MULTIDISCIPLINARY OPTIMISATION OF CFRP FUSELAGES: STRUCTURAL MECHANICS, VIBRO-ACOUSTICS AND MANUFACTURING ASPECTS

H. Baier, M. Huber, J. Klammer
Institute of Lightweight Structures (LLB), TU Muenchen, Germany

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Abstract

For reasons of mass and total cost saving aircraft fuselages mainly based on carbon composites (CFRP) are under development. To achieve the full potential and to satisfy different requirements, multidisciplinary design optimisation (MDO) techniques are applied to investigate structural, external to internal noise and manufacturing aspects. In addition, techniques to quantitatively model qualitative knowledge are discussed. Technical results which can be generalised to a considerable extent are presented.

1. Introduction

Aircraft fuselages have to satisfy a set of different functional, structural and comfort requirements with low mass and cost. This shall be achieved by using CFRP as the main material together with proper design and manufacturing concepts. Because mass will be reduced and local bending stiffness will be increased in relation to “classical” fuselages based on aluminium alloys, the vibro-acoustic behaviour and capability of noise reduction (NR) from outer to inner noise levels has to be observed even more strictly. So in this paper this multidisciplinary design optimisation problem will be discussed which takes into account the structural and vibro-acoustic behaviour together with manufacturing considerations. This shall be achieved in the formalised design optimisation process in early development stages, which then also might require the transformation of qualitative knowledge into quantitative and parametrized models.

The modelling and interaction of structural mechanics, vibro-acoustics and manufacturing aspects will be addressed within the context of multidisciplinary optimisation (MDO) of CFRP fuselages. For that purpose, in the paper some essentials in vibro-acoustics will be discussed first. Then the formal MDO problem will be presented together with some remarks to solution algorithms and software organisation together with approaches for modelling qualitative knowledge. Finally, basic technical results allowing for some general conclusions will be given.

2. Essentials of fuselage vibro-acoustics and noise reduction

Noise in fuselages and cabins is generated by external sources such as those from the propulsion system and boundary layer flow, and also from inner sources such as the environmental control system, the latter of which are not further considered here. The basic principle of external to internal noise transfer becomes obvious from figure 1: external noise excites fuselage vibrations, which again radiate noise to the outer side (a type of “damping”) but also in the cabin. Since for this mechanism the structural mass and stiffness are important parameters, this has to be specifically observed for fuselages mainly composed by CFRP. A series of passive and active means to improve NR exists such as

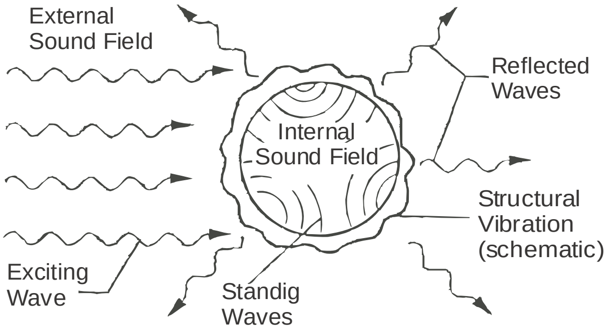

Fig. 1 Basic principle of external to internal noise transfer

- Passive means: structural design which also minimises coupling of structural vibrations with cabin acoustic vibrations, the inclusion of trim panels, acoustic absorber material etc.
- Active means ranging from actively supported and excited trim panels to loudspeakers within the cabin which generate some anti-noise

The focus in this paper is in proper structural design. The other measures can be considered to some extent as “add-on-means”.

Vibro-acoustic modelling

The vibro-acoustic behaviour in the lower frequency range is described via the finite element method (FEM) with structural elements for the fuselage and special fluid elements for the cabin air. The displacement degrees of freedom of the structural elements are to be coupled by certain techniques to the pressure degrees of freedom of the fluid elements. In order to cover a broader frequency spectrum of the modes involved, usually a large number of elements and dofs have to be used which limits the application range of FEM. So for higher modes and frequencies (say above several hundred Hertz) the statistical Energy Analysis (SEA) method is applied, where the energy flow between structural and acoustic vibrations is described by statistically representative quantities in volume and frequency octave bands up to several thousand Hertz. [4]

