PROJECT MAXWELL: A TECHNICAL OVERVIEW*

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ABSTRACT

We describe Project MAXWELL, a synergistic integration of a new, mathematically rigorous procedure for the concurrent design of shape and material composition of components, and a new manufacturing process in which parts are built up layer by layer. The concurrent design strategy is based upon homogenization design and yields information about the global shape of the component and its material composition. In layered manufacturing complex geometries/topologies can be built in layers, from single or multi-materials. Project MAXWELL is an integrated five-phase process for the realization of efficient mechanical structural components.

INTRODUCTION

Project MAXWELL is a synergistic integration of a new mathematically rigorous procedure for the concurrent design of material composition and shape of components, and a new manufacturing process for their realization. At the University of Michigan (U-M), a methodology has been developed for designing the form and material composition of mechanical and structural components based only on a description of the loading conditions and packaging requirements [1]. Layered manufacturing is a new manufacturing technology that enables the free-form fabrication of parts from single or composite materials by various processes, e.g., thermal spray shape deposition, fused deposition modeling, selective laser

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sintering, etc. [2]. In Project MAXWELL we aim at integrating the two novel technologies, for realizing strategic benefits rooted in the rapid realization of efficient mechanical and structural components. Such parts will possess superior structural and mechanical properties (e.g., lower weight to stiffness ratio), and will satisfy packaging and other manufacturing requirements (e.g., ease of assembly). The project goal is proof of concept through design, manufacture, and testing of actual parts. Finally, the design methodology in Project MAXWELL illustrates the importance of layered manufacturing techniques beyond prototyping tasks.

The current application domain is in automobile design and manufacture and includes sheet metal/composite panels, brackets and suspension components, and special structures for side impact energy absorption [3]. The process is also suitable for the design and manufacture of prosthetic devices in bioengineering applications.

In this paper, we provide an overview of the project by first motivating the concurrent design of form and material in the context of structurally superior products. Next, we describe the homogenization design methodology developed at U-M and two layer manufacturing processes. We conclude with the current status and future goals of Project MAXWELL.

CONCURRENT DESIGN OF STRUCTURE AND MATERIAL

Design of the Global Structure Using the Homogenization Method

A fundamental approach to the thermo-mechanical characterization of general composite materials was first put forth by James Clerk Maxwell (1831-1879) and was later generalized as the theory of mixtures to provide a rigorous foundation for studying the mechanics of composite materials [4]. Project MAXWELL aims at transforming those early ideas into engineering reality.

Necessity of topological design in addition to size and shape design is widely recognized by structural engineers [5, 6, 7]. If topological changes are not allowed, size and shape optimization procedures can improve a design by approximately 5~15%. Topological modifications can often yield 30~50% improvement. For example, to resist a bending moment, a hollow beam is more effective than a solid beam. Therefore, for the same amount of material, a beam with an interior void along the length (i.e., involves
topological changes) is better than one with material removed from the outside (but solid inside). Furthermore, consider the vibrational response of a beam like structure. Figure 1(a) shows the shape obtained by using traditional optimization techniques. It involves only geometric changes. However, much better frequency response is obtained for the shape shown in Figure 1(b). Note, this shape involves topological changes (introduction of voids).

![Figure 1: Shape Design and Topology Change of a Vibrating Structure](image)

The homogenization method is based on the above observation [2]. The topology and shape problem is formulated as a new optimization problem involving material distribution. Given a solid with a prescribed volume, we generate microscale voids in design domains where a solid structure is not required for supporting loads. Therefore, instead of designing the shape and physical dimensions of the cross section of a structure, we generate infinitely many microscale voids within the configuration wherever the stress is small. If a portion in the domain is highly stressed the homogenization method prevents the creation of microscale holes and that portion remains solid. Furthermore, the orientation of a non-circular void has a significant effect on the overall material response. Therefore, in the new optimization problem, the design variables are the density of microscale voids and their orientation over a specified domain. By removing material completely from portions of the domain densely packed with voids, the optimum shape of the structure is identified, while its topology is determined by accounting for the number of "global" holes (see also Figure 2).
This intuitive method of "shaping and drilling" a structure is based on the theory of homogenization -- a mathematically rigorous method developed in the mid-1970s for the study of mechanics of composite materials. Most composite materials possess a fine scale microstructure composed of fibers, whiskers, inclusions, and matrices. Applied mathematicians in France, Italy, and the former Soviet Union [8, 9, 10] developed the homogenization theory to derive the constitutive equation of a composite material, i.e., to evaluate the average stress-strain relation of the structure. Since we are interested in generating infinitely many microscale holes to form a possibly perforated structure, the stress analysis of such a structure requires the derivation of an equivalent effective average stress-strain relation. A homogenization approach enables the design of topology and shape without using spline functions. Difficulties in geometric modeling are avoided, and stress analysis iterations are performed on a fixed finite element mesh.

