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Topology optimization with manufacturing constraints: A unified projection-based approach

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ABSTRACT

Despite being an effective and a general method to obtain optimal solutions, topology optimization generates solutions with complex geometries, which are neither cost-effective nor practical from a manufacturing (industrial) perspective. Manufacturing constraint techniques based on a unified projection-based approach are presented herein to properly restrict the range of solutions to the optimization problem. The traditional stiffness maximization problem is considered in conjunction with a novel projection scheme for implementing constraints. Essentially, the present technique considers a domain of design variables projected in a pseudo-density domain to find the solution. The relation between both domains is defined by the projection function and variable mappings according to each constraint of interest. The following constraints have been implemented: minimum member size, minimum hole size, symmetry, pattern repetition, extrusion, turning, casting, forging and rolling. These constraints illustrate the ability of the projection scheme to efficiently control the optimization solution (i.e. without adding a large computational cost). Illustrative examples are provided in order to explore the manufacturing constraints in conjunction with the unified projection-based approach.

1. Introduction

This paper addresses manufacturing constraints by means of a *unified projection-based approach* restricting the range of solutions to the topology optimization problem. A domain of design variables is considered, which is projected in a pseudo-density domain to obtain the solution. The relation between domains is defined by the projection and variable mappings according to each manufacturing constraint of interest. The following constraints are considered: minimum member size, minimum hole size, symmetry, extrusion, pattern repetition, turning, casting, forging, and rolling.

Fig. 1 illustrates the relationship between the manufacturing techniques and the manufacturing constraints implemented. The figure shows the necessary manufacturing constraints in order to generate compatible designs for each manufacturing technique. It also relates each manufacturing technique to the pertinent manufacturing constraints that can be applied. For example, minimum member size, minimum hole size, symmetry, and pattern repetition constraints are apllied to allow a part be manufactured by the milling process. In summary, Fig. 1 illustrates the guiding philosophy of the present work.

This article is organized as follows. Section 2 presents the background and the state of the art in the field in order to place the present work in a proper context. Section 3 presents a brief overview of the topology optimization concepts. Section 4 describes the main idea associated with the projection and mapping techniques employed. Section 5 presents the actual manufacturing constraints addressed in this work. Section 6 provides details concerning the numerical implementation of manufacturing constraints and regarding the topology optimization procedure. Section 7 presents projection-based results associated with a diversity of examples. Finally, in Section 8, conclusions are inferred and the potential extensions of this work are indicated.

2. Background and state of the art

Topology optimization is a powerful tool to design effective and efficient structures. In the past few years, significant improvements have been made in order to improve the technique, such as development of filters based on gradients [1], image processing [2], and

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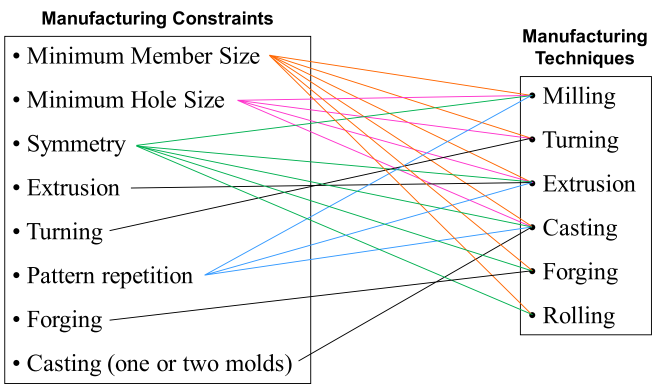

Fig. 1. Manufacturing constraints relationship scheme illustrating the philosophy of the present work.

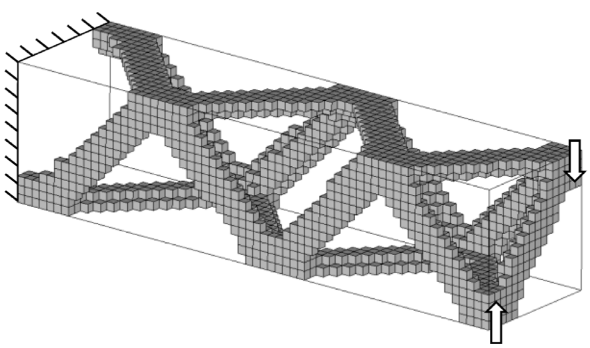

Fig. 2. Example of a complex solution obtained by using the topology optimization method – cantilever domain subjected to a torsion load at the end.

other procedures aiming at solving the long-standing checkerboard problem, the non-uniqueness of solutions, and the gray scale [3]. Even when the aforementioned techniques are employed, a major problem remains, which is the complexity of the obtained solutions, as illustrated in Fig. 2.