3. Representative formal design optimization problem statement

Such material and structural design optimisation problems are nonlinear multi-criteria optimisation problems of type

$$\begin{array}{lll} \text{„minimize“} & f_i(\{x\},\{y\}), & i=1,2,\ldots \\ \text{such that} & g_j(\{x\},\{y\}) & j=1,2,\ldots \\ \text{and} & s_k(\{x\},\{y\}) = 0, & k=1,2\ldots \end{array} \qquad (1)$$

where f_i and g_j are the objective functions (mass, displacement) and constraint functions e.g. on stresses, displacements, eigenfreqencies or sound pressure levels (SPL). The design variables {x} may be continuous (i.e. geometry) or discrete (i.e. types of materials), and for given {x} the response variables {y}(displacements, stresses, SPL, ...) are to be determined from the system equations s_k. Depending on the type of problem, these system equations might be composed from those of structural mechanics (ranging e.g. from laminate plate theory to large finite element models) and e.g. those related to vibro-acoustics. Irrespective of the degree of coupling between structural and cabin air vibrations, there might be a strong „design coupling“. This then means that variations of design variables {x} cause variations in structural quantities *and* in vibro-acoustics.

Especially in early development phases not every type of system equations might be fully available in time, which typically holds for manufacturing aspects. In order to assure the necessary completeness of the problem statement, approximate models based e.g. on response surfaces derived from qualitative knowledge should or even have to be included instead.

4. Modeling of qualitative and fuzzy knowledge with Fuzzy Rule Based Systems

To integrate fuzzy and qualitative knowledge at least in a roughly estimated way into the set of system equations and

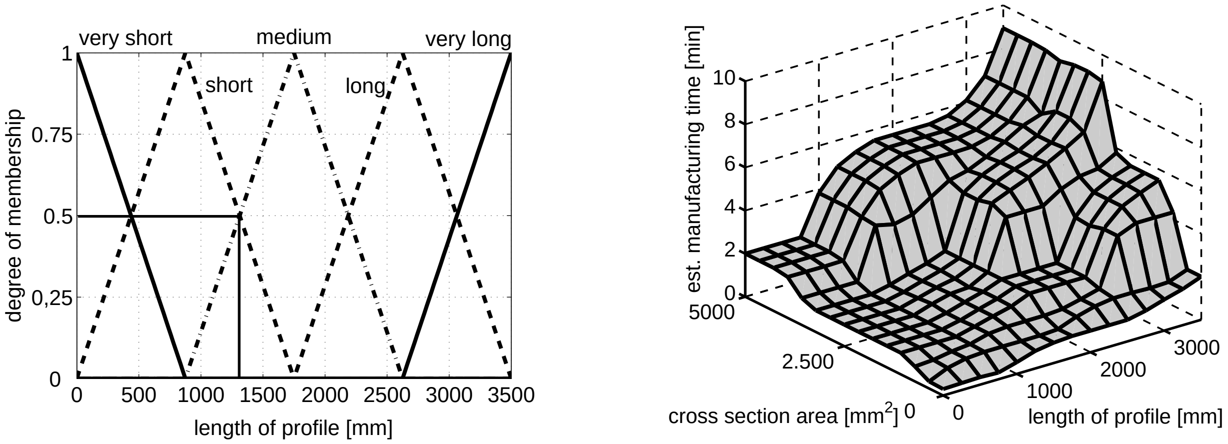

Fig.2. Membership functions for parameter stiffener length (left); output of a manufacturing time estimation model for extrusion molding (right)

optimization model which could not be covered otherwise, Hajela suggests the use of fuzzy models to utilize expert knowledge [5]. Fuzzy logic provides the basics for fuzzy modeling and it was introduced as a method of formally describing linguistic information. So-called fuzzy rule based systems (FRBS) have the ability to model complex behavior. The most important task is to build the knowledge base, which includes the *j* rules describing the relationship between inputs and outputs. The framework for the problem considered here is a system with n inputs $[x_1, \ldots, x_n]$ and one output y.

These rules R_j have the following structure:

$$R_j : \text{if } x_{j1} \text{ is } A_{j1} \text{ and } x_{j2} \text{ is } A_{j2} \text{ and ... and } x_{jn} \text{ is } A_{jn} \text{ then } y_j \text{ is } B_j. \qquad (2)$$

where $x_{j1}, \ldots, x_{jn} \in [x_1, \ldots, x_n]$ and A_{ji}, B_j are fuzzy sets on the respective domains of the variables. The degree to which an input or output belongs to a fuzzy set is defined by a membership value between zero and one. A membership function associated with a given fuzzy set maps a value to its appropriate membership value. Gaussian, triangle, trapezoidal and monotonically in-/decreasing membership functions are used. In fuzzy logic, a certain crisp value does not belong to one set or another but can belong partly to different sets. For example, a certain beam with a length of 1250 mm would have a 0.5 degree of membership in the “short” set and a 0.5 degree of membership in the “medium” set in figure 2 on the left side. Then rules combining such design or input parameters to relevant properties or output parameters such as required manufacturing effort or time are established which are finally transferred to quantitative polynomial relations between input and output parameters as shown on the right side of figure 2.