Introduction of Microstructure

Although the optimization process permits the perforation of the domain, the resulting optimum configuration is often a homogeneous solid. In our design optimization scheme, we consider the domain to be a very specialized, fictitiously constructed, composite material consisting of solids and voids. In order to determine the best microstructure, we allow the design domain to include other composite materials, e.g., ones that can improve strength, toughness, vibrational characteristics, acoustics, impact resistance and impact energy absorption.
Non-homogeneous composite materials result in significant improvements in thermo-mechanical properties without increase in weight. For example, while bending rigidity of a beam or shell-like structure is proportional to Young's modulus of the material, it is also proportional to the cube of its thickness. Therefore, a design criterion such as bending rigidity can be dramatically improved by using composites with a stronger material in the outer surfaces and weak and lighter materials in the inner core, Figure 3. Composite structures can also improve vibrational characteristics without increasing weight or changing the overall configuration. If large damping is desired, a material with high damping characteristics can be inserted.

For crashworthiness, an important issue in automobile panel design, complex microstructures must be introduced. Plastic deformation or destruction of the fine microstructure can absorb large amounts of energy. In front- or rear-end crash situations, the need for fine scale microstructures is often eliminated by building simple reinforcing frames that absorb crash energy in the available space. For side impact, however, space for design is much more limited and use of fine scale structures may be very advantageous.

Use of such structures has not been realized in practice due to the lack of an attractive manufacturing process that delivers non-homogeneous and anisotropic materials. For example, it is impossible to create internal voids within a component (such as in Fig. 2) by conventional NC machining. Instead, one has to build voids in the workpiece material prior to machining. As a result, the void orientation which often has a significant impact on overall material response cannot be handled explicitly. In MAXWELL, we propose to use CMU's MD* process where a the component is built up layer by layer, allowing the possibility of creating and orienting the voids as desired. Therefore, MD* enables serious consideration of these unusual and highly efficient structures for the first time.
OPTIMIZATION MODELS FOR CONCURRENT DESIGN OF MACRO-
AND MICRO-STRUCTURES

A Simple Formulation of the Optimization Model

Relating microstructure to global shape requires a new approach to design optimization and is enabled by homogenization. Concurrent design optimization can be performed to obtain the best microstructure in addition to optimal shape and topology.

Let $f$ be the objective function, such as the total weight, cost, or other scalar quantity. Suppose $g$ is a vector function representing the set of design constraints introduced by mechanical and manufacturing requirements. Then the design problem can be posed as the following optimization problem [2, 11, 12]

$$\min_{d} f(d,u)$$
$$d \quad g(d,u) < 0$$

where $d$ is the set of design variables and $u$ is the state variable vector describing the thermo-mechanical behavior of the structure defined by the state equation

$$L_d(u) = 0$$

The operator $L_d$ of the state equation is a function of the design variables. The overall formulation is similar to standard optimization except for the design variables. For the layout design described in the previous section, design variables are the size of a rectangular hole in the unit cell characterizing the microstructure and its angle of rotation. If two different materials are considered, the design variables might define the constitution of the unit cell. For example, if we consider three different microstructures, Figure 4, we might choose to design the layout of the lamination, the mixture, or the fiber density of the resulting composite material.
Figure 4: Design Variables at the Microstructure Level

This approach allows inclusion of material composition in the model, but is insufficient for concurrent material and structural design, since the configuration of the microstructure is specified *apriori* (although the designer has considerable flexibility in choosing the size of the lamination, mixture, and fiber). Clearly, the chosen microstructural configuration need not be the optimum. Therefore, we must derive the optimal microstructure and optimal global layout for the structure concurrently.

