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Structural Optimization Methods: A General Review

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ABSTRACT : In present era of technological enhancement, every manufacturing organization is striving to focus to lower production costs and to reduce weight of component while meeting the required performance characteristics. Saving of material and energy can be achieved through optimizing the shape and topology of the structure on choosing a more efficient structural configuration. Design engineers are looking for rigorous methods to solve optimization model. Efficiency and economy are critical parameters for selecting innovative methods to improve the performance of the existing systems. The present review will develop an understanding of shape and topology optimization is, and the theory behind, how it can be used to improve the design process.

KEYWORDS: Optimization, Topology, Material Saving, Design, Efficiency, Innovative Methods.

I. INTRODUCTION

Optimization techniques [20] [21] have become more important as the prospect of simulating complex mechanical structures has become a reality. A common approach in the layout design of structural parts is the topology optimization, which find an optimum material distribution [6] within a selected geometrical design space to best meet loading conditions and constraints. Another important approach for optimizing the structure is shape optimisation, which optimises weight(mass) in given parametric geometric constraints. In the case of complex shaped parts, like automobile body structures, shape optimisation is still hard to do; mainly due to the difficulty in translating shape design parameters into meaningful analysis models. Sizing, shape and Topology optimization address different aspects of structural design problems.

II. STRUCTURAL OPTIMIZATION

Structural optimization a class of optimization problem, can easily be traced back to 1904 when Michell [1] derived formulae for structures with minimum weight given stress constraints on various design domains. Save and Prager 1985 [2] proved that the resulting structures (Popularized as Michell structures) had the minimum compliance for corresponding volume structures and hence were global optimum of minimization of compliance subject to volume problems.

In engineering, the optimization of an objective function is basically the maximization or minimization [22] of a problems subjected to given constraints. In Structural optimization, the purpose is to find the optimal material distribution according to some given demands of a structure. Some common functions to minimize are the mass, displacement or the compliance (strain energy). This problem is most often subject to some constraints i.e. mass or the size of the component.

This optimization is traditionally done manually using an iterative intuitive process that roughly consists of the following steps

1. A suggested design.

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2. The evaluation of design requirements, for example by a Finite Element Analysis (FEA)
3. Insure that requirements are fulfilled or not. If some lacking than repeat process 2 & 3

The result depends heavily on the designer's experience, knowledge, and perception regarding understanding of the problem. Changes to the design are can be made in trial and an error. This process can be very time consuming and may result in a suboptimal design. The problem of structural optimization can basically be categorized into three types, Sizing (mass), Shape and Topology (layout). Refer Fig 1.

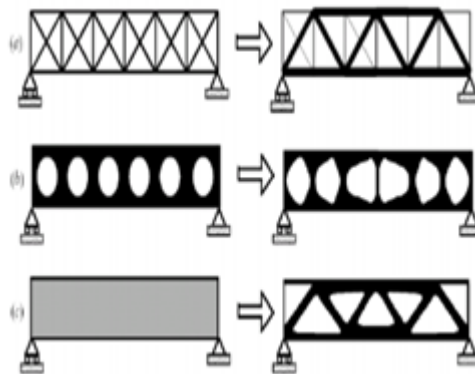


Fig. 1. a. Sizing b. Shape c. Topology Optimization (Courtesy: Ref. 6.)

III. STATEMENT OF OPTIMIZATION PROBLEM

Majority of engineering problems often involve constrained minimization. An example of such constrained minimization problem is finding the minimum weight design of a structure subject to constraints on stress and deflection. Constrained problems may be expressed in the following general nonlinear programming form:

$$\begin{aligned} &\text{minimize} && f(x) \\ &\text{subject to} && \\ &g_i(x) \leq 0 && i = 1, \dots, m \end{aligned} \quad (1.1)$$

$$\text{and,} \\ h_j(x) = 0 \quad j = 1, \dots, l \quad (1.2)$$

where $x = (x_1, x_2, \dots, x_n)$;

$f(x)$ = objective or cost function,

g 's are inequality constraints, and h 's are equality constraints.

The inequality constraints in Eq. (1.1) include explicit lower and upper bounds on the design variables may also express Eq. (1.2) in the form: minimize $f(x)$. Focusing on reduction of weight may be obtained by focusing on optimization and description of size, shape and topology optimization have been considered in the present work .

IV. METHODS OF STRUCTURAL OPTIMIZATION

Structural optimization is now targeting area of mechanical product development & design phase of any structure or component which are subjected to loads. The design engineer is focused with the rigorous task of designing a structure by considering various objectives that are like minimizing total weight (mass) [17] or volume[13], minimizing stress (fluctuating or static), maximizing stiffness, homogenizing distribution of stress, minimizing production costs, etc. Structural optimization implies finding the optimum geometry of selected design space each targeting different types of parameters .It can be divided in three distinct branches,. Size, shape and topology optimization. The techniques generally target either size, or shape, or topology, sometimes integrated approach is followed. It is easy to control a

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structure's shape and size as the design variables are the coordinates of the boundary (shape optimization) or the physical dimensions (size optimization), but more exercise is needed to control the topology of the structure. Various method of structural optimization are discussed and reviewed as:

4.1 Sizing optimization

Sizing optimization is the simplest form of structural optimization. The shape of the structure is known and the objective is to optimize the structure by adjusting sizes of the components. Here the design variables are the sizes of the structural elements, for example the diameter of a rod or the thickness of a beam or a sheet metal. As in size optimization where the diameter of the rods are the design variables. In a sizing optimization problem, the design variables are usually geometrical parameters such as length, width or thickness of the part being optimized.

