Topology Optimization of an Aircraft Component as a Fluid-Structure System with Unstructured Mesh

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ABSTRACT

This work presents the development of a methodology that will perform the optimization, or maximization, of the stiffness of a structure while its structural volume is gradually removed, in order to obtain a structure having stiffness close to the original one, however using only a fraction of the material. This structure may be part of a fluid-structure system and is subject to external static loads, as well as loads imposed by the fluid. The discretization can be made with an unstructured and irregular mesh, and the BEFSO (Bi-Directional Evolutionary Fluid-Structural Optimization) method is used. The developed software was capable of optimizing cases found in the literature, and also allowed the optimization of cases not easily optimized when conventional methods that use regular meshes, found in non-commercial programs, are employed.

Keywords: Topology optimization, FEM, fluid-Structure, unstructured mesh.

INTRODUCTION

Recently, the topology optimization methods have been widely studied as an alternative into the development of optimal structural concepts, especially in situations where the mass of the structure is of great importance, such as in the aircraft and aerospace industry. A presentation of these studies can be found in Paulino (2013). These concepts are used in the early stages of a project, where is looking for an initial form of the structure which will then be improved over its development process, and it is therefore critical, because it limits the ways that the final structure may have.

There are several general methods of topology optimization, the main ones being the BESO (Bi-directional Evolutionary Structural Optimization) and SIMP (Solid Isotropic Material with Penalization), as described by Huang and Xie (2010). The main difference between these methods is how the optimized variable is treated, in this case the elements of the structure: BESO method treats them in discrete manner, *i.e.*, each element may have a value that represents its presence or another value that represents its absence, while the SIMP method treats them continuously, *i.e.*, each element has a density value between 100% and 0%. A detailed analysis of the differences can be found in Huang and Xie (2010). A variation of the BESO method is the BEFSO method (Bi-directional Evolutionary Fluid-Structural Optimization), termed by Vicente (2013). This work includes a modification to the BEFSO method, which deals specifically with the evolutionary topology optimization applied to systems with fluid-structure interaction.

The main objective of this work is to contribute with the improvement of the BEFSO method. This unfolds in two specific objectives: to develop an extension of the method that allows its use with irregular and unstructured meshes, and to develop software with open source, programmed completely, capable to solve cases of more complex boundary geometries. To verify these developments, comparisons were made with cases found in the literature, and a new case is optimized to exemplify the capabilities of the expanded method. The proposed expansion consists of a change in the calculation of the sensitivity values.

Several cases to be optimized cannot be efficiently discretized with regular meshes, such as aircraft wings, because the domain cannot be divided into regular elements. In such cases, the domain can be approached using a greater quantity of regular elements, but with the proposed method it is possible to discretize the structure with less elements without losing the boundary profile.

THEORETICAL BACKGROUND

Structural optimization

The structural optimization looks for the improvement of structural efficiency through the optimization of some predefined parameter or function, such us minimum mass, maximum stiffness, maximum buckling load, etc., while reducing cost. A structural optimization example is the removal of unnecessary material in square section beams, giving rise to I-beams, which have less weight and consume less material and is more economical. The optimization should also take into account constraints such as failure stress, critical natural frequency, allowed displacements, etc.

One may define three classes of structural optimization: size optimization, shape optimization and topology optimization. The first seeks to change only the dimensions of the structural members. Shape optimization also scales the cross-section of structural members, but in addition, one can modify the position of members in order to support more efficiently the load. Both of these methods depend, however, on an initial structural concept, not being able of adding or removing members. Unlike other methods, the topology optimization is used to generate this initial concept.

Topology optimization

Topology optimization serves to generate a conceptual structure that is superior in some domain. In this work, one seeks to improve the structural efficiency. To this end, one must increase the stiffness and decrease the material. Thus, starting with an arbitrary structure under loads and constraints, the optimization removes areas of material that are not very requested, and therefore, do not contribute much to the structural stiffness.

Topology optimization methods require a discretization of the domain, an objective function which represents the performance of the structure, and a set of constraints limiting the modifications. The method BEFSO is used in this work, a modification of the BESO method considering fluid-structure systems. The objective function is the energy absorbed by the structure because it is a way to quantify its stiffness, and the amount of material is considered as a constraint. One structure that uses more material has more stiffness, it improves the objective function but with material addition, which turns the structure less efficient. To prevent this, the amount of material that can be used is limited, and thus the optimization seeks to improve the stiffness of a structure using less material.