Applied mathematicians at Courant Institute, University of Paris, and in the former Soviet Union, have conducted research on optimal composition, without considering global structural configuration; see [13] for a survey. These methods concentrate on finding the lower bound on the complementary energy of a generalized mixture of two different materials. Typically, sequential lamination is used to yield a closed-form homogenized effective stress-strain relation. These elegant theoretical developments have not led to substantive engineering applications. Furthermore, these studies have primarily concentrated on optimum composite structure independent of the stress field generated in the structure. Namely, material constitution is obtained in its ideal setting independent of the true stress field. That is not acceptable for structural configurations carrying thermo-mechanical loads.

An Optimization Model for Concurrent Macro-Micro Layout

To overcome these limitations, we formulate a new design problem that optimizes both the microstructure and the global structural configuration. We consider minimizing an objective function that represents the complementary energy of the unit cell consisting of two materials. The constraints are the equilibrium equations and the periodic boundary conditions. We further require that the average stress over a unit cell is equal throughout the global structure under a specified volume fraction of
the two materials forming the composite. To minimize this objective function defined over the unit cell, we apply the same method as in layout optimization of the global structure. That is, the microstructure is designed by using a refined microstructure; see Figure 5.

Thus, two microstructures are introduced, one to determine the layout of a global structure and the other to define the optimum material layout in the microstructure. This allows designing a possibly non-homogeneous, anisotropic, composite structure, optimal with respect to topology, shape and material.

Figure 5: Concurrent design of microstructure & material

In contrast to the applied mathematics approach, our choice of objective function in material design need not be restricted to the complementary
energy. For example, if a desired stress or strain field is "specified" at an arbitrary point of a structure, it is possible to determine the optimum microstructure to meet the desired condition. If the response of some material at a specified point is required to have a negative Poisson's effect (which might well be unrealistic), the homogenization design can be used to design the microstructure to yield such an effect. Following the pioneering work by [14], we at UM have generated a microstructure that has considerably large negative Poisson's ratio. It is shown in Figure 6. In other situations, we may wish to design a structure and its material that can absorb, say, crash energy. Then the objective function may be defined as the integration of the complementary strain energy over the period of crash. There has been limited research in structural optimization with nonlinear state equations. Methods for linear state equations must be extended for history-dependent nonlinear state equations, in order to meet challenges such as side impact energy absorption in automotive body design.

Figure 6. Example of a microstructure with negative Poisson's ratio
The true benefits of deriving such optimal topologies and microstructures in a rigorous fashion can only be measured after the designs are transformed into physical products and tested. However, conventional manufacturing such as NC milling and truing are insufficient for the realization of such designs, since it is not possible to affect the "inner core" of the object being machined. On the other hand, layered manufacturing techniques are ideally suited for such fabrication tasks since they can create internal voids and complicated external geometries simultaneously. Therefore, our design method in MAXWELL promotes the use of layered manufacturing beyond prototyping tasks into the mainstream product development and fabrication phase.

FABRICATION BY LAYERED MANUFACTURING

In Project Maxwell, the parts designed by the homogenization method can be manufactured by conventional methods, e.g., 5-axis NC milling, or by layered manufacturing if the the part geometry and topology is complex.

The typical output of the homogenization method is a material density distribution in the design domain. This density data is interpreted and a CAD model of the part is created using geometric modeling techniques. Then, based on the (geometric/topologic) complexity of the CAD model, we determine if the part can be manufactured by conventional NC milling, or will require layered manufacturing. Next, we briefly describe two layered manufacturing techniques that are available for use in Project Maxwell.

Layered manufacturing by the Stratasys 3D Modeler®

In Project Maxwell, we have the 3D Modeler®, a layered manufacturing machine built and marketed by Stratasys Inc., MN. The 3D Modeler® uses the fused deposition technique for layer manufacture. Briefly, it involves melting a thermoplastic and pressure-depositing it through a nozzle (much like tooth paste from its tube) along a prespecified trajectory, layer by layer, until the part it built [15].

