuous parametric models and discrete models. NURBS (Non-Uniform Rational B-splines) (Piegl & Tiller, 1997), which are continuous parametric models, are often used for geometric design in CAD systems; while meshes, which are discrete models, are used in BEA. Due to the incompatibility of the involved different representations and models, the post-processing in geometric design or the pre-processing in BEA is essential. Therefore, conversion and remodeling are required for iterations between geometric design and BEA. Errors are inevitably introduced during the conversion and remodeling. The integration of geometric design and BEA has become more and more important.

One of ways in the integration of CAD and CAE components is direct using the CAD model for CAE downstream applications. Therefore, directly usable and accurate CAD models and data are highly desirable for the cycle of geometric design and BEA. However, CAD/CAE environments are generally heterogeneous due to highly task-dependent components with corresponding mathematical models. The requirements for the properties of the objects and mathematical models are different in areas such as grid generation and boundary element analysis (Andrey & Thomas, 1999), which are different from geometric design. Therefore, trimming operations for continuous parametric CAD models to generate trimmed patch boundary elements (Kane, Maier, Tosaka, & Atluri, 1993) and modifications of CAD models are often a necessity as a precursor to effective BEA mesh generation (Dan, 1998). Furthermore, CAD models with boundary representation can contain errors, such as gaps, incorrect topology of trimming curves. In most cases, the problems of these CAD errors do not affect the efficiency of graphical applications because these errors are too small to be observed visually. However, major problems are encountered in the creation of the downstream CAE mathematical models such as finite/boundary element meshes, which require the global continuity of the object boundary. Therefore, a CAD mathematical model of the object should be pre-processed to meet specific requirements of the downstream BEA application. The problem of CAD geometric model pre-processing is known as CAD repair (Andrey & Thomas, 1999). CAD model repair is defined as the process of fixing geometric and topological definition errors in a design model so that it can be used for the efficient creation of its computational model in a given downstream process, e.g. finite/boundary element simulation. There are various errors, which can be detected in CAD models. These errors include: inverted faces, gaps between surfaces in a volume, folded geometry, surface geometry with no bounding face, faces with no finite area, self-intersecting edges and faces, face/edge sloppiness, boundary edges that do not lie on the faces, overlapping faces, etc. Editing and fixing the geometry directly is cumbersome, tedious, and expensive (David, Sunil, & Steven, 2003). Informal studies reveal that engineering analysts are spending more than half of their time on re-working

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doi:10.1016/j.cie.2009.01.009

CAD files before analysis can begin. This situation gets worse with the growing usage and complexity of these models (Dan, 1998).

Subdivision methods can provide a common model or a unified representation for geometric design and BEA, avoiding the above problems inherent in traditional spline patch based approaches. Geometric discretization (mesh generation) in BEA is one of the major sources in the BEA error (Zhao & Wang, 1999). The accuracy and the convergence of the BEA solutions are strongly related to the quality of the BEA meshes (Liapis, 1994). The adaptive BEA can significantly improve the accuracy of BEA (Zhao & Wang, 1999). Therefore, automatic and adaptive BEA mesh generation is an important issue. Adaptive schemes in subdivision methods can generate adaptive BEA mesh automatically. Subdivision methods have multuresolution capability, and can generate different levels (fine or coarse) of mesh according to the requirement in accuracy. The goal of the research in this paper is to realize the advantageous features resulting from the integration of CAD and BEA based on subdivision methods. The subdivision-based integration can lead to at least the following advantageous features.

- A common model, unified framework and representation for geometric design and BEA.
- No post-processing in geometric design or pre-processing in BEA.
- No error due to the conversion from a geometric design model to a BEA model.
- Automatic and adaptive BEA mesh generation.
- Capability of mesh generation at different levels due to the multuresolution property of subdivision methods.
- Providing a new approach to studying the shape optimization for complex shapes.
- Allowing vigorous consideration of BEA issues at early design stage.

• Seamless integration, reduction in the trial-and-error, and remarkable shortening of the lead-time at the geometric design and BEA stages.

