Topology Optimization of Aircraft Fuselage Structure

Muniyasamy Kalanchiam and Baskar Mannai

***Abstract*—**Topology Optimization is a defined as the method of determining optimal distribution of material for the assumed design space with functionality, loads and boundary conditions [1]. Topology optimization can be used to optimize shape for the purposes of weight reduction, minimizing material requirements or selecting cost effective materials [2]. Topology optimization has been implemented through the use of finite element methods for the analysis, and optimization techniques based on the method of moving asymptotes, genetic algorithms, optimality criteria method, level sets and topological derivatives. Case study of Typical "Fuselage design" is considered for this paper to explain the benefits of Topology Optimization in the design cycle. A cylindrical shell is assumed as the design space and aerospace standard pay loads were applied on the fuselage with wing attachments as constraints. Then topological optimization is done using Finite Element (FE) based software. This optimization results in the structural concept design which satisfies all the design constraints using minimum material.

***Keywords*—**Fuselage, Topology optimization, payloads, design optimization, Finite Element Analysis.

I. Introduction

IN the tough international competition, companies are moving towards innovations to provide strongly cost optimized products. Therefore the stress engineers are introducing new technologies in concept phase of the product development process. Topology Optimization is one of the innovative and powerful procedures to come up with optimized concept design [3]. Almost all FEM codes have integrated sizing optimization capabilities to support the calculation engineer. The recent two decades have witnessed a tremendous development of the field of topology optimization. It works based on deterministic iterative optimization approach using repeated finite element analysis, analytically obtained sensitivities and design updates.

Topology optimization can be used to optimize shape for the purposes of weight reduction, minimizing material requirements or selecting cost effective materials. It can be used to determine design concepts but can also be used to improve existing structural components and systems. This leads to a highly efficient initial product design concept analyzed in less time and results in a higher quality product with lower overall development cost.

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In this paper typical "Fuselage design" is taken as a case study to illustrate the role of Topology Optimization and its benefits. Fuselage is the structure which forms the central body of any aircraft. This is one of the critical structures in the aircraft. This structure should be capable of withstanding pay loads, inertial loads, etc. Usually, this is made up with aluminum material. Designing a Fuselage to take all kinds of loads is really a challenging task. The design has to undergo number of iterations to arrive at a concept which can take all the loads. Topological optimization approach helps engineers to come up with an optimized concept design and cost effective too.

Initially a cylindrical shell is taken as a design space. And the various loading requirements are imposed in the model with appropriate boundary conditions. Then the design objective is defined as input for the optimization. Topological optimization is done using Finite Element based software. The program will run iterations to come up with minimum weight and required stiffness. As a result, an optimized structural concept design is delivered. This design is highly efficient and cost effective. Similar methodology can be adopted for various other designs for material and cost saving and to determine optimum shape.

II. What Is Topology Optimization?

The word topology originates from the Greek word "topos", which means landscape or place. In other words, topology optimization means optimizing the "landscape", consisting of the number, shape and connectivity of the elements that make up a structure.

Optimization is a mathematical discipline that deals with the finding minima and maxima of functions, subjected to so called constraints. Optimization is an act of obtaining best results under given circumstances. Conventional structural design process is iterative in nature. In each step various relevant analyses are performed. The results obtained (displacements, stresses, etc.) are characterizing the performance of that particular design. Based on these results, the design is modified and reanalyzed. The loop has to be repeated until the desired output is obtained. The number of iterations depends on the experience of the designer and in complexity of the structure. Using Optimization techniques the number of design iterations can be minimized to get the best results.

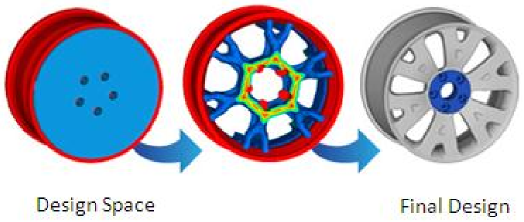

Fig. 1 Figure illustrating Topology Optimization

Topology optimization involves the optimal distribution of material within the structure. It is used to find a preliminary structural configuration that meets predefined criteria. This type of optimization sometimes gives a design that can be completely new and innovative. Typically, the design process starts with a block of material called the design domain. The design domain is comprised of large number of candidate elements, and topology optimization process selectively removes the unnecessary elements from the domain.

