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Engineering feature design for level set based structural optimization ☆

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HIGHLIGHTS

- A method to design engineering features in structural optimization is proposed.
- It combines CSG modeling and level set based shape and topology optimization.
- Feature design and structural optimization are unified under the level set framework.
- A truly optimal structure with features can be designed conveniently.

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ABSTRACT

Engineering features are regular and simple shape units containing specific engineering significance. It is useful to combine feature design with structural optimization. This paper presents a generic method to design engineering features for level set based structural optimization. A Constructive Solid Geometry based Level Sets (CSGLS) description is proposed to represent a structure based on two types of basic entities: a level set model containing either a feature shape or a freeform boundary. By treating both entities implicitly and homogeneously, the optimal design of engineering features and freeform boundary are unified under the level set framework. For feature models, constrained affine transformations coupled with an accurate particle level set updating scheme are utilized to preserve feature characteristics, where the design velocity approximates continuous shape variation via a least squares fitting. Meanwhile, freeform models undergo a standard shape and topology optimization using a semi-Lagrangian level set scheme. With this method, various feature requirements can be translated into a CSGLS model, and the constrained motion provides flexible mechanisms to design features at different stages of the model tree. As a result, a truly optimal structure with engineering features can be created in a convenient way. Several numerical examples are provided to demonstrate the applicability and potential of this method.

1. Introduction

In structural design, engineering features refer to regular and simple shape units containing specific engineering significance [1]. They generally serve as a bridge between computer-aided design (CAD) and computer-aided manufacture (CAM), and also have a great impact on assembly [2]. Recently, as structural optimization techniques have been widely utilized to design innovative and lightweight products, it is practically meaningful to generate an optimal structural layout containing engineering features at an early stage of product lifecycle. However, this has been a challenge for standard structural shape and topology optimization.

Current structural optimization techniques for continuum structure can be categorized into three mainstreams based on different model representations. Firstly, the B-rep model based approaches [3,4] are the most suitable for feature design, as engineering significance is captured directly through the dimensional parameters or constraints in a CAD modeler. But it rarely supports topology optimization over an explicit model by modifying its parameters. In comparison, the density based approaches, such as the Homogenization Method [5], the method of Solid Isotropic Material with Penalization [6,7] and the Evolutionary Structural Optimization [8], are able to optimize structural topology conveniently. However, it is difficult to employ geometric constraints into optimization, because neither an explicit geometry nor feature concept is readily available from a finite element (FE) mesh model. Implicit model based approaches, such as level set based optimization [9,10], have the advantage of maintaining a clear structural boundary during a shape and topology optimization process. But due to its infinite dimensional nature, to track geometric consistency between consecutive updated models is nontrivial, such that feature constraints can hardly be imposed during optimization.

To enhance the applicability of structural optimization, several techniques have been developed for a simultaneously optimization of engineering features and structural layout. The key to address

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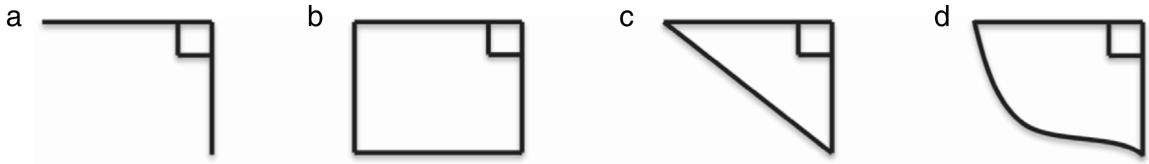

Fig. 1. (a) A right-angle feature; ((b)–(c)) feature in fixed geometry; (d) feature with a freeform boundary.

this problem is that the model representation must support both feature definition and topological change. In [11,12], a finite circle method was proposed to approximate the exact geometry of predefined feature components with circumcircles. The location and orientation of these circles can be determined together with a density based structural topology optimization. Besides, Kang and Wang [13] presented a novel topology description model to design movable hole-features by combining material density and level set models. On the other hand, for dynamic feature design problems, that the feature shape is not fixed a priori, the state-of-the-art solutions are mainly geometric primitives based. In [14], the Bubble method [15] was utilized to insert basic hole-features, such as circles and triangles, into a structure according to topological derivative analysis. The optimal design eventually comprises several simple feature shapes, which approximate the merged holes. Another parametric solution can be found in [16,17], in which they represented feature primitives by *R*-function and combined them with a *B*-spline model.

