Finite Elements in Analysis and Design 120 (2016) 80–91

Contents lists available at ScienceDirect

Finite Elements in Analysis and Design

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

A moving bounds strategy for the parameterization of geometric design variables in the simultaneous shape optimization of curved shell structures and openings

Dan Wang*, Weihong Zhang, Jihong Zhu

The Laboratory of Engineering Simulation and Aerospace Computing, Northwestern Polytechnical University, Xi'an 710072, China

ARTICLE INFO

Article history:
Received 13 January 2016
Received in revised form
22 June 2016
Accepted 5 July 2016

Keywords:
Moving bounds strategy
Shape optimization
Mesh mapping
Arc-length rule
Shape preserving

ABSTRACT

A moving bounds strategy is proposed to implement simultaneous shape optimization of curved shell structures and openings. Design variables related to the hole shape are constrained in a planar reference domain by the moving bounds whose values are adaptively updated as functions of design variables related to the surface by an arc-length rule. It is shown that this strategy is essential not only to ensure the geometric consistence in the simultaneous design process but also to hold the shape-preserving of the mapped FE mesh from reference domains. Numerical results are presented to validate the proposed method.

1. Introduction

Thin-walled structures are widely used in aeronautic and aerospace engineering. To attain specific functional and structural purposes, such as weight-reduction, structure maintenance and detection, openings are always designed on the curved surfaces. For example, the cutout design of a fuselage is a typical case of perforated shell structures. Although this particular kind of design problems are very important, a full literature review shows that it is indeed a rather new research field in the community of shape optimization and few efforts are found on this subject. Until now, most contributions have been focused on shape optimization of either 2D planar curves [1–3] or 3D free surfaces [3–5] of a structure.

In the design procedure, coordinates related to control points of a parametric curve or surface are usually defined as shape design variables [1,3]. The parametric shape is therefore updated by the linear combination of these control points weighted with interpolation functions. Raghavan et al. [6] used shape interpolation to construct a hyper-surface and thus morphed exclusively between feasible shapes with a small number of variables. Parameter free optimization was carried out by Bletzinger and his co-workers [7,8]. In the approach, design variables are associated directly with the FE model, which provides an opportunity to define shape design variables without parameterizing the involved shape and also takes advantage of a large design space. The pioneer work of Zienkiewicz and Campbell [9] was, in fact, an earlier attempt to the parameter free approach but failed with a non-smooth zigzag boundary shape. It was not until related numerical problems were solved or avoided by regularization or filtering techniques [7,10] that the approach became effective.

However, shape optimization of openings on a 3D curved surface is a shape constrained problem. The idea of associating directly shape design variables with either the continuous or discrete boundary is no longer practicable in this case. Within this framework, a parametrical mapping method (PMM) for the definition of geometrical design variables of the openings on the 2D parametrical space, i.e., the planar reference domain was therefore proposed [11,12] by the authors. The PMM has the advantage of ensuring the moving boundary of the involved hole always on the specific curved surface during the optimization process. Meanwhile, the FE mesh attached to the perforated 3D surface is obtained by mapping the mesh attached to the reference domain. The virtual punching method (VPM) [13] provides another option to solve the problem by employing the existing commercial CAD software but suffers from the inefficiency of zero-order algorithms. Further investigations were made to generalize the PMM for the simultaneous shape optimization of curved surfaces and attached holes [14], as shown in Fig. 1.

* Correspondence to: P.O. Box 552, Northwestern Polytechnical University, 127 You Yi Xi Lu, Xi'an, Shaanxi, 710072, P.R. China. Fax: +86 29 88495774.

http://dx.doi.org/10.1016/j.finel.2016.07.002
0168-874X/

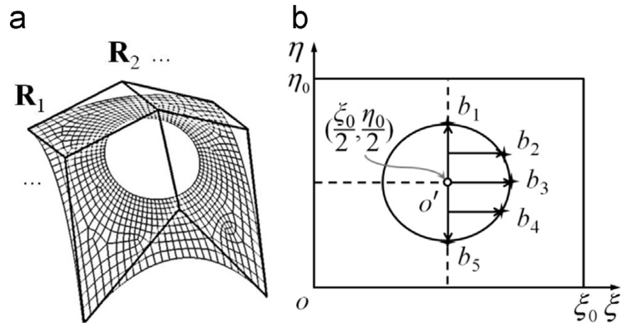

Fig. 1. Simultaneous shape optimization of the curved surface and attached holes: (a) definition of global design variables (GDVs) related to the curved surface shape; (b) definition of local design variables (LDVs) related to the hole shape.