For progressing development stages with increased quantitative knowledge taken from simulation results and tests, the response surfaces can be continuously updated.

5. Solution algorithms and software

For solving the MDO problem, different models have to be combined together with the definition of goals and constraints. These tasks are handled via the application management system MOSES [6], while the iterative determination of optimal design parameters per se is done via optimisation algorithms such as the evolutionary algorithm GAME [6]. Both tools are briefly described in the following.

5.1 The application management system MOSES for MDO tasks

In such composite and hybrid material design optimisation task one has to deal with

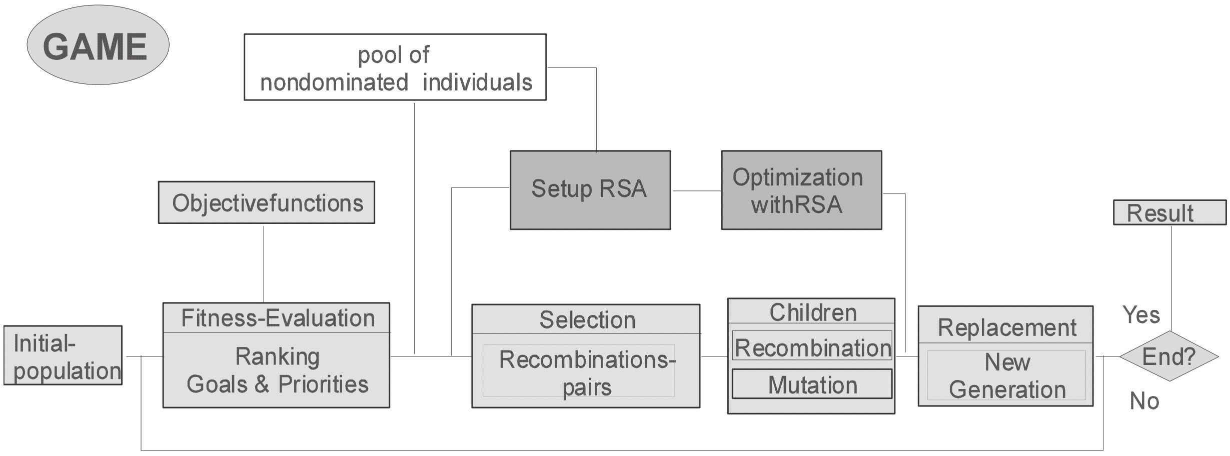

Fig. 3. Process flow in Evolutionary Algorithm GAME

different disciplines such as structural and production engineering and eventually also heat conduction together with related models and software tools. Therefore an important aspect for the realisation of multidisciplinary design is the integration of discipline specific software codes into a common analysis and optimisation environment. This is achieved by an application management system, which controls the data flow, job administration and execution process. It also provides tools for optimisation, approximations and visualisation. It has been implemented into the code MOSES (Multidisciplinary Optimisation of Structures and Electro-mechanical Systems), which mainly builds upon the numerical analysis language MATLAB. MATLAB provides a flexible environment for numerical analyses per se and also the integration of other software tools and for own algorithms. Because of the very different nature and problem structure of different design optimisation cases, the management and process flow has to be flexible and adjustable with a rather loose coupling of different tools, such as

- a CAD tool for appropriate geometrical description,
- representation and parameterisation
- different mathematical and a evolutionary/genetic optimisation algorithm capable of handling discrete and continuous variables, as well as disjunct and „rugged“ design spaces
- the parameterised simulation models, eventually ranging from closed form solutions over response surface approximations to finite element and/ or finite difference methods

As mentioned in the introduction, in the early product development stages some of the relevant aspects might be only representable by qualitative models, which then have to be transferred to quantitative approximations. This briefly outlined in the following for the case of manufacturing aspects.

5.2 The evolutionary optimisation algorithm GAME

For handling of such problems different optimisation algorithms as well as user program management tools have to be available. The mix of different types of models and constraints leads to weakly structured optimisation problems where for example gradients for response quantities w.r.t. design variables are difficult to obtain. The required handling of such weakly structured problems with multiple objectives and discrete optimisation parameters has lead to our evolutionary algorithm GAME (Genetic Algorithm for Multi-citeria Engineering).

