Topology optimization for mass reduction in aeronautical industry

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Abstract

In the current context, since Paris agreement on climate change, reduction of greenhouse gas emission has been a main issue for manufacturers in different industrial sectors and particularly in aeronautical sector. In order to address this new challenge, the improvement of part performance is crucial, especially the reduction of mass which allows to reduce gas emissions. Therefore, optimization allows to reduce effectively the mass of structural parts and tackle environmental issues. In this white paper are explained the interest of optimization and its set-up. In addition, different types of optimization are explained such as sizing optimization, shape optimization, topology optimization and materials optimization. A focus on topology optimization is done, especially on challenges and interests, limits and perspectives for the future.

1 Introduction

1.1 Reduction of greenhouse gas emission

In the current context of growing population and global warming, the reduction of greenhouse gas emissions is a main issue for a lot of countries and industries. Like many industrial sectors, the aeronautical industry should take responsibilities and adapt to these new constraints.

In the context of Paris climate agreements (12 December 2015), a quantitative target on the limitation of global warming was fixed. In order to respect this agreement, the aeronautical sector was the first in 2016 to equip itself with mechanisms to contain CO_2 emission through CORSIA standards (Carbon offsetting and Reduction Scheme for International Aviation).

The objective of this standard, which was signed by 70 countries, representing 88 % of international aeronautical activity, is to stabilize CO_2 emissions not to exceed the level of future emissions in 2020. All CO_2 emissions exceeding this level should be compensated by investment in projects to fight against global warming. In this context, the reduction of gas emissions is a main subject of research for manufacturers.

1.2 How to reduce greenhouse gas emission ?

With a sector that represents 2 % of CO_2 gas emissions in the world, and with a growth of 5 % each year, the stabilisation of gas emissions is an important challenge. Nevertheless, for manufacturers there can be different paths to take.

The first axis is to improve engine performance in order to reduce its CO_2 emissions. A second direction is to work on the aerodynamics of planes to reduce aerodynamic drag. Finally, the last axis is to reduce the mass of the plane.

In addition to the reduction of carbon footprint through the optimization of fuel consumption, the mass reduction of planes is a good way to reduce the impact of material cost.

For manufacturers, the mass reduction of planes or engines is crucial to respect agreements on global warming and to have better performance for planes and continue to gain market shares in this competitive sector.

2 Optimization

2.1 Why optimization ?

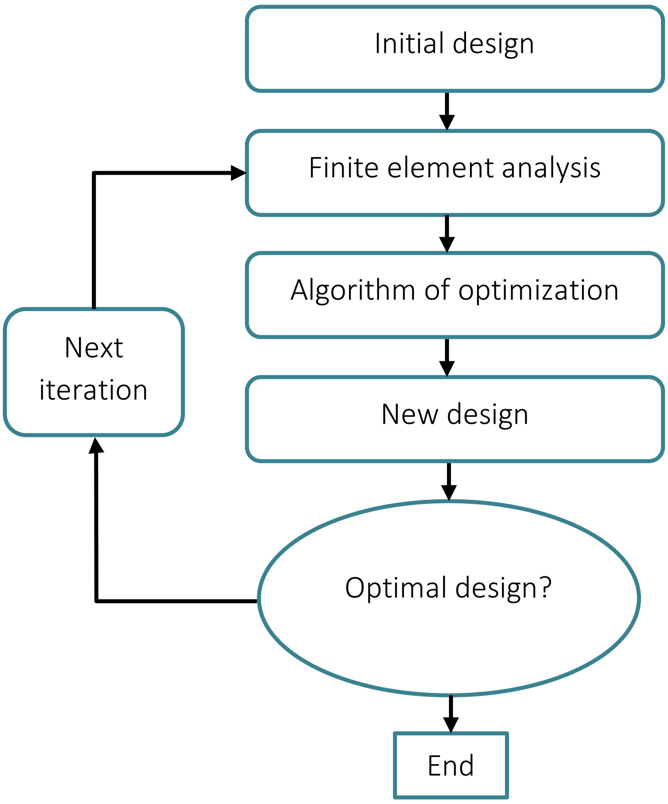
Optimization techniques are used in different sectors as logistics, finance and in mechanical design.

Engineers working in mechanical design departments as stress engineers or design engineers have to find solutions to given problems. The solutions must meet a fixed objective and must satisfy a number of constraints. The objective of optimization is to find “the best conception” against the performance criteria defined by the engineer.