The integration of feature and freeform boundary design has profound meaning in structural optimization. For example, if a right-angle feature shown in Fig. 1(a) is expected in final design, all the shape of Fig. 1(b)–(d) are potential candidates to be modeled into an initial structure for optimization. Obviously, the one with a freeform boundary, as shown in Fig. 1(d), can lead to a better structural performance than the other two fixed geometry because of the extra design freedom over the non-critical boundary. This example reveals that under certain circumstances, it is unnecessary to use fixed high-level primitives to capture the critical engineering significance. Instead, if one can separate out feature characteristics and freely optimize non-critical regions, a truly optimal design of maximum structural performance can be eventually realized. In the literature, the method proposed in [16,17] can accomplish this task by carefully conceiving parametric constraints over the primitive's boundary.

A level set based optimization method has good potentials of designing freeform boundary meanwhile supporting flexible shape and topology optimization. However, there are two fundamental challenges to design features with the level set method. Firstly, as a structural boundary conventionally embeds inside an implicit model, a continuous shape evolution will make the underlying geometric consistency unpredictable. Hence, it is complicated to track any predetermined feature shape during optimization. Secondly, engineering features usually contain sharp characteristics, such as corners in 2D model or corners and edges in 3D model. Due to the inherent dissipation nature of numerical calculation, all of these high curvature regions will be gradually smoothed out during optimization.

In this paper, the above modeling difficulties are resolved by leveraging a CSG representation and an accurate constrained motion scheme. Inspired from the multiphase level set description in [18], a structural model here is built upon two types of entities: a level set model containing either a feature shape or a freeform boundary. These entities are the operands in a CSG model tree and serve as either feature models containing necessary engineering significance or freeform models (non-feature model) otherwise. An inherited advantage from the CSG modeling is that a structure can be flexibly constructed with different levels of entities according to design requirements. In this way, feature characteristics can be identified either through the shape of a particular feature model or the relation between lower-level feature entities (e.g. the right-angle determined by two line feature models in Fig. 1), rather than by simply resorting to a fixed high-level geometry.

Besides modeling features, it is important to devise a workable mechanism to preserve and optimize them. The idea of imposing motion constraints has been proven a viable way in designing structures for practical requirements. In [19], the design velocity of level set equation was regularized to ensure the optimal structure can be formed by casting. Moreover, the rigid body motion was justified in [20], which spurs polygon-shaped components to be positioned and oriented optimally inside design region. In this work, a constrained affine transformation coupled with an accurate particle level set updating scheme [21] is adopted to design feature characteristics. Specifically, it consists of translation, rotation and scaling, which can simulate most of the effects in deforming a geometric primitive by modifying its parameters [17]. The transformation velocity is determined from a least square fitting to the continuous shape variation. Meanwhile, non-feature models just undergo a conventional level set updating for freeform shape and topology optimization.

To demonstrate the proposed approach, this paper is organized as follows. Section 2 introduces the CSG based level sets representation. Section 3 presents a sensitivity analysis for linear elastic structural optimization problems. The constrained motion and implementation details are described in Sections 4 and 5 respectively. Section 6 shows several numerical examples. Finally, discussion and conclusion are stated in Section 7.

2. CSG based level sets

Constructive Solid Geometry is a ubiquitous solid model representation, which facilitates both set operations and boundary evaluation. In CSG modeling, because a structure can be assembled flexibly with different solid entities, it becomes possible to interpret practical machining or assembly requirements in terms of the geometry of and relation between feature entities (e.g. a low-level linear entity for a flat edge or surface, an angle intersected by two entities, or a high-level predefined mating geometry). The level set method, on the other hand, provides an effective way to freely optimize the boundary of a solid model. Intuitively, by combining the strengths of CSG modeling in feature definition and level set method in shape and topology optimization, a CSG based Level Sets (CSGLS) model description is adopted to address the problem of feature design in structural optimization.

The CSGLS represents a solid structure in terms of m individual sub-level set models $\Phi = [\phi_1, \phi_2, \dots, \phi_{m-1}, \phi_m]$. Each ϕ_i ($i = 1, 2, \dots, m$) is a well defined half-space model, denoting a geometric entity in the model tree. Among these models, a "feature model" contains feature geometry according to the engineering requirement, as opposed to a "freeform model" (non-feature model) with freely designable boundary embedded. The design domain D with a underlying structure Ω is thus formulated as $\Phi_D = \bigcap_{i=1}^{m} \phi_i$, and the followings are hold by convention:

$$\begin{aligned} &\phi_i(\mathbf{x}) > 0 \quad \forall x \in \Omega_i/\partial\Omega_i \text{ (inside)} \\ &\phi_i(\mathbf{x}) = 0 \quad \forall x \in \partial\Omega_i \text{ (on the boundary)} \\ &\phi_i(\mathbf{x}) < 0 \quad \forall x \in D/\Omega_i \text{ (outside)}, \end{aligned} \tag{1}$$