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Stability-ensured topology optimization of boom structures with stress constraints

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Abstract

The use of giant boom cranes has gained an ever-increasing popularity due to their superior handling abilities. Lightweight design of a giant boom structure, which is usually achieved by topology optimization, becomes critical in reducing the energy consumption of the whole crane. In topology optimization of giant boom structures, geometrically nonlinear analysis has been adopted to capture the accurate structural response. A common issue is that the stiffness of some members keeps decreasing during the optimization process, which is often a generator of some slender struts leading to buckling issue. Therefore, a stability-ensured topology optimization algorithm for structural design is needed to maintain sufficient stability of boom structures while reducing the weight.

The stability performance is studied either as a constraint or as an objective in topology optimization problems [1]. The evolutionary structural optimization (ESO) method was extended to linear buckling problems, and a simple method not involving variational calculus or Lagrangian multipliers was presented for the optimum design of columns and frames [2]. Kemmler et al. [3] considered the lowest critical load level as an inequality constraint and conducted topology optimization of structures including kinematics. The design problem of maximizing the buckling load factor of laminated composite shell structures was investigated using the discrete material optimization approach [4-6]. Lindgaard and Dahl [7] investigated a range of different compliance and buckling objective functions for maximizing the buckling resistance of a snap-through beam structure. The gradient-based optimization methods have been widely applied in many stability constrained problems, but they are not appropriate for topology optimization problems with large number of local stability constraints due to difficulties in calculating the sensitivities of numerous constraints with respect to each of the design variables.

In the presence of aforementioned drawbacks of gradient-based methods, non-gradient-based methods are put forward to provide a convenient way for topology optimization of geometrically nonlinear boom structures. Although non-gradient nature-inspired methods are not viable alternatives for the vast majority of topology optimization problems, they actually solve discrete topology optimization problems with surprisingly high efficiency [8]. For example, the Soft Kill Option (SKO) method is a heuristic topology optimization method based on the simulation of the biological growth rule of biological growth carriers like bones [9]. It reduces human error to a minimum, and even in really complex cases makes it possible for the first time to find a draft design that is already close to the optimum [10]. Even though sensitivity analysis is not used, the results obtained with the SKO method are very similar to those by gradient-based methods using OptiStruct [11,

12]. Our previous work [13] extended the SKO method into topology optimization of bars structures and sets the foundation for this research.

A couple of member buckling judgment methods for bars structures have been presented in recent years. Shen et al. [14] proposed a middle plastic hinge model of the member, assuming that the member is in a completely elastic deformation condition before buckling. Fan et al. [15] adopted the curve of axial force-relative deflection of the member and the energy method to judge the member buckling. To better monitor the stability of the structure, global stability index (GSI) and compression member stability index (MSI) are defined in this paper. The global stability constraint can be easily formulated by GSI, while member buckling of any compression member can be detected by MSI. Apart from stability, the volume and stress should also be taken into consideration in topology optimization of boom structures so that the topology design is close to industrial application. However, it is very difficult to find optimization algorithms for discrete problems that can treat multiple non-trivial constraints [8]. The traditional volume constraint always conflicts with global stability and stress constraints, thus the predetermined target volume fraction may not be achieved. Adaptive volume constraint algorithm is proposed by Lin and Sheu [16] so that the maximum stress in the optimal structural configuration is guaranteed to be below the predefined stress limit.

The stability indices are utilized as a part of a novel Stability-Ensured Soft Kill Option (SSKO) algorithm, which is a heuristic topology optimization approach proposed in this work on the basis of the existing SKO method. The objective is to minimize the discrepancy between structural volume and predetermined target volume, while the global stability, member stability and stress are regarded as constraints. To demonstrate the effectiveness of the proposed approach, the SSKO algorithm with different scenarios is applied to topology optimization of a ring crane boom, and stable topologies are achieved with high efficiency and consistency.

Keywords: boom structures; topology optimization; stability index; stability-ensured soft kill option; geometric nonlinearity.