Deutscher Luft- und Raumfahrtkongress 2009
DocumentID: 121336

CONCEPT DESIGN OF A COMPOSITE AIRCRAFT DOOR THROUGH INTEGRATED FINITE ELEMENT ANALYSIS, MULTI-BODY SIMULATION AND STRUCTURAL OPTIMIZATION

H. Bartosch, S. Cabrele, P. Hänsch, M. Mast

Eurocopter Deutschland GmbH– Airplane Components Division
Industriestraße 4 86607 Donauwörth, Germany

Abstract

This paper highlights the new approach to structural optimization undertaken by Eurocopter by showing the optimization procedure for an experimental airplane passenger door developed at Eurocopter's Airplane Components division.
The optimization strategy consists in the preliminary, parallel optimization of the three main components of the door:

- A free size optimization of the basic CFRP structure with the scope of assessing the optimal shape, size and orientation proportions of plies to be used.
- A MBS optimization of the mechanisms responsible for the safe opening, closing and in-flight lock of the door aimed at minimising the loads transferred to the structure while complying with certification and safety requirements.
- A topology optimization with the purpose of defining the basic geometric layout of the aluminium structure connecting the mechanism to the CFRP door structure.

These preliminary optimizations on the stand-alone components are necessary because free-size and topological design variables are element based and therefore exceedingly numerous, making a concurrent optimization of the whole door structure too demanding in terms of computing resources.
Main goal in this preliminary phase was then to define the basic structural layout of the single components and the corresponding size and shape design variables. As these design variables do not act at element level, they are remarkably fewer. This allows in turn a second, integration phase in which the three components are assembled in a single model and subject to a fine-tuning optimization in which the interactions among the three components of the door can be accounted for.
One of the main breakthroughs in this design philosophy is represented by the use of optimization in the very first stages of conceptual design as opposed to the traditional approach of optimising single components in the detailed design phase. This allows for dramatic improvements in terms of weight reduction and development time and is therefore progressively becoming the standard design procedure for future projects at Eurocopter's Airplane Components division.

1 KEYWORDS

Structural optimization, composites, design process, CAE

2 INTRODUCTION

The present paper describes the new approach to structural optimization undertaken by Eurocopter by showing the optimization procedure for an experimental airplane passenger door developed at Eurocopter's Airplane Components division.

3 MODEL DESCRIPTION

The passenger door in question is made up of three main subcomponents:

- The door structure itself, made up predominantly of carbon fibre reinforced plastic.
- A system of shafts, connecting rods and similar kinematics mechanisms assuring the safe in-flight lock of the door as well as the opening and closing actions through the operation of a handle.
- An aluminium framework (nicknamed Kinematics Boxes) holding the kinematics mentioned above and connecting it to the door structure overcoming the difficulty of integrating bearing housings in a composite structure.

4 PRELIMINARY OPTIMIZATION

Given the different functions, loads and requirements for the three subcomponents described, it is clearly not feasible to perform a one shot optimization of the whole door.
Consequently, a preliminary "stand alone" optimization for the single subcomponents has been carried out according to the breakdown scheme shown in the following Figure 1.

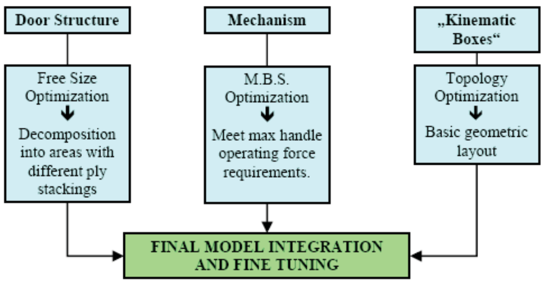

Figure 1: Breakdown Structure of Preliminary Optimization.

The optimization strategy consists in the preliminary, parallel optimization of the three main components of the door (described more in detail in the following points 4.1 to 4.3) with the following main objectives:

- Door structure: determine the optimal breakdown into different lay-up areas aimed at the determination of size and shape of the different plies composing the doors (leaving the exact number and stacking sequence to the final integration stage).
- Mechanism: comply to the requirement that max handle operation force be less than 150N by acting on position of joints and stiffness of springs. How this affects the loads that are than transmitted to the structure is again left to the fine tuning optimization in the integration stage.
- Kinematic boxes: define a conceptual design through topology optimization leaving further refinements (e.g. via shape optimization) to the final stage.

4.1 Preliminary Optimization of Door's CFRP Structure

Optimization of the door structure was performed on the basis of the following inputs:

- Design: dimension and position of stringers as well as frames had already been chosen and "frozen"; that is, no shape design variables are considered.
- Loads: mainly inner pressure and fail safe conditions assuring that the door remains operational following failure of one of its parts.
- Requirements: material must of course not fail, structure should not show signs of buckling in any flight condition (no post buckling allowed) and door skin may not exhibit waviness of more than 5mm to comply with aerodynamic requirements.
- Objective of the study was to minimize the mass of the subcomponent.