Currently, one of performance criteria for transport industry is the mass. Indeed, as mentioned previously, the mass reduction of mechanical structures is one of the possible answers to the current environmental stakes and optimization can allow to reduce mass of structural parts. Therefore, integration of optimization phases in a design cycle is a crucial issue for manufacturers and one of the possible answers to the reduction of CO_2 gas emissions.

2.2 Description of optimization process

As mentioned earlier, optimization process consists in “finding the best conception”. This process is an automatic process based on initial conception defined by a number of parameters that are “design variables”. Optimization allows to determine these parameters in taking objectives and constraints defined by engineer into account. This iterative process is defined below:



2.3 Formulation of the optimization problem

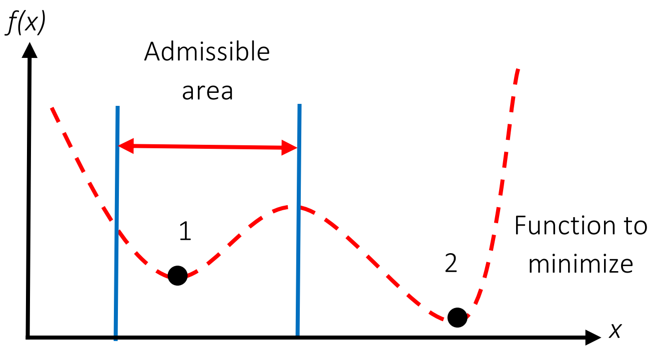
So that the optimization process goes well, it is necessary to formulate correctly the problem.

Any optimization problem has one objective. In mechanics, objectives often consist in minimising mass or maximizing the structural stiffness. For the mathematical resolution, the goal takes the form of a scalar function which depends of design variables.

Design variables are the quantities that appear in the definition of the optimization problem, and whose optimal values have to be determined. For example, for a composite panel, design variables can be ply orientation, thickness of plies or also number of plies. These variables can evolve within upper and lower bounds in a continuous or discrete way. Indeed, the thickness of plies is limited by the range product defined by manufacturers and by the available space in the product design. In this case, the thickness can evolve continuously within the bounds; on the other hand, for composite panel, the number of plies must be a discrete value.

To optimize a problem, we usually try to minimize the objective function by finding the optimal design variables values. In mechanics, the optimization problem is often "constrained". These "constraints" usually relate to the results of finite element calculation, they are expressed as function of design variables and are written in the form of inequalities or equalities. For example, the first Eigen frequency should be less than a given value, or the maximum displacement of node should be less than a given value.

To sum up, the optimization problem is limited by the usual constraints on frequency or displacement and the bound constraints on design variables. The optimum is inside the admissible design space bounded by these constraints.



The one-dimension example above explains an optimization problem. The optimum configuration of the function *f* is the point 2, but if one considers the constraints delimited by the area in blue, the solution of the problem is the point 1. In fact, at this point, the minimum value of the function *f* does satisfy the constraints of the problem.

2.4 Different types of optimization

In mechanical optimization, it is possible to classify problems according to the type of design variables. So, optimization problems are classified in 4 classes: sizing optimization, shape optimization, topology optimization and materials optimization. All optimization problems will be described in this paragraph. Often, topology optimization is used at the beginning of the project to determine a optimum design while shape and sizing optimization are used at a more advanced stage in the design process.

2.4.1 Sizing optimization

In the sizing optimization, the design variables are transverse dimensions of thin structures. Applied to the Finite Element Method, the design variables are the bar section and the thickness of membranes or shells. With this type of optimization, neither the shape nor the topology of the structure are changed. No geometry changes are made, only physical properties of elements are modified.

This optimization type is used in many industries, among which the aeronautical industry. The formulation of sizing optimization is rather simple, but it can involve many design variables for complex structure parts.

2.4.2 Shape optimization

In shape optimization, design variables are associated with the external border of the structures. No new border can be defined, so the topology of the structure remains the same. With the shape optimization, there are two possibilities to define design variables, and so set the external border. The first solution is to work directly on the meshing of the structure, the second is to associate design variables to CAD geometry. With the second solution the remeshing of the structure is necessary after each geometric change.

When design variables are based directly on the mesh of the structure, it is not necessary to remesh the structure afterwards. However, in this configuration each node of the mesh is moved independently from the others and often the obtained solution is not satisfying.

In addition, as the mesh is not modified, the number of meshing elements doesn't change in the finite element model. When the shape of the structure is modified, as there is the same number of elements, they become distorted and the quality of the solution is no longer guaranteed.