However, as the 3D curved surface and the involved holes change their shapes simultaneously, it is necessary to match the variations described by the global design variables (GDVs) and local design variables (LDVs), respectively. This is essential to ensure the geometric compatibility between the surface shape and the hole shape. In other words, the LDVs have to be adaptively limited within the reference domain defined by the moving bounds to ensure the compatibility of the hole attachment on the shape-varying surface. Therefore, it is no longer valid to apply the traditional formulation of optimization problems with side constraints of fixed bounds. Until now, this issue has not been highlighted.

Another important issue is how to preserve the mesh quality when the latter is mapped from the reference domain along with the variations of GDVs and LDVs. In shape optimization of a curved surface, the mesh generation has to make sure that the discretization well approximates the surface geometry with an allowable precision [15] because the FE discretization of a CAD model is not only used for the CAE structural analysis but should also be updated after each design iterative step. This is therefore a hard nut to crack and spontaneously receives high attention of many researchers. A direct meshing of the curved surface would bring about many issues to be resolved [16–18] and undoubtedly deteriorate shape optimization procedure. Firstly, the FE discretization should follow the geometrical variations of the surface shape and openings of the CAD model. Secondly, the surface normal and tangent should be computed to direct the mesh generation. Thirdly, any inserted nodes must be precisely located on the curved surface and the intersection calculations are also required to avoid the element overlap. Moreover, as the stress concentration always occurs around the hole boundary, the neighboring mesh should be locally controlled with high density.

An alternative discretization approach is to mesh the parametric reference domain and then make the mapping to the curved surface [19,20]. This is applicable provided that the parametrical equation of a curved surface establishes a one-to-one correspondence relationship between points on the curved surface and the parametric space. However, as the mapping is generally a nonlinear operation, a regular mesh in the parametric space generally deforms after the mapping even for developable surfaces and degrades the FE analysis in the extreme case. For this reason, many researchers have committed themselves to generating isotropic mesh over a 3D surface from anisotropic mesh related to the planar reference domain of the parametric space. Usually, the mapping is carried out from a normalized square reference domain (NSRD) with 0–1 bounds. For example, Chen and Bishop [21] adopted the property of empty circumellipse instead of empty circumcircle to create Delaunay triangulation in the parametric space and used the surface curvature to control the surface mesh density. Based on the metric map, the advancing front approach [22] was improved by controlling the size and shape of the triangular mesh in the parametric space to generate well-behaving grids on the 3D surface. Soni and Yang [23] utilized the arc-lengths of four outer boundaries of a NURBS surface to discretize the parametric reference domain. Khamayseh and Hamann [24] proposed an improved elliptic grid generation method for NURBS surfaces. In a general way, to obtain a mesh with good quality, each node has to be located properly inside the standard reference domain to meet the requirement of changeable curvatures of the involved curved surface. Unfortunately, these algorithms are relatively time-consuming with many iterative steps and therefore unsuitable to shape optimization since the optimization itself is a heavy iteration process. Moreover, the above methods are very problem-dependent in practice as indicated in reference [25] and a general rule of meshing the planar reference domain for the achievement of a good discretization of curved surface still lacks.

For this reason, general methodologies for the simultaneous shape optimization of the curved surface and involved openings are developed and the underlying issues listed below are highlighted in this paper.

- Establishment of a suitable rule for the definition of a planar reference domain in the parametric space to ensure the mesh quality of the 3D curved surface.
- Relationship analysis between GDVs related to the surface shape and LDVs related to the hole shape.
- Establishment and implementation of the moving bounds strategy to control LDVs within the reference domain in the whole optimization process.

On the one hand, the iso-morphing concept, i.e., shape similarity is adopted here and a triangular or a rectangular reference domain is used for the parameterization of a curved surface patch. On the other hand, an arc-length rule is proposed to calculate the moving bounds of the reference domain instead of using the 0–1 normalization. One such non-standard reference domain technique makes it possible to achieve a uniform mesh over the curved surface as much as possible when the reference domain is uniformly meshed. Although this is not theoretically ensured to be the best parameterization that exactly yields an equal arc-length discretization over the 3D surface with a uniform partition of parameter variables in the parametric reference domain, the arc-length variation would not vary widely at least over the domain with respect to the variation of parameter variables. In this way, the meshing process is largely simplified.

In this way, the moving bounds of the reference domain are updated during the simultaneous shape optimization of curved surfaces and attached openings to follow the shape variation of curved surfaces and their values will be used to coordinate LDVs in the reference domain with GDVs in the real space. Finally, relevant optimization problems are formulated and solved by the proposed design procedure. By means of three representative examples, it is shown that the moving bounds strategy is successfully applied to coordinate two types of design variables for the achievement of satisfactory results.

2. Bi-space parameterization with mesh shape preserving

As is well-known, a 3D curved surface has two parametric coordinates, also called parameter variables, and can generally be