Homogenization Design and Layered Manufacturing of a Lower Control Arm in Project MAXWELL

Roy Johanson
Noboru Kikuchi
Panos Papalambros

Department of Mechanical Engineering
& Applied Mechanics
The University of Michigan
Ann Arbor, MI 48109

and

Fritz Prinz
Lee Weiss

Engineering Design Research Center
Carnegie Mellon University
Pittsburgh, PA 15213

Abstract

We briefly describe a new methodology for the design and manufacture of mechanical components and demonstrate the process for the design of an automobile suspension component. The methodology is a unique coupling between advanced technologies for product design and manufacture, which leads to the rapid realization of superior products. The concurrent design and analysis strategy yields information about the optimal structural layout, as well as details about the material composition. The fabrication of such designs requires unconventional manufacturing processes, such as layered manufacturing. Project MAXWELL, therefore, offers the possibility for the integration of layered manufacturing into the mainstream product development and fabrication process.

1. INTRODUCTION

Project MAXWELL embodies a methodology that provides a rigorous technique 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 new 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. At Carnegie Mellon University (CMU), a new manufacturing process has been developed for the free-form fabrication of parts from single or composite materials by thermal spray shape deposition. The goal of Project MAXWELL is to demonstrate the validity of an integrated approach for the rapid realization of superior components. Such components will possess superior structural and mechanical properties, and will satisfy packaging and assembly requirements.

The current application domain is in the design and manufacture of automobile components. The design methodology has been applied to the design of stiffened sheet metal/component panels, suspension components, and a variety of other structures. Ongoing work involves the extension of the methodology to other applications.

In this paper, we briefly discuss the concurrent design of layout and material using the homogenization method. After describing the Recursive Mask and Deposit (MD*) process, we then demonstrate the MAXWELL methodology for the design of a lower control arm for an automobile suspension.

2. TOPOLOGY DESIGN IN MAXWELL

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 (see, e.g. [FUN65]). Project MAXWELL aims at transforming those early ideas into engineering reality.

The necessity of topological design in addition to size and shape design is widely recognized by structural engineers. If topological changes are not allowed, size and shape optimization procedures can improve a design by roughly 5-15%. Topological modifications can often yield 30-50% improvement. The homogenization method is a rigorous methodology to perform topology optimization. The problem is reformulated as a problem involving material distribution. Given an initial design domain, we discretize the domain and introduce microscale voids throughout the structure. The optimization problem then becomes the determination of the size and orientation of the microscale voids inside the initial design domain. If an area is highly stressed, the voids in that area will tend to zero -- the method will force solid material there. 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 1).

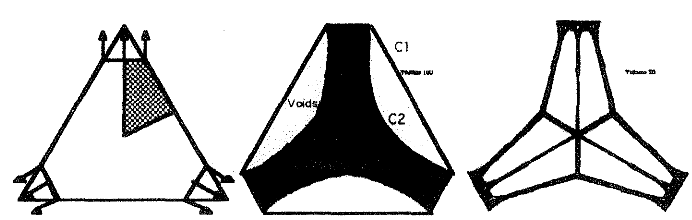

Figure 1: Identification of the Shape and Topology

This intuitive method of "sculpting" a structure is based on the theory of homogenization -- a method developed in the mid-1970's for the study of mechanics of composite materials. Applied mathematicians in France, Italy, and the former Soviet Union [LUR84, SAN80, TAR77] developed the homogenization theory to derive the constitutive equation of a composite material.

Although the optimization process often yields homogeneous solids, we consider the design 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, and other measures of structural performance. Such structures have 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 by conventional NC machining. In MAXWELL, we use CMU's MD* process where the component is built up layer by layer, allowing the possibility of creating and orienting the voids as desired. Therefore, MD* allows serious consideration of these unusual and highly efficient structures for the first time.

3. FABRICATION BY THE MD* PROCESS

In the MD* (recursive Mask and Deposit) process developed at CMU, parts are manufactured by successively spraying cross-sectional layers. 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. For each material in a layer, a disposable mask is made that exposes the area where that material occurs. The mask is placed upon the top layer of the growing part shape and a robotically manipulated thermal spray gun traverses the areas exposed by the mask. Masks are made from paper stock cut with a laser. Several alternative strategies are feasible for creating support structures for the part as it grows, including retaining a part of the mask or spraying the support material in place after the primary materials are deposited. A more detailed description of the MD* method can be found in [WEI92]. Two features of MD* make it particulary attractive in the context of Project MAXWELL: the ability to perform selective material deposition, and the prospect of a robust process for the forming and joining of composite structures. Availability of the MD* manufacturing process provides the requisite technology for the realization of novel designs (at the macro and microscale level) generated by the homogenization method. Additionally, MD* has the potential to create dense 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. Beck [BEC92] describes the manufacture of an integrated electro-mechanical structure created with the MD* process.