III. Aircraft Fuselage Structure

Aircraft design is a highly complicated process, where so many critical load paths have to be determined. In aircraft, Fuselage structure is one of the most critical structures. This structure forms the central body of an aircraft.

Fig. 2 Aircraft Fuselage

The fuselage is designed to carry the payload, and is the main body to which all parts are mounted. It must be able to resist bending moments (caused by weight and lift from the tail), torsional loads (caused by fin and rudder) and cabin pressurization. The structural strength and stiffness of the fuselage must be adequate enough to withstand these loads. At the same time, the structural weight must be kept to a optimum level. In transport aircraft, the majority of the fuselage is cylindrical or near-cylindrical, with tapered nose and tail sections. The semi-monocoque construction, which is virtually standard in all modern aircraft, consists of a stressed skin with added stringers to prevent buckling, attached to hoop-shaped frames [5].

The fuselage also has structural members perpendicular to the skin, and supports to keep its shape. These supports are called frames if they are open or ring-shaped, or bulkheads if they are closed. Disturbances in the perfect cylindrical shell, such as doors and windows, are called cutouts. They are usually unsuitable to carry many of the loads that are present on the surrounding structure. The direct load paths are interrupted and as a result the structure around the cut-out must be reinforced to maintain the required strength. In aircraft with pressurized fuselages, the fuselage volume both above and below the floor is pressurized, so no pressurization loads exist on the floor. If the fuselage is suddenly de-pressurized, the floor will be loaded because of the pressure difference. The load will persist until the pressure in the plane has equalized, usually via floor-level side wall vents.

Frames give the fuselage its cross-sectional shape and prevent it from buckling, when it is subjected to bending loads. Stringers give a large increase in the stiffness of the skin under torsion and bending loads, with minimal increase in weight. Frames and stringers make up the basic skeleton of the fuselage. Pressure bulkheads close the pressure cabin at both ends of the fuselage, and thus carry the loads imposed by pressurization. They may take the form of flat discs or curved bowls.

Fig. 3 Fuselage in the Airplane structure

IV. Conventional Fuselage Design Cycle

The conventional design process is given in the following flow chart.

Fig. 4 Conventional design cycle of Fuselage

It starts from the concept generation, then step by step up to validation. In the stress analysis, if the design is found OK, the loop ends. If it is not OK, the loop again starts from the concept generation. Since there are so many load cases associated with Fuselage, coming up with right concept design is tricky.

Topology optimization is the better remedy for this problem. In the following chapter, the topology optimization case study is given.

V. Fuselage Topology Optimization

FE based approach is used to perform topology optimization [6]. The following steps are followed in topology optimization of the Fuselage structure.

A. Step – 1: Design Space Construction

The design space is determined using aircraft design layout. It will be like a cylindrical shell and it is shown in the following figure.

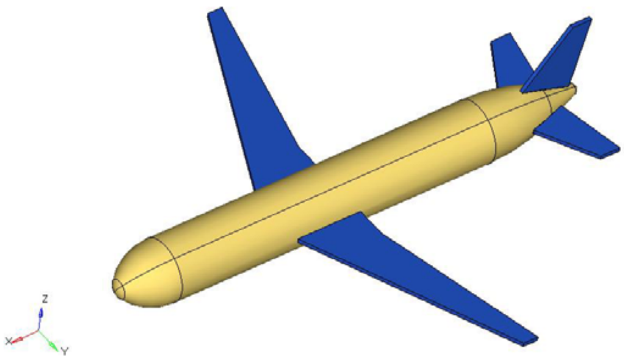

Fig. 5 Design space – CAD Model

The finite element model is made for the design volume using 4 node shell elements. The material properties are assigned to the model. Element qualities have been checked to the acceptable level.