Fluid-structure

A fluid-structure system comprises fluid and structural domains. Some examples could be a pipe, a pumping piston, an airplane wing, among others. The system is said coupled when each domain affects the other, what happens in dynamic cases and prevents their separation into two separate problems, forcing their coupled resolution. However, in static cases, like in this work, the two domains could be solved separately; the fluid is calculated, and the solved pressures are enforced on the structure.

Although the calculation by finite elements is done separately for each domain, the modification of the structure during the topology optimization can affect both domains simultaneously if some interface elements are added or removed. Thus, every time the structure is modified, the fluid needs to be recalculated. Therefore, some modification to the method should be made.

The method BESO

The BESO method is the basis of BEFSO method, and its goal is the optimization of an objective function by removing or adding elements of a structure that may be subject to a given constraint, and this constraint is partially applied, increased gradually, through several iterations. The method consists of a series of modules, each having a specific purpose, but no a fixed form. Details of implementation of the method can be found in Huang and Xie (2010).

Huang and Xie, 2010, compare the methods SIMP, ESO, BESO and continuous variation. Although the latter presents the best results, BESO method achieves a similar result, while it requires less processing time among all compared methods. Moreover, this method has advantages concerning to its modularity and relative simplicity; because of these characteristics it was selected as optimizer tool in this work.

This method requires an objective function, which quantifies the structural feature to be optimized. This depends on the structural configuration at each iteration. In addition, the objective function is used to define the sensitivity function. The most frequently used functions are frequency response (Yoon *et al.*, 2007; Vicente, 2013) and stiffness (Huang and Xie, 2010), but many others also exist, such as energy dissipation rate due to the viscosity of a fluid (Gersborg-Hansen *et al.*, 2005) or effective diffusivity of nutrients through a porous structure, among others.

Structured, unstructured and regular mesh

A structured mesh is a mesh where the numbering of the elements follows a defined order. As an example, consider a mesh of quadrilaterals with 5 elements horizontally and 4 vertically. Examples of meshes with these characteristics are shown in the left column of Fig. 1.

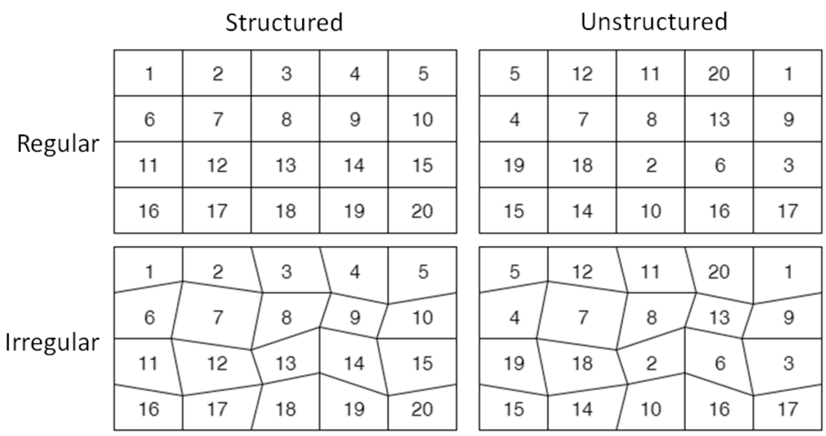


Figure 1: Examples of regular and irregular meshes, structured and unstructured.

A structured mesh does not need extra information to determine the connectivity of the elements; while unstructured meshes depends on a connectivity matrix that determines which elements are connected to each other, which increases the complexity of the implementation.

All elements are identical in a regular mesh. Meshes with these characteristics are shown on the upper row of Fig. 1, with the advantage that it is only necessary computing and storing a matrix of elementary stiffness; while irregular meshes require the calculation of the elementary matrix of each element, which significantly increases the computational cost.

In general, the topology optimization of a system is performed using a structured and regular mesh. This simplifies the implementation, but imposes limitations on the type of system that can be optimized. An alternative to this type of mesh is the use of conventional finer meshes; increasing the number of elements enables the discretization of curves and other features through ladders. However, as more elements are used, the computational cost is significantly increased because of the quantity of variables.

METHODOLOGY

This work was programmed in MATLAB, implementing a 2D hard-kill BEFSO method. The choice of this method instead of a soft-kill version is due to lower computational cost of the first, which has very similar results as the second one. The procedure of the program is shown in Fig. 2.