4.2 Shape optimization

Shape optimization is performed similarly as the topology optimization. The main difference is in how the design variables are defined. Design variables are the coordinates of the boundary. The process of shape optimization consists of three modules [19]: geometrical representation, structural analysis, and optimization algorithms. To select a geometrical representation is the first step in the shape optimization process, The nodal coordinates are chosen as design variable because it is very simple by using ANSYS. Considering the architectural or structural requirements, the initial design model is constructed. The design model is converted into an analysis model. So the past researches focus on the objective function i.e. lowest cost or minimum weight. As mature analysis software, ANSYS [13] & [15] can be analyzed almost all the structures, and has been used in many practical engineering.

Yunliang Ding [3] develop a numerical model for analysis of shape optimization of various structures. Described the several steps in the shape optimization process. According to him, the steps of shape optimization are model description, selection of the objective function and shape variables, representation of boundary shape, finite element mesh generation & refinement, sensitivity analysis and solution methods. These steps are reviewed in detail in their work. X. Duan et.al. [8]. discussed the procedure of shape optimization on V-shaped anvil using Finite Element(FE) analysis interface. A FEA software MARC is used for this type of parametric optimization procedure

4.3 Topology optimization

Topology optimization is the most general structural optimization technique and it is mainly considered in a conceptual design stage. The Greek word topos, meaning landscape or place, is the origin of the word topology optimization. Topology optimization is perhaps the most difficult of all three types of structural optimization. The optimization is performed by determining the optimal topology of the structure. Optimization therefore occurs through the determination of design variable values which correspond to the component topology providing optimal structural behaviour [4] & [5].

In topology optimization a fixed finite element mesh is used and one design variable is connected to each element. The design variable determines if the corresponding element will represent structural material or a hole. The connectivity of the structure, while connecting the applied loads to the given boundary conditions, is thus changed such that the objective function is minimized subjected to the specified constraint. Applying topology optimization to structural design typically involves considering quantities such as weight, stresses, stiffness, displacements, buckling loads and resonant frequencies, with some measure of these defining the objective function and others constraining the system.

Topology optimization rapidly expanding a new research field, which has interesting theoretical implications in the field of mathematics, mechanics, multi-physics and computer science, but also important practical applications in product development (particularly car and aerospace) industries, and is likely to have a significant role in micro and nanotechnologies. A century ago, the first paper on topology optimization is published by the Australian inventor Michell (1904)[1], who derived *optimality criteria for the least weight layout of trusses*. After seven decades, authors and his research group extended Michell's theory to grillages (beam systems) which are quoted in many papers (starting with Rozvany 1972). Based on these applications, Prager and Rozvany (1977) formulated the first general theory, "optimal layout theory" of topology optimization (for a review, see Rozvany 1993 or Rozvany et al. 1995). They applied this primarily to exact analytical optimization of grid-type structures, but it has also important implications for numerical methods and continuum-type structures. Many papers deal with extensions of this theory and discussed the

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exact solutions of popular benchmark problems (Lewinski and Rozvany 2007-08) [12]. The development of topological optimization can be attributed to Bendsoe and Kikuchi (1988) [5] & [6]. They presented a homogenization based optimization approach of topology optimization. They assumed that the structure is formed by a set of non-homogenous elements which are composed of solid and void regions and obtained optimal design under volume constraint through optimization process. In their method, the regions with dense cells are defined as structural shape, and those with void cells are areas of unnecessary material. At the World Congress, Seoul(2007) many papers were discussed on application and approaches of topology optimization. In the Hyper works Technology Conference (HTC), Varun Ahuja et al. (2012) presented paper and discussed about Optimization Techniques in Reducing the Weight of Engine Mounting Bracket[14] and concluded 15 % weight saving of the bracket using Opti-Struct Software tool. In this conference some other papers on topology optimization is discussed. M.V.Aditya Nag(2012) in HTC Conference showed the result how the weight of engine mounting bracket is reduced up to 60% without compromising the strength of the bracket[16]. Dheeraj Gunwant et.al Misra (2012) compared The results of ANSYS based Optimality Criterion [18] which was a gradient based method, were compared with those obtained by Element Exchange Method which was a non-gradient based method

V. CONCLUSION

Size optimization required to find the optimal values of the various dimensions. Shape optimization is the further extension of size optimization; it allows extra freedoms in the configuration of the structure such as the location of connections between members. Modified designs are restricted to a fixed topology and thus can be written using a limited number of optimization variables. Topology optimization advances the size and shape optimization and gives no restrictions to the optimized structure. It simply tries to find the optimal domain of the governing equations contained within some design field. It provides minimum distribution of material in selected design space. Compared to size and shape optimization, topology optimization allows more freedom as no initial structure is required. Only the design space, the loads and the boundary conditions are required in order to find an optimized structure which satisfies the given restriction.

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