Computational aspects of numerical optimization for large scale aircraft multimaterial structures

Phd proposal for IRT Saint-Exupéry

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1. Overview of the document

This document summarizes conjoint AIRBUS-ICA-ONERA proposal for Phd thesis within IRT-Saint-Exupéry. The overall organisation of this joint proposal is described as well as the overall description of the proposed subjects. Industrial benefits are also reviewed as well as the scientific and challenging aspects of the propositions. A first timeline is also suggested, finally the skills of the expected candidate are also suggested.

2. Overall organisation

Partners: **Institut Clément Ader, ONERA, AIRBUS FRANCE**

Title: **Computational aspects of numerical optimization for large scale aircraft multi-material structures**

Duration: **3 years**

Expected timeline : **September 2015-September 2018**

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Place : **IRT Saint-Exupéry, Toulouse**

3. **Overall description of the subject**

Carbone fiber reinforced plastics were increasingly used in recent civil large passengers aircrafts for primary structures. However, current developments still require much more sophisticated strategies to draw the full benefits of using composite materials instead of traditional aluminium alloys. Besides fatigue and corrosion aspects of composite for which knowledge is not as much as developed as for metallic materials, one major difficulty for the generalization of their use is the inherent combinatorial problem to be solved to reach a good design. Unlike traditional isotropic structures, the anisotropic behavior of the composite can be tailored to reach specific overall mechanical properties provided the combinatorial complexity of the design can be address. Indeed, typical composite materials for aircrafts structures uses prescribed discrete ply orientations (e.g. 45°, 90°, 0°) and tailoring composite structures require not only to treat the amount of each ply orientation but also their precise order (known as stacking sequence). As a matter of fact, a thin structure of a given thickness made of the following stacking sequence

[45°/0°/-45°/0°/90°/0°/90°/0°/-45°/0°/45°]

is likely to behave in a much better way than the same structure made of the following stacking sequence

[0°/0°/45°/90°/-45°/0°/-45°/90°/45°/0°/0°]

This therefore leads to much more difficult sizing problems than for metallic structures. Indeed, for metal structures only thickness is to be set to design a thin structure, while for composite structure the thickness as well as the material is to be set. However, setting a stacking sequence is a discrete combinatorial optimization while setting a thickness is a continuous problem. This leads to an overall optimization problem over mixed variables (discrete/continuous). Strategies to solve such problems fall in the Mixed Integer Non Linear Programming (MINLP) and are limited to few variables (around one hundred), while typical aircraft structures require thousands of optimization variables.

Besides Carbon Fiber Reinforced Plastics, new metallic alloys (AirWare I-Gauge for wing inner structure of the A350 for instance) are also more and more integrated in aircraft carrying loads structures. Moreover, new structural concepts to challenge the traditional stiffened panels such as isogrid, lattice structures or geodesic fuselage where panels do not carry loads are investigated as a way to achieve important weight savings in the future. Such new design principles and technological concepts along with the use of highly integrated composite structures and manufacturing are to be considered in an early design phase. However, these new structural concepts and new materials increase the design complexity as the best design strategy should allow to switch from for instance composite to metallic component of the overall aircraft structure. This in turns implies that the design process should consider jumping from one category of design to another one. In terms of structural optimization, such design variables are referred to as categorial variables (switch from traditional stiffened panels structures to isogrid structures for instance cannot be considered as a continuous change). Even when considering only stiffened panels structures, the type of the stringers is also such a categorial variable. In definitive, to design such a complicated integrated structures, one has to face a structural optimization problems with

- Discrete, continuous, categorial optimization variables
- Varying number of design variables, the choice of a given value for a categorial variable implies a specific set of design variables. For instance, switching from a Al-Ti structure to a composite adds the design variables associated to stacking sequence optimization.
- Large number of design variables (several thousands)
- Several levels of mechanical simulations from linear Finite Elements models at overall aircraft level to energy methods at panel levels, including also nonlinear Detailed Finite Elements

models at aircraft level for complex multi-materials components.