2. Subdivision methods and related research

Subdivision methods (Dyn, Levin, & Yoon, 2007; Kobbelt, 1996; Levin, 1999; Levin, 2000; Litke, Levin, & Schröeder, 2001; Sabin, 2005; Zorin, Schröder, & Sweldens, 1996a, 1996b; Zulti, Levin, Levin, & Taicher, 2006) generate a sequence of recursively-refined meshes (polyhedral surfaces) starting from an initial coarse control mesh. At each step of the subdivision, a finer polyhedral surface with more vertices and faces is constructed from the previous one via an iterative refinement process. After a few steps, the geometric design model of the object can be obtained. Fig. 1 shows the iterative refinement process for a 3D shape through the subdivision method.

2.1. Background review of subdivision methods

Chaikin (1974) first introduced the concept of subdivision to the graphics community for generating a smooth curve from a given control polygon. Since then, many subdivision schemes for modeling smooth surfaces of arbitrary topology have been derived. In general, these subdivision schemes can be categorized into two distinct classes: approximating subdivision and interpolating subdivision.

Catmull and Clark (1978) and Doo and Sabin (1978) were credited for the development of the approximating subdivision schemes. They extended bicubic and biquadratic B-splines respectively to arbitrary meshes. Later, Loop (1987) generalized the quartic 3-direction Box splines to arbitrary triangular meshes. Peters and Reif(1997) and Habib and Warren (1995) independently introduced schemes that generalized quadratic 4-direction Box splines on irregular meshes.

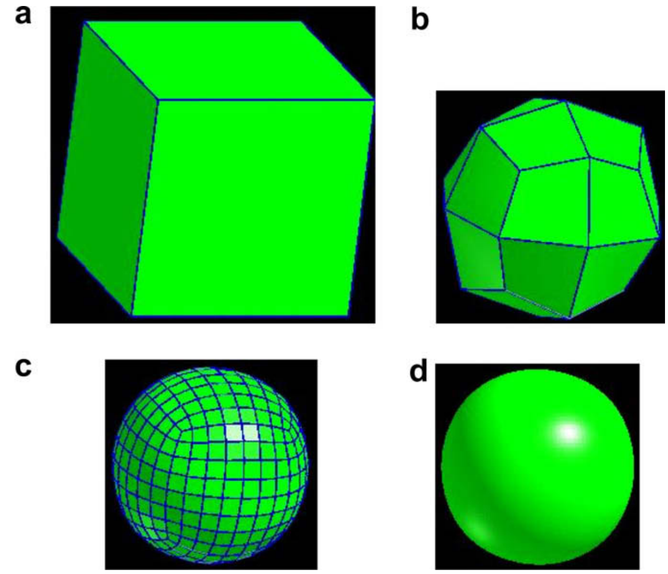

Fig. 1. 3D shape modeling by a subdivision process: (a) Initial control mesh. (b) Mesh after one subdivision. (c) Mesh after three subdivisions. (d) Limit surface and geometric model.

The most well-known interpolation subdivision scheme is the "butterfly" algorithm proposed by Dyn, Levin, and Gregory (1990). The Butterfly subdivision scheme, like other subdivision schemes, uses a small number of neighboring vertices for subdivision. It requires simple data structures and is extremely easy to implement. It was subsequently improved by Zorin et al. (1996).

Adaptive subdivision schemes (Cheang, Dong, Li, & Kuo, 2000; Dong, Li, & Kuo, 1999; Kobbelt, 1996) use local flatness information to perform selective subdivision refinement, which sharply reduces the numbers of the vertices and polygons of subdivision mesh. These schemes skip a large amount of flat mesh without performing subdivision on it, and focus on the feature-rich regions of the surface.

Combined subdivision schemes (Levin, 2000) consider boundary conditions based on conventional subdivision schemes. Special schemes are used on and near the boundary. Away from the boundary, ordinary subdivision schemes are used. Adi Levin used combined subdivision schemes to fill an N-sided hole (Levin, 1999). Trimming subdivision surfaces was also studied (Levin, 1999). Combined subdivision schemes can be used to design and preserve features of geometric shapes.

2.2. Subdivision schemes

Table 1 gives a brief overview of some subdivision schemes (Kobbelt, Bischoff, et al., 2000) and their basic properties. C^k really

Table 1
Subdivision schemes.

Doo–Sabin	Approx.	C^1	Quadrilateral	Dual
Catmull–Clark	Approx.	C^2	Quadrilateral	Primal
Kobbelt	Interp.	C^1	Quadrilateral	Primal
Butterfly	Interp.	C^1	Triangular	Primal
Loop	Approx.	C^2	Triangular	Primal
$\sqrt{3}$ Subdivision	Approx.	C^2	Triangular	Other