These inputs are the main drivers of the performed free size optimization. Each element is assigned 3 "super-plies" in 0^o, 90^o, and $+\text{-}45^o$ orientation and their thicknesses are then allowed to vary to define the optimal lay-up thickness and composition for each element delivering the results represented in the following figure 2. Please note that as the skin is made of orthogonal woven plies, the 0^o and 90^o plies would be identical. Therefore skin elements where assigned only two plies in 0^o and $+\text{-}45^o$ direction

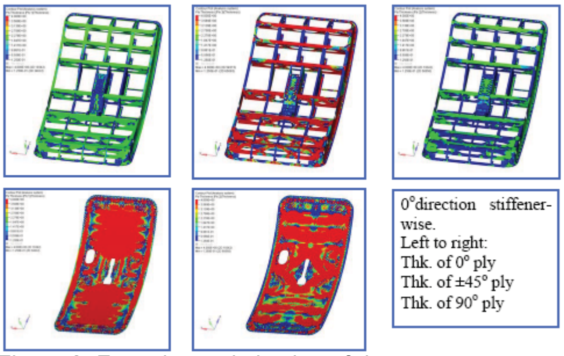

Figure 2: Free size optimization of door structure

The interpretation of these results allows subdividing the structure into lay-up areas of optimal shape, size and orientation proportions according to the desired trade-off between ease of manufacturing and structural efficiency as shown in the following Figure 3.
Because of this, cooperation with design and production teams has proven to be instrumental in reaching the best compromise.

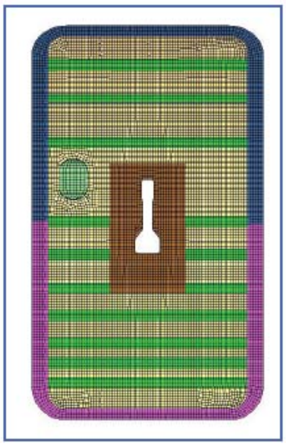

Figure 3, Subdivision of the door: areas of same colour share the same composite lay-up.

4.2 Preliminary Optimization of the Mechanism

The mechanism has been idealized as a rigid body system shown in the following Figure 4, with position of joints and stiffness of the torsion spring being the main design variables.

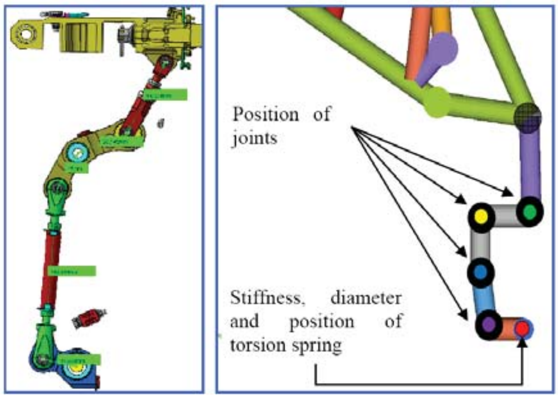

Figure 4: Kinematics MBS

With reference to figure 5, the curve shows the necessary actuation force on the handle necessary for the operation of the door based on the multi-body analysis performed on the original model.
While the requirement that this force be negative at the handle's end positions (to insure that these are stable) has been satisfied, the peak level is well beyond its maximum of 150 N. The preliminary MBS optimization of the mechanisms was aimed at minimizing the handle operating force and succeeded in reducing its peak value from the original almost 600N to a value little in excess of the 150N limit.

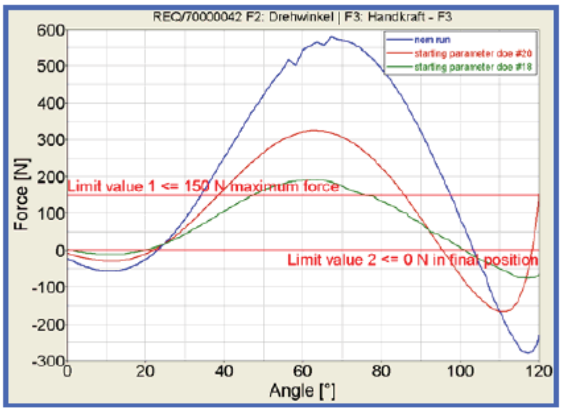

Figure 5, Handle operating force, schematically shown in red. Right: Force vs. Operating Angle.

4.3 Preliminary Optimization of the Kinematics Boxes

The loads arising from the operation of the mechanism are transferred to the door CFRP structure via the Kinematic Boxes.
The preliminary topological optimization of this subcomponent has the purpose of defining the basic geometric layout of the aluminium structure and delivers the results shown in the following figure 6.