To face this utterly intreatable complexity aircraft industry has developed mixed approach combining rigorous optimization strategies with either approximations (pre-computed catalogues and surrogate models) or relaxation (making discrete variables continuous) and to face the large scale of the optimization problem and the varying number of design variables decomposition approach has been also suggested [1]. Furthermore, the different levels of design variables is addressed by different levels of mechanical simulations. For instance, at linear FE model level of the aircraft, the precise description of the type of stiffener is not mandatory and a first optimization process can be based only on a rough description of the global structure. At stiffener level, however, these design variables are to be used to size locally the structure. Therefore, the multi-level approach with different level of representativity is a major solution to treat the multi-material and the large-scale of the problem. However, even though several important tools were already developed in past research projects, there is not yet global strategy that guarantees that the best design in terms of manufacturable structure (or a very good design close the best design) has been reached. In particular, in the multi-level, it is not clear what quantities should be exchanged between local and global sizing and how the global level can help driving the local (it can be by setting targets and penalization). This relates to the field of MDO with the notable exception there is only one discipline (mechanics) but each local structural component is considered as a discipline.

The overall objective is therefore to enhance and challenge the existing strategies and propose new strategies or new tools if proven to be more efficient than the existing strategy (denoted as the 'multi-step approach' in the following section. Such a research work should therefore question and seeks continuously to improve the multi-step optimization strategy by analyzing its computational aspects and relating them to the best design objective. Challenging questions rising from combinatorial theory, statistics and optimization such as

- 'How many stacking sequences feasible with respect to manufacturing constraints should be analyzed for a given design?'
- 'How can we manage smooth switch from metallic to composite structures in a way suitable for numerical optimization?
- 'How do we ensure continuity between discrete stacking sequences for different thicknesses?'
- 'How many design points do we need to build a reasonably good approximation of the question of interest?
- 'What is the effect over the optimum design of using approximation of the constraints?'
- 'What is the effect of the accuracy of the derivative for gradient-based optimization methods?'
- 'How could we improve the accuracy of the derivative?'

are to be answered in order to improve the existing strategy. The PhD will obviously start from analysing the existing strategies under all its theoretical, computational and mechanical aspects to get a clear and critical view of what parts should be amended or even possibly removed to improve and enfore efficiency. Therefore, the candidate with the help of the network should be able to suggest a new global strategy that addresses all industrial needs for composite and multi-material structures sizing (including non-scientific organisational aspects) but at the same time, that also addresses theoretical ('Did we reach a good optimum'), numerical and efficiency aspects ('How many computations do we need?'). The overall problem should therefore be looked at from all its aspects and besides should also be looked at from a more general design point of view as far a simple brick of an integrated Multi-Disciplinary Optimization strategy.

4. Industrial benefits and link to the overall MDA-MDO project

1) The industrial problem

It is very important in the highly competitive domain of commercial aircraft to develop tools which allow to optimize the airframe at best, while mass minimization is the main objective because of its direct impact on fuel burn and operational cost.

Yet structure optimization is a very specific and difficult field which naturally mixes large numbers of continuous and discrete variables which do not accept continuous approximation.
For example the engineer has to determine all thicknesses of a structural cover but also choose the material either in a range of materials or between two types of them (metallic; composite). Moreover if CFRP (Carbon Fiber Reinforced Plastics) are concerned, there exists no real continuous formulation for small thicknesses or they might be proved.

Therefore it is particularly difficult in this context to afford the overall needs for structure optimization with a single algorithm.
Moreover the aforementioned kind of variables can rely to different design phases.
For example very early on in the design process is decided whether a structural component will be metallic or composite. For AIRBUS decision to build a composite fuselage for the A350XWB was almost part of the early top level aircraft requirements.

Thus because of mathematical issues but also for industrial reasons it makes sense to separate the structure optimization process in two steps which consist in the choice of design principles and the mapping of structural dimensions (thin wall thicknesses; stiffener section geometries).
Anyway they have to be coordinated for the best consistency of decisions and the continuity of the design process.