The best solution is to set directly the border of the CAD. With the remeshing of the structure and the good quality of elements, a right calculation of tension (the name of mechanical constraints in optimization) is possible. Then the quality of the solution is better than when using the setting on the meshing. Nevertheless, the difficulty is linked to the faculty of linking optimization phases and automatic mesh. It is thus necessary to have a good coupling between CAD software and calculation software. That is why the shape optimization is not widely used in the industry.

2.4.3 Topology optimization

The goal of topology optimization is to find the optimal distribution of material properties in a specified area design. In this type of optimization, the initial mesh is the design area, and one researches elements that will receive mechanical properties of the used material. With this type of optimization, no elements are deleted even if they are no longer visible at the end of the process, mechanical properties just change.

On topology optimization, design variables are called pseudo density, each element on the finite element models has pseudo density. Therefore, the number of design variables is huge in the model. The pseudo density μ_i is defined as follows, with ρ_0 the density of reference material and ρ_i the effective density of the finite element.

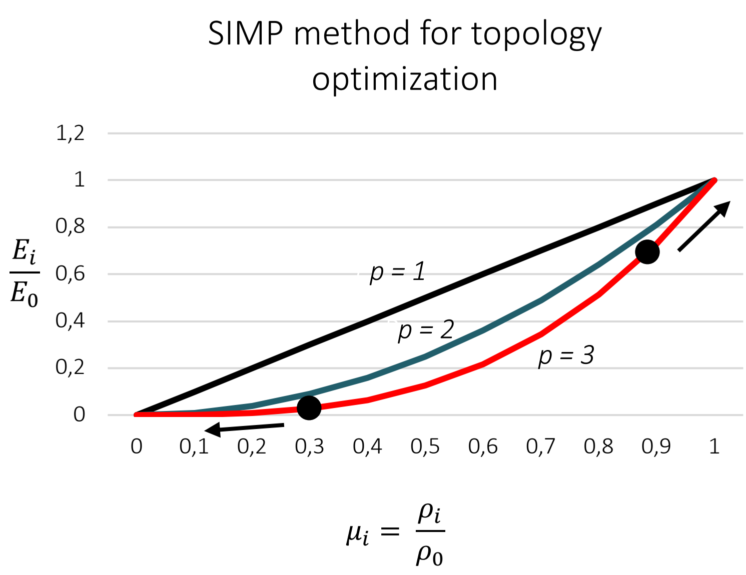
$$\rho_i = \mu_i \times \rho_0$$

In topology optimization, the pseudo density can evolve continuously between ε (value close to 0) and 1. The pseudo density cannot be 0, in order to avoid numerical singularity.

In the same way, we can define the Young modulus of the finite element *i* by the following equation:

$$E_i = \mu_i^p \times E_0$$

In this equation, E_0 is the Young modulus of reference material, E_i is the young modulus of the finite element *I*, and *p* is a factor to penalize intermediate density between ε and 1. This way to use *p* factor to modify material property is the SIMP method (Simply Isotropic Material with Penalization). The interest of this method is to eliminate as much as possible the intermediate pseudo-density between ε and 1. So the pseudo-density values are close to ε or 1, then it is easier to interpret results and decide if there is matter or not.



The graphic above explains the interest of the SIMP method for topology optimization problem. The graphic shows the evolution of relative stiffness depending on the pseudo-density for different values of penalization.

Stiffness is proportional to the Young modulus, that is why it is called relative stiffness for $\frac{E_i}{E_0}$.

For values of p equal to 2 or 3, when the pseudo density is close to 1, a small increase of mass allows a significant increase in stiffness. On the contrary, if the pseudo density is close to ε, a significant decrease of mass induces a slight change in stiffness.

Usually, in topology optimization problem with a goal of mass reduction one tries to maximize stiffness with constraint on mass or one tries to minimize mass with constraint on stiffness. Then, with a penalization one forces intermediate values to approach ε or 1, to minimize impact of mass reduction on the stiffness, or to increase stiffness while limiting the increase of mass. The interest of the penalization is valuable for penalization values greater than 1.

Regarding to maximization of stiffness in the optimization problem, it is not possible to maximize the function, only to minimize it. That is why compliance tends to be minimized to maximize stiffness in optimization problems. The compliance is defined as the work of the applied force. In minimizing the compliance, the strain energy of the structure is minimized, thus maximizing its stiffness.

2.4.4 Materials optimization

The goal of materials optimization is to find the optimal location for the optimal material for the structure. For isotropic materials one searches the optimal Young modulus. For composite materials, the goal is to determine the optimal orientation of layers and the optimal stack. For composite structures, one can use different types of settings for design variables that are not detailed here.

