A parallel nodal-based evolutionary structural optimization algorithm

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Abstract  This paper is concerned with the minimum weight design of structures using Finite Element Analysis (FEA). A new evolutionary structural optimization (ESO) algorithm is presented. This method departs from previous studies of ESO in that it exploits the movements of the nodes in an unstructured finite element mesh in an appropriate way. An attractive feature of the scheme presented is that it carries out topology optimization in the interior of the domain concurrently with shape optimization of the exterior of the domain. Circular cavities are inserted into the interior of the domain from which the internal topology is then revealed by migration of the cavity edge nodes. Due to the complexity of the resulting cavity geometry the FE mesh tends to be refined internally. A scheme for maintaining a roughly uniform density unstructured finite element mesh throughout the optimization in a two-dimensional domain is presented. The designs produced posses smooth internal and external boundaries. The method uses iterative finite element analysis and re-meshing to correct for any element distortion. The benchmark “Michell Arch” problem is used to demonstrate the approach.

Key words  evolutionary, node, optimization, topology, shape

1  Nomenclature

\begin{align*}
A_{\text{initial domain}} & = \text{area of initial design domain.} \\
A_{\text{domain}} & = \text{area of design domain in each cycle of optimization.}
\end{align*}

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2  Introduction

Shape and topology optimization of structures is a rapidly developing field (e.g., see Rozvany et al. 1995) that has significant industrial importance. Within this field most real-world analysis is carried out using Finite Elem-
ent Analysis (FEA). In finite element formulations, the structural geometry is defined using nodes, elements and material properties such as element thickness, elastic modulus, etc. The objective of structural optimization is usually to produce low mass designs while at the same time ensuring smoothness of the structure boundaries. In early work on finite element based shape optimization, the coordinates of the boundary nodes were treated as design variables (see Hsu 1994) because it was believed that boundary smoothness could be achieved by slowly migrating the edge nodes. However, this idea was discarded because experience showed that it was very difficult to maintain a smooth boundary shape using the approach (see Hsu 1994). The more recent approach has been to treat the element or material properties as design variables.

This more intuitive evolutionary method pioneered by Xie and Steven (1997) is based on removing inefficient (low stress level) material from an initially oversized domain. The removal process can be carried out by either varying the elastic modulus as a function of the stresses or by deleting regions occupied by elements with low stresses. By repeating this step and “removing” small amounts of material at each stage, the topology for the structure gradually evolves. There have been a number of modifications and refinements proposed for this basic approach, (e.g., see Querin et al. 1998, 2000; Kim et al. 2000; Yang et al. 1999). However, the weakness of classical ESO methods (adding and/or removing elements) in generating optimum topologies was recently pointed out by Zhou and Rozvany (2001). They demonstrated through a simple test example that the classical ESO rejection criteria for compliance or stress design can produce an extremely non-optimal topology.

In contrast the soft kill method developed by Walther and Matteck (1993) is based on varying the elastic modulus by using a simple linear relationship with some scalar measure of the stresses evaluated within each element. The hard kill method developed by Hinton and Sienz (1995) used a step function to adjust the elastic modulus.

The homogenization method originally developed by Bendsøe and Kikuchi (1988) is based on defining the initial design domain with an infinite number of microscale cells with voids. The porosity of this medium is then optimized. The optimization problem is defined in such a way that the solid/void ratio in the base cells are the design variables. If a portion of the medium consists only of voids, it is assumed that no material lies in that area. On the other hand, if there is no porosity in some portion, solid structure must be located there. Bendsøe (1989) also proposed various ways of predicting the optimum topology of a mechanical element by introducing an artificial density. He concluded that the most satisfactory method is to employ a porous material approach, using simple square voids at the microscale.

A similarity in all the above methods is that the initial design domain is filled with elements of equal size and shape. Analysis of this mesh then provides a measure of the stress distribution within the domain. Based on the relative stress levels within the structure, the shape and topology of the structure are then modified. However, by using identical elements in the optimization, the final shape of the converged geometry is limited by the shape of the elements used. As a result, a “stair-case” effect may emerge. Therefore, post-processing is often required to smooth the final geometry.

It has also been demonstrated that a solid isotropic microstructure with penalty (SIMP) method for intermediate densities combined with new optimality criteria methods (see Rozvany and Zhou 1991) results in very satisfactory solid-empty type topologies in generalized shape optimization. In addition, the solution obtained with a SIMP model is much closer to theoretical solutions than those obtained using square cells (see Rozvany et al. 1992).

Nowadays commercial packages such as ANSYS are commonly used for geometric and finite element modelling. Most commercial modelling packages have one or more auto-meshing tools. The meshes generated by these tools usually consist of irregular sized elements and different orientations. Increasingly, layout and topology optimization methods are being incorporated into these commercial packages. The idea of using optimization strategies with irregularly meshed domains and evolutionary methods is, therefore, a natural next step in the use of FE methods in design. Methods applicable to this way of working are the subject of this paper.

In this paper a parallel nodal-based evolutionary structural optimization (PNESSO) method that is capable of optimizing unstructured meshes by treating boundary node positions as the design variables is proposed. In this method, boundary smoothness is achieved by migrating boundary nodes from their initial lightly loaded positions to higher stress locations. Both the magnitude and direction of each nodal movement are calculated by the proposed “NESSO equation”. This algorithm carries out three optimization operations in an iterative fashion. The first of these moves the external edges of the structure and is similar in logic to the “nibbling” ESO, of Xie and Steven (1997). The second operation of the algorithm is an internal cavity formation stage, where small circular holes are made in the structure. The final operation is the movement of the boundaries of these holes. The overall structure of the method is illustrated in Fig. 1.

An outline of the basic PNESSO method is presented in Sect. 2. Details of the PNESSO algorithm are then presented in Sect. 3. Mesh control considerations are discussed in Sect. 4. Cavity formation considerations are discussed in Sect. 5. Section 6 discusses the computational costs involved in the implementation of the PNESSO algorithm. Section 7 presents an application in which the PNESSO algorithm is validated using the benchmark “Michell Arch” problem.