Synthesis of structures by means of topology optimization may lead to complex shapes (Fig. 2) and, in general, are neither cost-effective nor practical to manufacture. A common procedure consists of post-processing the result by interpolation functions and smoothening of curves/shapes [1]. Sometimes, in order to achieve a practical solution, the original design needs to be substantially modified, losing its optimized characteristics. This problem has motivated the topology optimization community to seek solutions tailored for specific manufacturing processes [4–11]. These solutions are useful for both traditional and additive manufacturing processes; however, the focus of this paper lies on the latter. References addressing the connection between additive manufacturing and topology optimization can be found in Leary et al. [12].

The approach of this work consists in defining the constraints of an optimization problem, by employing projection techniques [13,14] tailored to meet the requirements of the manufacturing processes, thus, simplifying the process of interpreting topology optimization solutions. The current tendency to develop a product cycle leads to procedures in which design, simulation, and optimization with manufacturing constraints can be simultaneously executed in computer-aided engineering (CAE) phase design [15], instead of the traditional procedures, in which the design and optimization are developed separately, in computer-aided design (CAD) and CAE phases, respectively. Final shapes with high resolution incorporating manufacturing constraints can be obtained by adopting highly discretized FEM models [16], reducing time and product development cost.

Previous works have addressed manufacturing constraint techniques. For instance, Zuo et al. [4] considered manufacturing and machining factors in the topology optimization problem. They introduced manufacturing constraints according to requirements for different applications. Harzheim and Graf [5] compared the topology optimization of cast parts with and without manufacturing constraints, and observed better results for cast part design when a minimum thickness control is included in the optimization problem. Ishii and Aomura [6] proposed a methodology based on the homogenization method to produce optimized structures with constant cross section, which is easily manufactured by extruding. An alternative method to design continuum structures subjected to extrusion constraints was developed by Lia et al. [7], who combined a parametric level set method with a discrete wavelet transform approximation for this purpose. Gersborg and Andreasen [8] applied the Heaviside design parametrization to obtain manufacturable cast designs in a gradient driven topology optimization. Later, Zhu et al. [9] proposed an alternative linear interpolation to allow the topology optimization of large-scale stretch-forming die designs. Sørensen and Lund [10] included explicit manufacturing constraints to topology and thickness optimization of laminated composites as a large number of sparse linear constraints. Wang et al. [11] demonstrated that the local length scale control in topology optimization is difficult to obtain by employing simple projection filtering techniques. Therefore, they proposed a modified robust topology optimization formulation that combines three projection schemes into a min-max problem to overcome this difficulty, however, at a high computational cost.

In contrast, a novel integrated approach is proposed herein, combining a projection technique with a mapping technique, in which different kinds of manufacturing constraints are implemented in the topology optimization process. The goal is to achieve feasible engineering solutions, with smaller computational effort, which can be fabricated by means of well-known and well-controlled manufacturing processes [17].

3. A few remarks on topology optimization

In a general sense, topology optimization leads to optimized structures by means of optimization algorithms that provide a distribution of mass within a design domain. Some of the optimization algorithms commonly employed include Sequential Linear (or Quadratic) Programming [18], Method of Moving Asymptotes [19], and Optimality Criteria [1], to name a few.

The topology optimization method employs some basic concepts such as a fixed design domain and relaxation of the optimization problem [1]. The latter consists in solving the problem in a continuum form, rather than addressing the original 0-1 (void-solid) problem in discrete form. Usually, the domain is discretized with the Finite Element Method [20] and the problem is solved based on the sensitivities obtained for the optimization cycle by means of a proper material model. Various material models have been proposed in the literature [1]. Here, the so-called SIMP model (Solid Isotropic Material with Penalization) [21,22] is applied, using penalization coefficients on the pseudo-densities (ρ) of each element in order to reduce intermediate regions that appear due to relaxation, as follows:

$$\boldsymbol{C}^H = \rho^p \boldsymbol{C}_0 \tag{1}$$

where C^H is the resulting stiffness tensor, p is the penalization factor, and C_0 is the tensor for the basic isotropic material used. In this process, intermediate pseudo-densities and checkerboard instability appear in the solution. To address such problems, complexity control such as filters [2] and projection techniques [13] have been the solution of choice in the technical litera-