One of the problem of composite optimization is that the design variables are ply orientation and they are not continuous variables. So, it is not possible to use the mathematical algorithm usually used for optimization problem. However, several settings for design variables allow to obtain continuous variables.

One of this method is based on topology optimization principle. Coefficients can take values between 0 and 1. If the coefficient equals 1, then the associate ply orientation is chosen. As with the SIMP method for topology optimization, the appearance of intermediate values is penalised.

3 FOCUS ON TOPOLOGY OPTIMIZATION

Topology optimisation is a focus point because of technical challenges in the aeronautical industry and potential developments for the future.

3.1 CHALLENGES AND INTERESTS

The use of topology optimization has several advantages. First, its implementation in design offices allows to considerably reduce the length of studies. Indeed, as explained previously, topology optimization allows to determine a design according to the constraints of the specification of the structure. Obtaining in a few steps the optimal design allows to get rid of constant back and forth between design and calculation departments and so to gain time during design phases. However, to obtain the optimal design in one step, there are still setbacks that will be treated in other part.

Furthermore, optimization makes it possible to improve the performance of structural parts, especially the mass of structures, which is the subject of this white paper. Therefore, topology optimization allows to reduce the cost of development and fabrication, with the reduction of time design studies and the material cost.

3.2 Limits

3.2.1 Numerical limits

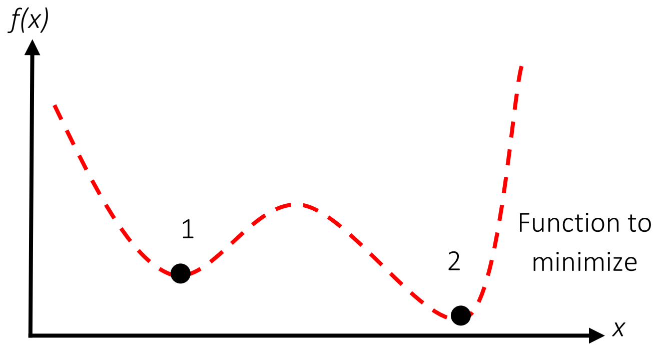
As seen previously, the number of design variables is huge for this type of optimization. For each element, on design area, there is an associated pseudo-density, so one design variable for one finite element. The number of design variables is directly dependent on the number of elements, so it is easier to have more than one hundred thousand variables in a topology problem. However, a good discretisation of the problem is crucial to obtain a fine distribution of matter. The challenge is also to find the right compromise between time of resolution and quality of the solution by well choosing the number of elements.

Currently, it is also difficult to work on problems with a lot of constraints. Indeed, with the big number of design variables, the resolution of problems with a lot of constraints and variables is not possible with the actual industrial methods of resolution. That is why it is not possible to take mechanical constraints (called tension in optimization) into account in topology optimization. So topology optimization ensures a solution that meets the specifications, especially concerning tension on the structure.

The validation of results is not easy for engineers. First, after topology resolution one obtains a solution with different values of pseudo density between ε and 1. Even if the SIMP method allows to reduce intermediate values of pseudo-density, it is not simple to choose the required level of pseudo-density. The result of the optimization process also depends on the chosen penalization. Second, in order to definitively validate the result of the optimization, a calculation is necessary to validate tension on the model. But before that one needs to rebuild geometry using kept elements in the model. Often, in industrial software, automatic function exists to build CAD from elements, but sometimes, the automatic reconstruction is difficult, and must be done manually by designers. That is why it is not possible to obtain the optimal design in one step with topology optimization.

If one wants a better solution, it is also possible to do another optimization after topology optimization. For example, after obtaining new topology and build the new CAD, the new solution can be optimized with shape optimization considering tensions on the structure. Like this, the solution is refined while ensuring that tensions are admissible.

Another issue that can be found in all types of optimization is that it is not sure to find the global optimum of the problem. It is possible that the optimum found is a local optimum. See the example on the next diagram:



In the example above, the function is not convex, so there is a local minimum at point 1 for the function and the global minimum is at point 2. When a no convex function is minimized, it is not possible to know if the given solution is the global or a local minimum. In topology optimization problems, the objective function is not necessarily convex.

Usually, in industrial software, optimization methods are based on the gradient method associated with convex sequential approximation method. According to the chosen type of approximation, different paths are taken, and different local optimum could be found (In this white paper, algorithms won't be described). The uniqueness of the solution is not necessarily guaranteed, and one is not sure to reach the global optimum.