On the other hand come also in the choice of design principles genuine needs of performance, if the wish is really to answer the full combinatorial of all different structural options.

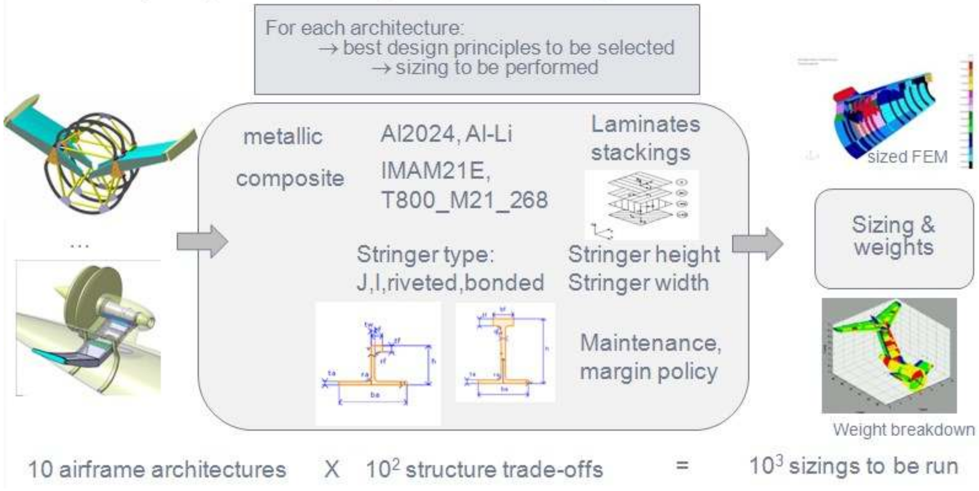

Figure 1 : Picture of different structural choices for an airframe: The several structural options lead to consider a performance for sizing algorithms, which is several orders of magnitude higher than current standards.

The usage of stress computational tools even if they are not based on finite elements can reveal not fast enough and the anticipation of performance requirements through surrogate models becomes a necessity.

Beyond the continuous nature of sizing variables which can be challenged (at manufacturing level everything is discrete for sake of rationalization and standardization), it is essential to manage structural responses linked to continuum mechanics: displacements, stiffnesses, natural frequencies, aeroelastic damping coefficients.
The usage of gradient-based algorithms is then inescapable.

A multi-step approach is currently being set up at AIRBUS to answer the structural optimization needs. But it cannot be qualified as a real multi-level approach because nothing can really guarantee its coordination and convergence.
It mixes:

- A “rapid sizing” tool which is mainly discrete, whose objective is to decide among several structural options and which requires the usage of pre-computed data-bases: PRESTO.
- A “pre-sizing” tool which leans on gradient-based optimization today materialized through the NASTRAN commercial optimization module (SOL200).