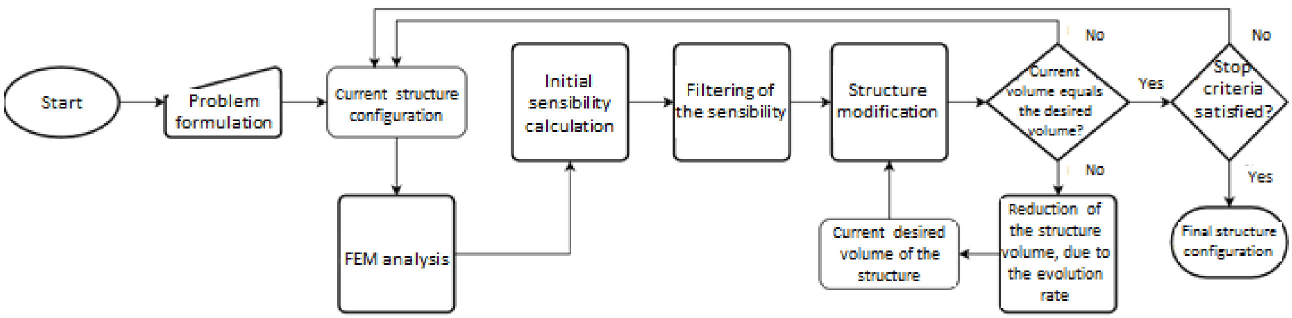


Figure 2: General procedure of optimization used by the method BEFSO.

Problem formulation

The analyzed problems involve the structural optimization of fluid-structure systems, seeking to minimize the structural compliance, which is equivalent to maximize the stiffness. The mesh of the system is not changed during the optimization. All problems are firstly described by a series of data concerning the mesh (position of nodes and connectivity matrix), boundary conditions (forces and displacements, and prescribed pressures, on certain degrees of freedom), structural material properties (Poisson's ratio and Young's modulus) and initial regions of the fluid. It is also informed the final desired volume fraction and rate of evolution, as well as regions in which the structure cannot be removed.

Current configuration structure

The configuration of the structure in a given iteration is determined by a vector x of size equal to the number of elements used to discretize the domain. Each element of this vector can take a value of 0, representing an empty space or filled with fluid, or 1 representing a structural element. A second vector distinguishes between void elements having no stiffness, and thus they are removed from the total stiffness matrix, or fluid elements.

An empty space will be occupied by fluid if there is fluid in the neighborhood. Some elements are always fluid, defined in the formulation of the problem. To determine the fluid elements, the flood-fill is used, where empty elements beside fluid elements are occupied, repeating the process until there are no more empty elements in this condition.

Modification of the structure

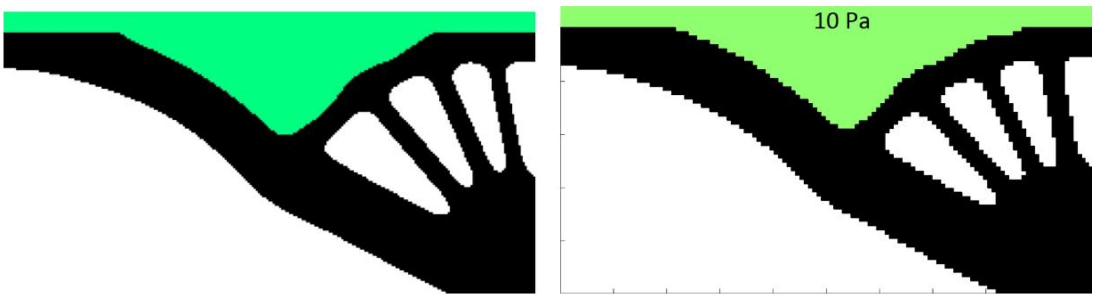
After calculating all elementary filtered sensitivities, the elements are sorted according to their sensitivity value, and the elements with the lowest values are removed until the volume of the retained elements is equal to the volume defined by the constraint. This corresponds to the removal of elements that contribute less to the structure. That is, the least loaded elements are removed because their removal has the least impact on the structure as a whole when compared to the impact of the removal of other more loaded elements. In this sort are also considered previously removed elements, having a sensitivity value due to the filtering process. Thus, if a removed component has a value larger than an element that would be maintained, the first is re-included and the second is removed. However, only a certain volume of elements may be re-included.