3.2.2 Limits due to process and activity sector

After topology optimization, the good repartition of matter is obtained, to have the best compromise between mass and stiffness. Usually, the part is not manufacturable with conventional processes like matching and moulding. To ensure that the structure is manufacturable with the chosen process, constraints on geometry need to be added to traditional constraints on the stiffness or natural frequency. Nevertheless, by adding these constraints one won't obtain the best solution to reduce the mass of the structure. That is why additive manufacturing process allows to manufacture topology optimization part without constraints on geometry, and so get a better reduction of mass.

Indeed, additive manufacturing allows to overcome manufacturing constraints, but this process has also disadvantages. It is more expensive and suitable for production at a smaller scale.

Specifications of aeronautical sector can also limit the development of optimization process, even if optimization is more and more used in aeronautical sector. The main setback is the strong security need and therefore many associated certifications. Before validating new manufacturing processes, new simulation methods, a long process of verification is necessary to make sure that new parts will be certified. That is why the implementation of new processes or simulations like optimization is more complex than in other sectors. One has to make sure that results of the optimization are correlated with tests, in order to validate the new simulation process.

3.3 Perspectives

Even if the length of studies for topology optimization problems is huge due to the number of elements, the time of calculation is going to reduce with the development of calculation capacity.

With the apparition and the development of additive manufacturing, which is capable to manufacture parts designed by topology optimization, the interest in this technology is growing. That is why development of topology optimization and additive manufacturing are linked. In addition, research is growing in that field, both in the academic world and in software development to improve software performance and algorithms. Currently, a lot of software allows to optimize structures, like OptiStruct, Nastran or NX…

As seen in this white paper, topology optimization is used to determine an optimal design according to performance criterion while respecting the specification of the structure. In the current context, implementation of technologies and electronics considerably increases the mass of planes or cars. That is why technologies like optimization are crucial to better tackle environmental issues.

Currently, using optimization is expensive, regarding to the needs of computing power, qualified engineers and adapted means of production. But in the future, the global cost of this technology should decrease due to progress made on additive manufacturing and optimization software.

4 Conclusion

As seen in this white paper, there are different levels of optimization process. First, part section or thickness of bar and shell elements can be optimized. A second step of the optimisation is shape optimization. In this type of optimisation, the topology of the part is defined, and the shape of the part is adjusted to optimize the structure. The end level of optimization is the topology optimization. In this type of optimization, initial design is not necessary, only an admissible space is required, inside which one will obtain presence or absence of matter. On the contrary of the first two steps, in the third one, initial design is not necessary. Nevertheless, as it is difficult to consider a big number of constraints like tension in topology optimization, respecting the specification in one step is not ensured.

Even if there are many limits on topology optimization, its implementation at the beginning of design process is a good solution to reduce cost and time of development. Indeed, with topology optimization, one obtains an optimum solution quicker while avoiding going back and forth between design and calculation departments. In addition to saving time in studies, performance of parts can improved.

Currently, the topology optimization process is used to different extents depending on the sectors. But with the development of research on optimisation and development of additive manufacturing, the costs will decrease, and the use of optimization will be more and more common.

Finally, for aeronautical sector, with the new environmental standard CORSIA, and the goal of greenhouse gas emissions reduction according to Paris climate agreements, the reduction of mass is one of the means to reduce gas emissions. That is why topology optimization makes sense in this context and will be brought to be more and more used in the future.

5 References

1. **Michaël BRUYNEEL, Jean-Charles CRAVEUR, Pierre GOURMELEN** (2014). *Optimisation des Structures Mécaniques : Methodes numériques et éléments finis. Paris : DUNOD, 334 p.*

2. https://www.edp-open.org/images/stories/books/fulldl/livre-blanc-de-la-recherche-en-mecanique.pdf

3. http://www.cobratex.com/lenvironnement-pousse-laeronautique-a-voler-plus-leger/

4. https://www.actu-environnement.com/ae/news/aviation-civile-mecanisme-limitation-emissions-co2-27653.php4

5. http://blog.ametragroup.com/optimisation-topologique-et-fabrication-additive/

6. http://www.ctif.com/fabrication-additive-et-fonderie-le-duo-gagnant-au-service-de-linnovation-en-aeronautique/

7. https://www.cetim-certec.com/expertise/innovation-et-conception-mecanique/conception-pour-la-fabrication-additive/

8. https://metalblog.ctif.com/2017/11/07/loptimisation-topologique-pour-accelerer-la-conception-des-pieces/

9. https://www.ecologique-solidaire.gouv.fr/sites/default/files/plaquette%20GMBMpap.pdf

6 Authors

- Florian Larzul, stress engineer
  flarzul@nalys-group.com