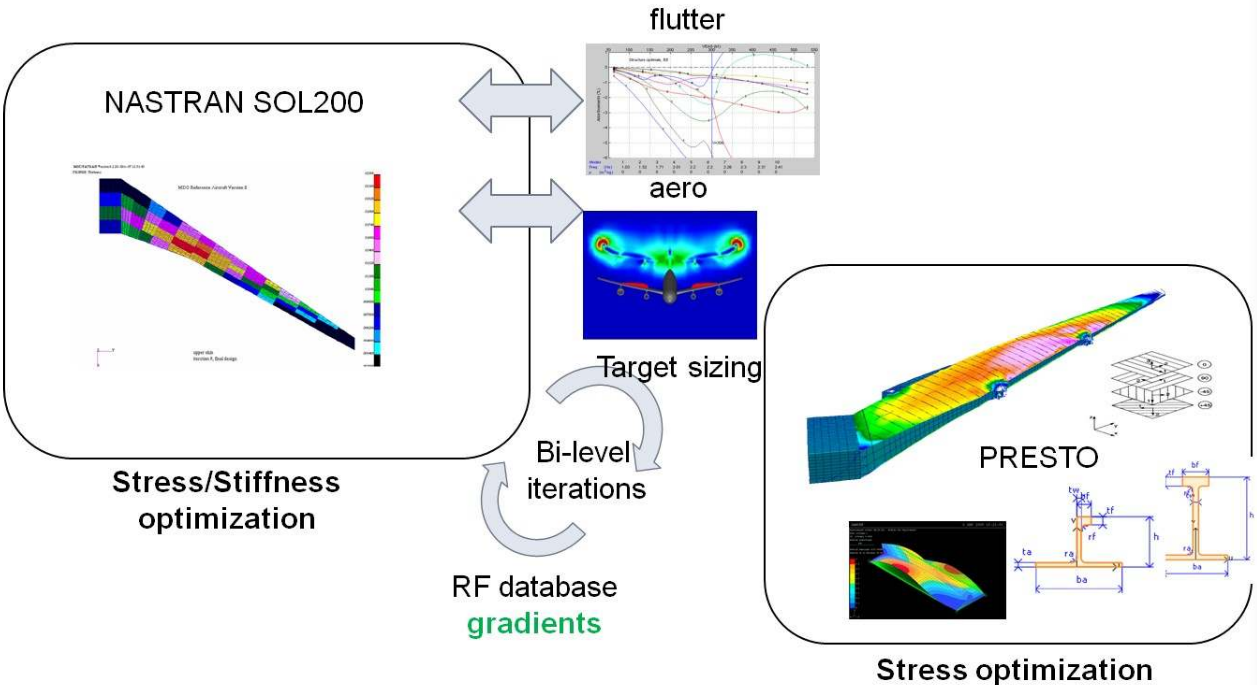

Figure 2 : Multi-step approach based on PRESTO and MSC Nastran SOL200 : gradient-based algorithm from SOL200 allows to treat both multi-disicplinary aspects and stiffness optimization. It has a link to a in-house Airbus tool PRESTO allowing fast modification of general structural principles (metal vs. composite) . Coordination is the hardest part and should based on realistic in-house approaches.

So in this PhD a multi-level structure optimization scheme is to be proposed which answers the aforementioned requirements while perturbing at least the eco-system of AIRBUS processes, methods and tools. This PhD will be articulated around the discrete optimization methods, the continuous ones (based on gradients) and the multi-level strategies, it will also lean on model reduction methods (surrogate models).

2) Link to the MDO-MDA platform

The multi-level structure optimization process will bring to the overall MDO process a unique means to manage continuous structural responses (stiffness-oriented) as well as discrete structural choices, to be sure that the minimum weight solution is really proposed at structure level by opening all structure degrees of freedom. By using surrogate model approaches fed by AIRBUS databases, it will also allow to integrate skill criteria in the structure optimization problem in phase with later design stages (detailed sizing).

This approach will really reconcile MDO with a really skilled structure optimization process, which is often neglected in scientific literature and will really make the IRT MDO platform a professional platform for aircraft manufacturing engineers.

This PhD will use small test-cases, but will definitely be applied to the use-case of the platform which will be a wing and powerplant configuration, the goal being to deal with a consistent sizing of the wing and the engine pylon itself.

5. Scientific aspects of the proposed Phd

Here several mathematical questions that should be raised in this PhD, ranging from statistical methods for surrogate modelling (construction of the approximation), complexity theory (combinatorial) and numerical optimization are listed.