4. EXAMPLE: LOWER CONTROL ARM DESIGN

As an example of the integrated design and manufacturing process of project MAXWELL, a lower control arm was designed using the homegenization process and fabricated using MD*. This component is typical of vehicle chassis structural components; their design is typically driven by stiffness requirements. Phase I of the MAXWELL process begins with the description of an appropriate design domain and boundary conditions, shown in Figure 2. In this particular example, packaging requirements for other suspension and wheel components severely limit the allowable design space. In addition, appropriate attachment material for the strut must be provided in the final design. Translational displacements are constrained at the two pivots (to the right in Figure 1) , and loads are applied at the strut and at the ball joint. Three separate loading conditions are considered, with the primary load case being vertical (z-direction) loading at the strut attachment point.

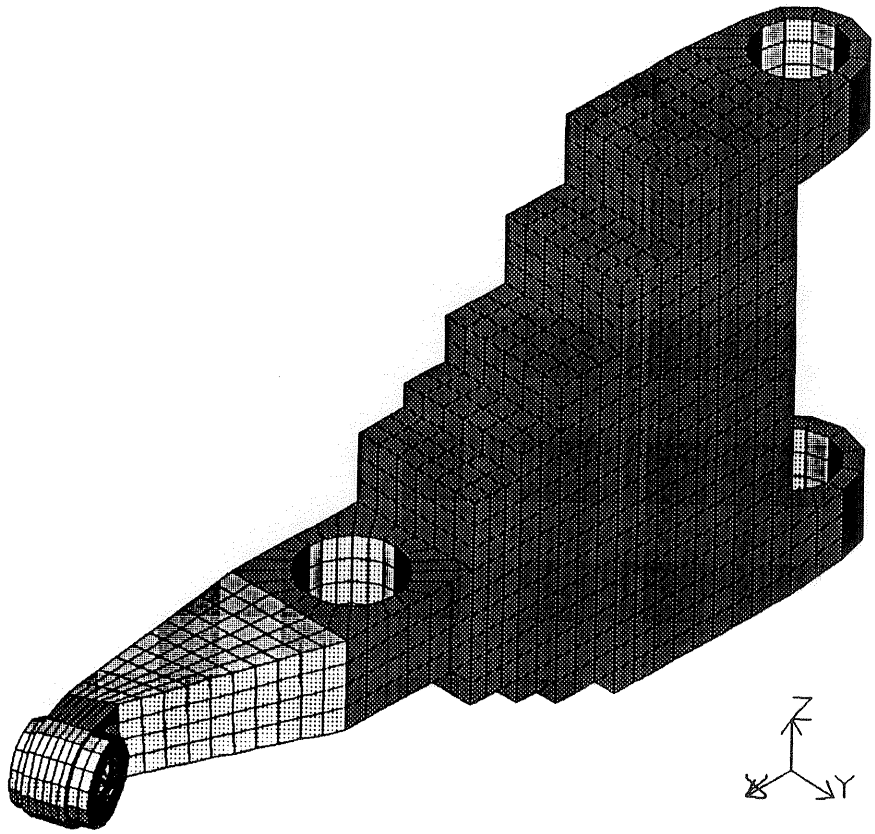

Figure 2: Design Domain for Lower Control Arm

The homogenization process produces a topology which possesses the maximum stiffness for a (user-supplied) constraint on the percentage of the design domain to be filled with material. Figures 3 and 4 show the result of the homogenization process, showing two cross-sections of the resultant structure. Note that the optimal topology which is designed using the homogenization procedure would be difficult to manufacture using traditional techniques.