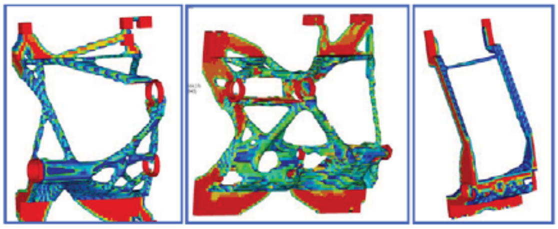

Figure 6, topology optimization results for the kinematics boxes.

The optimization performed relies on 4 inputs:

- Design space, arising from consideration concerning space availability
- Loads transmitted to the bearings by the kinematics as calculated in the kinematics optimization.
- Manufacturing constraints: basic geometrical layout must be compatible with a milling process.
- Material allowables and stiffness requirements are of course to be met under all operating conditions.

Topology optimization assigns each element a density which is in turn linked to the element's stiffness. In this particular optimization we pushed for this density to be as closed as possible to either 0 or 1. Following this step, elements with the lowest densities have been cancelled, resulting in the so called "Lego model", a block-wise representation of the subcomponent.
This "Lego model" is then translated into a CAD model suitable for further optimization, more specifically shape optimization within the integration step.

5 INTEGRATION PHASE

The preliminary optimizations on the stand-alone components described in the previous sections have been necessary because free-size and topological design variables are element based and therefore exceedingly numerous, making a concurrent optimization of the whole door structure too demanding in terms of computing resources.
The preliminary optimization of the stand alone subcomponent has instead allowed for:

- A door structure subdivided into lay-up areas, that is whose shape and position of plies has already been fixed.
- A kinematics scheme that is roughly in the maximum operating forces requirement range
- A basic geometry layout of the framework connecting the two above and ready to be fine-tuned into its final shape.
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These three optimizations have drastically reduced the overall amount of design variables and therefore laid the ground for a further optimization taking into account the interaction among door structure, kinematics and kinematics boxes. This "integration phase" (shown in the flowchart in the following figure 8) is in fact based on size and shape design variables that do not act at element level and are therefore remarkably fewer.

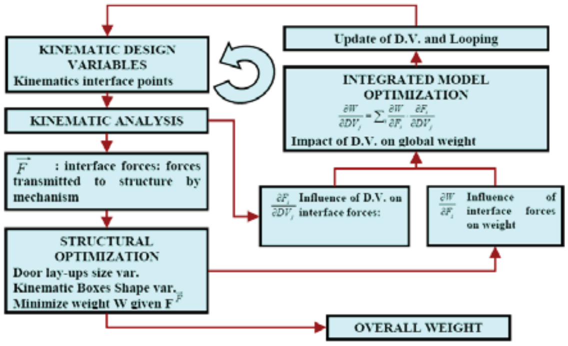

Figure 7, Optimization of the integrated model based on the results from the preliminary optimization of the subcomponents**.**

The figure above schematically shows the approach chosen: a kinematics analysis is performed which provides us with two main pieces of information: the entity of the loads transferred to the structure and how these loads are dependant on the kinematics design variables (mainly joint positions and spring stiffness).
These loads serve as inputs to the optimization of the kinematics boxes and the door structure, which in turn provides us with two main results: the optimized structural weight and how this optimized weight is dependant on the forces coming from the kinematics.
Knowing how the design variables affect the kinematics forces and how they in turn affect the weight provides us with the desired correlation between the kinematics design variables and overall weight which allows to update the design variables and iteratively optimize the overall weight of the door system..

6 CONCLUSION

At this stage the "integration phase" of this optimization approach is still being explored and the considerable challenges of implementing such a complex process are being addressed. Nevertheless, it appears reasonable to expect overall weight reduction to be in the range of 7 to 12% compared to the original, non optimized model. This activity has also shown that there are ample margins for the reduction of development time, provided that the overall product development process is adapted to the optimization driven design. As opposed to traditional FE analysis, in fact, this is not a mere verification of the structure but a way of shaping it, a feature sometimes ill-suited to the well established design-stress division currently in place in most companies of the sector.
Nevertheless, this project has proven that although optimization is far from a "fire and forget" solution, it is a phenomenal tool when used in synergy with sound

engineering judgment. We at Eurocopter are confident that a state of the art optimization approach can be instrumental in further boosting the advantages obtainable from the use of composite materials in aerospace structures and will play an increasingly crucial role in the development of door systems for the next generation of airliners.

7 ACKNOWLEDGMENTS

The authors would like to acknowledge Dr. Pietro Cervellera, Matthias Radny and Markus Schemat of Altair Germany for their support in the project

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