5.1 Surrogate-models

In recent years, the application of surrogate modeling (or metamodeling) techniques in structural/design optimization has grown. A surrogate model of an objective function constructed by a relatively small number of initial sample points can replace the true objective function within the optimization process. In this thesis we focus on enriching these initial sampling points using a interesting metamodel called Kriging. The first theory developed by D. G. Krige [2] was enhanced by the work of the French mathematician Georges Matheron [3]. Kriging methodology, then developed by for the construction of surrogate models of deterministic computer experiments, is a popular surrogate technique due to its flexibility to imitate objective function accurately and to its ability to provide an error estimate of the predictor. Kriging proved its effectiveness in the modeling and the optimization of a certain number of problems of design, see e.g., [4], [5], [8], [9], [10], but it has some drawbacks in high dimension which may be due to many reasons. The first one is that covariance structure of Kriging models may increase dramatically (adding a large number of new sample points sequentially is needed in high dimension). Therefore, the time required to inverse covariance matrix becomes expensive. The second is the sub-problem optimization, which is the estimate of parameters for the covariance matrix. The inverse of the covariance matrix must be computed several times and thus genetic algorithms are often used for this kind of problem.. Finally, optimization with constraints requires an independent Kriging models for both the objective function (function to optimize) and for each constraint functions. The challenge will be to develop new tools for metamodeling to surpass these limitations, and also to combine it with model reduce basis in order to limit the size of the mechanical problem (often posed as Kq=F, with size of K is equal to the number of DOF's of the finite element discretized structure). An extension using mixture of experts is also possible to deal with complex reconstruction [6] such as mode tracking (Buckling or Vibration problem in thin structure, see Fig. 3).

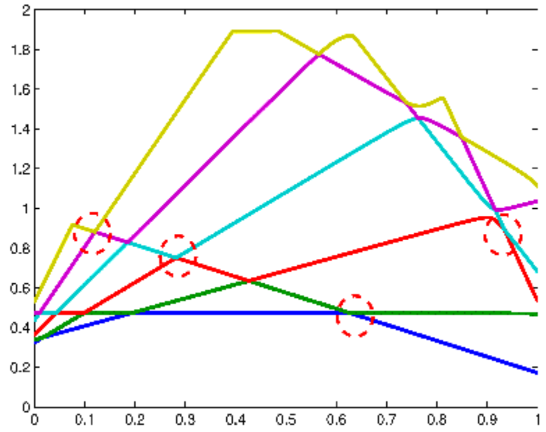

Fig 3. a) Typical mode dependance behavior of the function to approximate. In red dashed lines, the crossing phenomenon (discontinuous derivative).

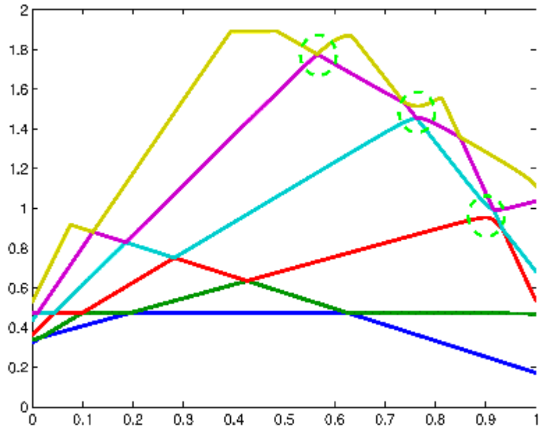

Fig 3. b) In green dashed lines, the veering phenomemon (modes are continuously swapped), where the curvature (second derivative) abruptly varies.