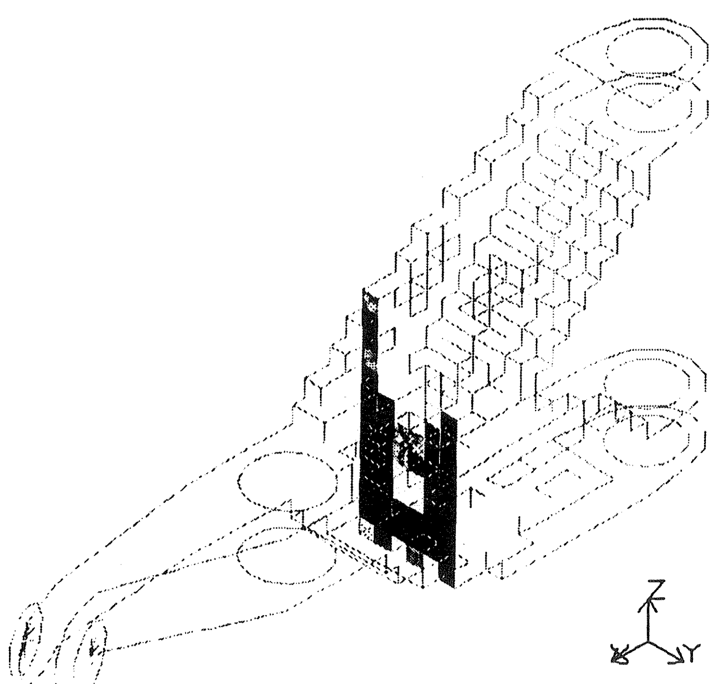

Figure 3: Cross-Section of Lower Control Arm at 45% Section

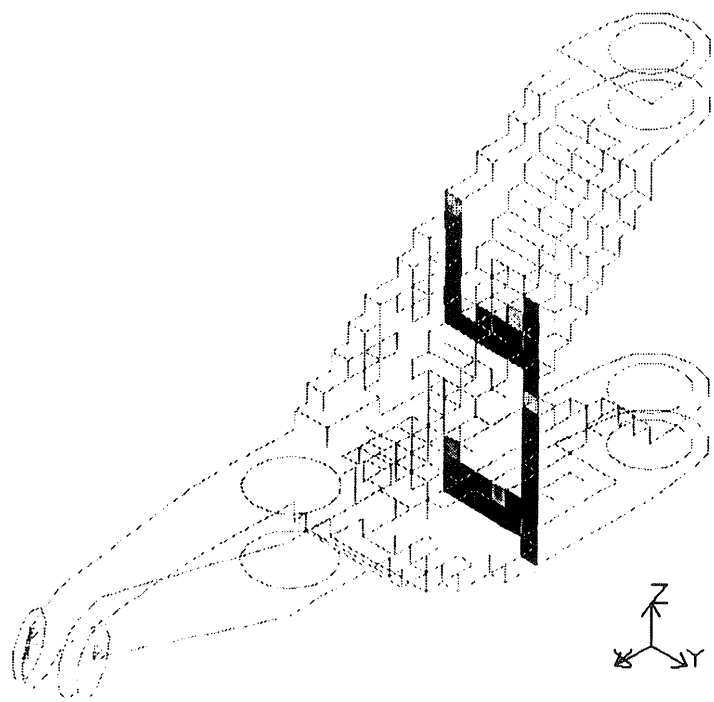

Figure 4: Cross-Section of Lower Control Arm at 60% Section

Often, the results from the homogenization procedure are smoothed, and detailed local structural constraints on allowable stresses and deflections are added and evaluated in a second sizing optimization procedure. In this example, however, we proceeded directly to the fabrication of the component using the MD* process. The data was transferred directly from the homogenization output to the MD* process through a standard stereolithography file. The control arm was interpreted as an isotropic component composed of one material, i.e., individual elements in the structure were interpreted as either all material (solid) or all void (holes), and the control arm was fabricated from a zinc alloy.

5. CURRENT STATUS AND FUTURE GOALS OF PROJECT MAXWELL

Project MAXWELL is a synergistic integration of two novel research efforts, one in design and the other in manufacturing, for the purpose of establishing a sound methodology for the rapid realization of superior products. Basic research directly relevant to MAXWELL has been ongoing at the participating institutions for over four years. The UM results to date can be summarized as the development of an integrated three-phase system for the concurrent design and analysis of superior structural components.

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 gray scale representation of the material composition and distribution that is optimal relative to some desired measure of structural performance.

Phase II: Using computer vision and geometric modeling techniques, this image is interpreted and translated into a realistic structure.

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 is performed.

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 UM system can develop structural layouts for 2D, 2.5D and full 3D components. A major area of current research is appropriate geometric representation of optimal topologies in three dimensions. Ongoing research at CMU directly relevant to MAXWELL can be summarized as the development of the MD* process for the rapid manufacture of single or multi-material components.

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