RESULTS AND DISCUSSION

Verification

A comparison between the results obtained by the developed program and those obtained by Vicente (2013), was performed in two cases. Figure 3 shows the comparison of results for one case.

The case refers to half a piston, halved due to its symmetry, having regular mesh and movable interface.



Half of a piston with 8375 elements

Figure 3: Comparison of results found by Vicente, 2013, at left, and the developed software, at right. The colored areas represent the fluid.

Aircraft wing

As an example of the capabilities of the program, it has been proposed the optimization of the inner structural cross section of an airplane wing. In this case, there is a fixed interface between the fluid and the structure, because the external profile of the wing is determined by its aerodynamic behavior that is not simulated here. One NACA 4412 profile was chosen, and the distribution of external pressure caused by air during its operation is given by Allen (1939), depending on the dynamic pressure, which is given by:

$$q = \frac{1}{2} \rho_{ar} U^2 \quad (1)$$

where ρ_{ar} is the ar density and U is the flow velocity. Table 1 shows the values used for the simulation. To generate the mesh of this case, the GMSH program was used. The result of the optimization is shown in Fig. 4.

Table 1. Values used in the simulation of wing profile NACA 4412

Flow velocity	U	200 km/h (55,6 m/s)
Air density	ρ_{ar}	1.007 kg/m^3
Dynamic pressure	q	1554.0 Pa
Altitude	H	2000 m
Wing profile		NACA 4412
Angle of attack	A	13º57'
Chord	c	2 m
Thickness of the fixed interface layer	T	10 mm
Number of elements	n	15790

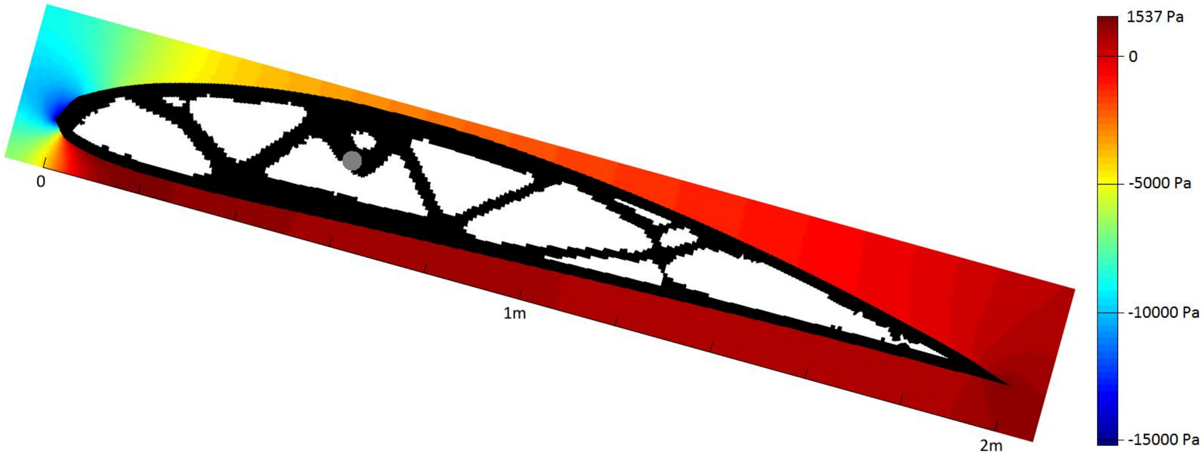


Figure 4: Results for optimization of the internal structural cross section in a wing profile NACA 4412. The colored regions represent the fluid with the fringe indicating the pressure levels. The gray circular region represents a beam perpendicular to image, where the fixed conditions are applied.

CONCLUSIONS

A comparison of solved cases for validation showed that the implemented software was capable to optimize cases with regular or irregular mesh, and with or without movable interface. The meshes used in these cases are structured, but for the developed program there is no difference between structured and unstructured meshes because it does not make use of the simplifications of the structured meshes.

The presented aircraft wing is optimized using an unstructured and irregular mesh. The wing was chosen as fixed only in a single beam. Wings of different aircrafts, even with the same profile, may have different structures; the simulated wing does not refer to some specific aircraft, it is used only as an example to show the functionality of the software developed.

It was possible to implement the topology optimization code BEFSO in MATLAB without any dependence on external commercial programs. This was verified with cases found in the literature, and it has been used to optimize an aircraft component to demonstrate its potential.

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