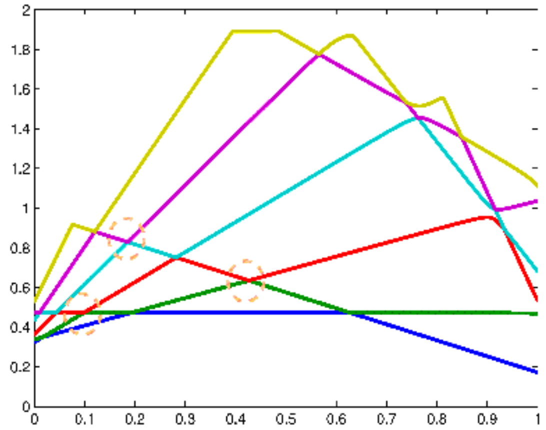

Fig 3. c) Misleading situations

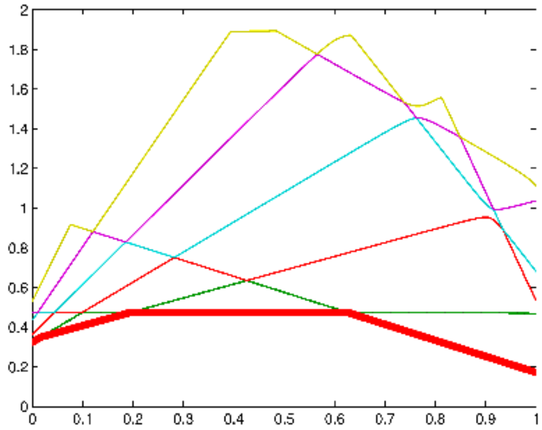

Fig. 3. d) In many cases, only the first mode is of interest for structural optimization.

5.2 **Computational aspects**

In connection with the field of surrogate modelling, estimating and assessing the number of computations before running the full strategy is of huge importance. Indeed existing strategy require previously computed catalogues that scans of range of loads that the component to be sized can meet. This catalogue building step require a large amount of computations that can be challenged with the help of surrogate-models. Two numerical aspects are to looked at, the first one is the accuracy of the approximation, the question require the study of the regularity of the function to approximate. So far, no much work has been done on the regularity of the simulation code output, while for most surrogate-models the accuracy of the approximations depends on its. A smooth function (in the sense of differentiability) can be very well approximated unlike a discontinuous function. The surrogate model strategy should be based on the observation of the behavior of the functions to approximate. Radial Basis Function approximation enjoys very good convergence properties but provides less flexibility than Kriging methods [7]. Last thing, most classical surrogate models usually perform bad for discontinuous functions. The scientific aspects here to assess through statistical methods the number of computations required to reach a given accuracy for the function to approximate. The other aspect is to compare the numerical accuracy of the derivative between the derivative of the surrogate-model and the sample-based derivative.

5.3 Numerical optimization

In that framework, such an optimization can be thought as the optimization of many interconnected systems. This leads to a large problem who could possibly be decomposed and then easier to solve provided we correctly treat the coupling of all these elements. For fuselage structures, this coupling remains essentially the internal loads redistribution that impact the stability analysis at sub-element level. In that context, the whole optimization problem can be thought in an instance of multi disciplinary optimization problems where each sub-component is considered as a discipline. Our problem though fits in the multilevel optimization framework since it involves only one discipline (mechanics) and two different levels of mechanical analysis: internal load redistribution vs. Stability analysis, each of them being performed at a different level of representation of the structure. The internal load redistribution is computed on a coarse representation (typically 2D plates and shells elements) while stability analysis needs a more detailed representation (typically 3D volumic elements). This structure naturally appeals for a bilevel optimization strategy.

There are though very few differences between multilevel optimization and multi disciplinary optimization at least in terms of resolution, practical algorithms and also in terms of the innovations required to allow the treatment of their respective problems. Quoting Jaroslaw Sobieski, one major figure of the field, in a recent talk [11], multi disciplinary optimization tools still require research and development effort in the following areas (besides surrogate modelling)

- Decomposition
- Sensitivity analysis
- Post-optimal sensitivity

Decomposition is concerned with breaking up the large optimization problem into many smaller problems allowing an efficient treatment. As far as optimization algorithms using derivatives are involved (gradient based approaches, quasi-Newton methods, gradient enhanced or hybrid global optimization methods...), **sensitivity analysis** of discrete physical systems is often required to compute these derivatives in an exact and efficient way. **Post-optimal sensitivity** refers to the area of estimating the sensitivity of a problem of optimization with respect to problem parameters [12]. Post-optimal sensitivity tries to answer these questions by giving Lagrange multipliers a fundamental role that allows to get the derivative of the optimal value function . For the adopted multi-level strategy, the sensitivity of local optimal design should be used to speed up convergence at global level.

6. **References**

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7. Milestones

8. Expected Candidate