The process begins by converting the CAD model (of the homogenization output) into several "slices". These slices are the XY sections of the oriented part. This orientation is in which the part will be built. The slices are actually the planar contours of the part. For example, if the part is a solid
sphere, the slices are circles of varying radii (increasing from zero to the sphere diameter and then decreasing again to zero). During building, the material has to be deposited to fill the interior of the circular cross-sections. If, however, the part was sphere with an interior concentric spherical void, then the XY slices would be a pair of concentric circles, and the material has to be deposited in the region bounded by the two concentric circles.

The 3D Modeler supports three materials – machineable wax, investment casting wax and a plastic polymer. During layer manufacture, the material is fed from a spool into an extrusion head. It is heated to a temperature just above its solidification and then deposited by the nozzle that moves on the XY plane like a gantry robot. Interior voids are created by using a separate filler material. Parts with complex geometry and/or topology can be made easily.

Layered manufacturing by the MD* Process

In the MD* (recursive Mask and Deposit) process, parts are manufactured by successively spraying liquified metal on the cross-sectional layers [16, 17]. Each layer may contain several different materials. The geometry of the part is not constrained and its shape and material composition can be changed continuously during fabrication. To create a part, its geometric model is first sliced into cross-sectional layers, typically 0.001 to 0.005 inches thick. A robotic thermal spray gun sprays the liquified metal and grows the part layer by layer.

Deposition of more demanding materials, such as steel, is feasible. However, support material is required to act as a surface to which the sprayed material will adhere and to "release" the part when completed. Low-melt alloys, such as tin-based compositions, satisfy these requirements for arc sprayed steel. The sprayed steel bonds locally to a tin/bismuth composition by superficially melting and abrading a very thin layer of the low-melt alloy, which is melted away when the part is fully completed. Selective material deposition is also feasible with the MD* approach. Building composite structures with several different materials within a layer can be also accomplished. This enables the capability to create integrated electromechanical devices, e.g., mechanical structures with embedded electronics and unique composite, multi-material structures as elaborated in Section 3.
In the context of Project MAXWELL, both layer manufacturing processes are important. 3D Modeler provides a quick method to create the complex part using plastics/wax. MD* is particularly important when metallic (and composite) parts are required. While the material properties of composites dramatically expands the possibilities for new product designs, current composite manufacturing technologies severely limit the possible geometries. Layer manufacturing has the potential to create dense composite and laminate structures of arbitrary geometric complexity, while masking also enables selective material deposition. Therefore, different regions within a layer can be composed of different materials. For example, integrated electro-mechanical assemblies are feasible such as encapsulated computer packages with embedded electronics.

CURRENT STATUS AND FUTURE GOALS OF PROJECT MAXWELL

Project MAXWELL is a collaborative effort in design and manufacturing with new materials. It has been ongoing at University of Michigan for over five years. The results to date can be summarized as the development of a three phase prototype system for the concurrent design of superior structural components with the possibilty of optimally designed microstructure. The manufacturing is enabled via the 3D Modeler and by collaboration with Carnegie Mellon University/Stanford University for the MD* process. The following steps describe Project Maxwell.

Phase I: Based on the specified boundary conditions (type and magnitude of loads) and designable space (packaging specifications) the homogenization method is applied to derive a grey scale image representation of the material composition and distribution that is optimal relative to desired structural performance measures.

Phase II: Using computer vision and geometric modeling techniques this image is interpreted and translated into a realistic structure, e.g., a radically new perforated or multi-material composition reminiscent of biological structures.

Phase III: A parametric optimization model based on finite element analysis is formulated and solved to determine a complete dimensional and material description of the structure.
Phase IV: The manufacture of the Phase III output (i.e., discrete parts of arbitrary geometry and possibly varying material composition) using the MD* process.

Phase V: The final phase in MAXWELL is the testing phase, where the Phase IV products will be subjected to various mechanical tests. Qualitative indices of performance in Phase V will include measures such as weight to stiffness ratio, impact energy absorption rates and fatigue life.

Currently the U-M homogenization design system can deal with 2D and simple 3D components (sheet metal panels, brackets, beams, etc.). The capability of 3D Modeler and MD* includes the manufacture of most designs developed at U-M. Therefore, current efforts in MAXWELL are geared towards the fabrication and testing of some sample parts produced in Phase III. Ongoing work focuses on three dimensional components and extensions to all five phases of MAXWELL are envisioned.

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