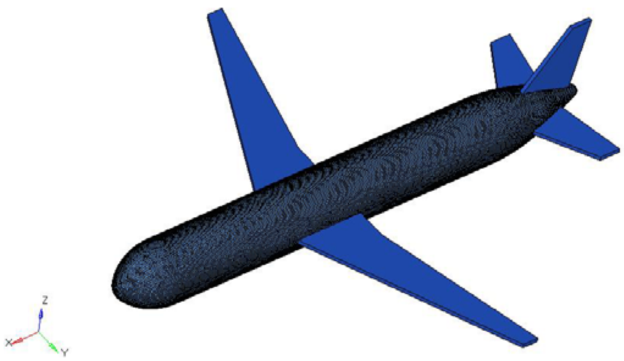

Fig. 6 Design space – FE Mdoel

B. Step – 2: Applying Loads and Boundary Conditions

In this step, appropriate boundary conditions are applied to the model. Loads are applied to the fuselage. Main loads considered are bending about the center of gravity, torsion loads and pay loads. Boundary conditions are applied at the fuselage-frame attachment region.

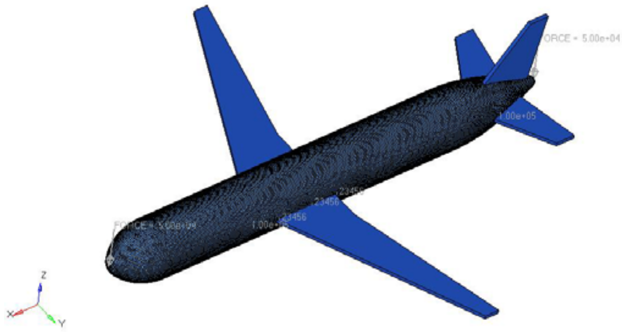

Fig. 7 Loading of Design Space

C. Step – 3: Defining Optimization Constraints

The topology optimization inputs are given in this step. Objective, design constraints and response are defined as per the requirement. In this case study, the objective is to minimize the volume [4].

D. Step – 4: Topology Optimization Analysis

In this step the model is solved for topology optimization. The maximum number of iterations has been decided based on the complexity of the problem and the capacity of computational resources used.

E. Step – 5: Optimized Structure

The optimized concept is arrived in this step. The model can be visualized and the optimized model can be exported as a neutral file. Based on this optimized model representation, the design engineer can decide the locations of bulk head, frames and stringers and he can determine the number of frames. Naturally at the fuselage-wing attachment region requires more material than other regions.

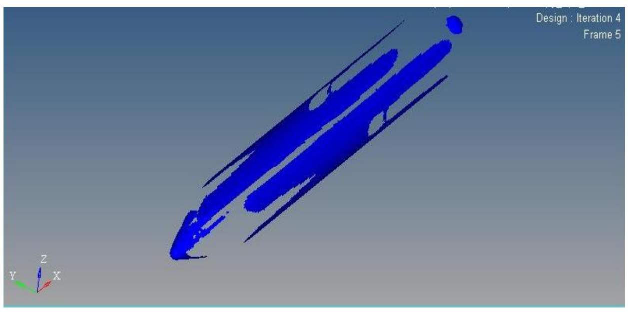

Fig. 8 Topology Optimization output

VI. Optimized Fuselage Design Cycle

The modified process flow chart is given in the following figure.

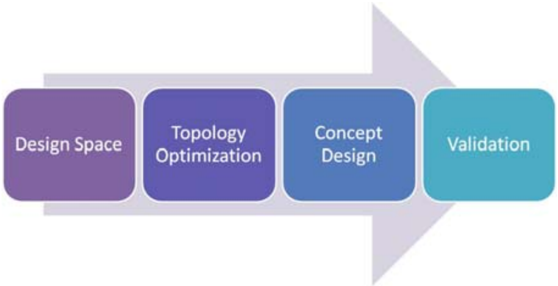

Fig. 9 Modified design cycle of Fuselage

Since the modified process starts with topology optimization, the design loop is avoided. This leads to time and cost saving in product development. Because of the optimization process, the material flow in the design is perfect and the strength to weight ratio is improved in the design.

VII. Conclusion

A case study on the Fuselage design is carried out to implement Topology optimization using Finite Element based approach and a new fuselage design cycle has been developed. The advantages of the new design cycle are minimum design time, less cost and reduced weight of the aircraft fuselage. This approach is applicable for all the structural components which are in the aircraft.

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