The general flow chart of GAME is shown in figure 3. In addition to standard evolutionary algorithms (EA), GAME offers the following features:

- special adaption for multi-objective optimisation
- treatment of continuous and discrete design parameters
- integration of response surface approximation (RSA) and math optimizers
- introduction of competing sub-populations with adaptive evolutionary operators
- high parallelization in the function evaluations for the EA and a SQP algorithm running in parallel and using RSA

These interesting features often more than compensate the high number of iterations needed compared to those of the more strict mathematical optimisation algorithms.

This algorithm is described in more detail in [6]

6. Basic results

In this chapter the basic results from parametric and optimisation studies are presented. These are related to the vibro-acoustic design of full fuselages as well as to the consideration of structural mechanics and manufacturing aspects for hybrid material stiffeners with metal base material being reinforced by high strength / high stiffness ropes or fibre bundles.

6.1 Fuselage structural concept and resulting vibro-acoustic design rules

For the fuselage the investigated structural concept consists of two connected shells (a type of sandwich structure): the inner shell is the stiff and load carrying part, the thinner outer shell “protects” the inner shell and together with the connecting core provides the bending stiffness e.g. to prevent buckling.

In order to achieve sufficient NR in addition to satisfying strength and stiffness requirements, the following main properties shall be observed

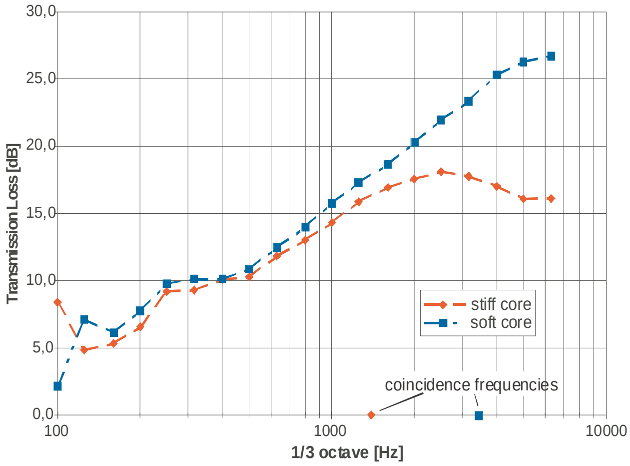

Fig. 4. TL for soft and stiff core (measurement data)

- the stiffness distribution in longitudinal direction shall be quite irregular in order to prevent “homogenous” vibration modes which could easily couple to cabin acoustic modes
- the coupling or core structure between inner and outer shell should be “flexible” or “soft” with respect to high frequency modes which are relevant for noise generation.

The desirable “high-frequency decoupling” between inner and outer shell results into a kind of acoustic double wall effect, where noise transmission is significantly reduced above so called double-wall resonance frequencies. This also becomes obvious from tested transmission loss (TL) results given in figure 4: the TL or NR is larger in higher vibration modes for the tested sandwich plate with “soft” core as compared to a plate with stiff core.

6.2 Optimization of reinforced stiffener profiles with manufacturing constraints

For extruded I-section framework beams to be made out of Aluminium or Magnesium base material, additional reinforcement is introduced during the extrusion process in order to increase strength and stiffness of the profiles. So material, structural and manufacturing aspects have to be considered simultaneously for optimisation [3]. The geometric relation between the global geometry, the material and

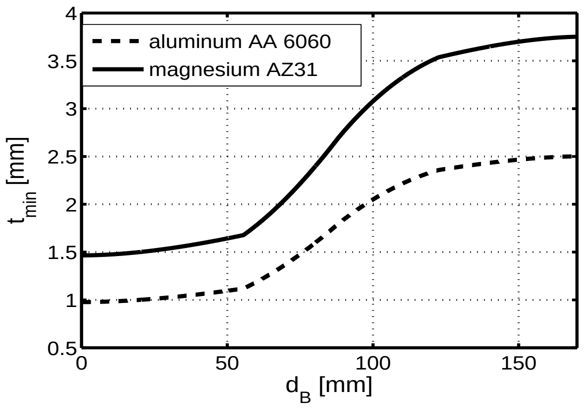

Fig. 5. Smallest possible wall thickness for aluminum and magnesium profiles the extrusion process.

the minimum wall thickness is modeled as shown in figure 5.

The minimum wall thickness for an extruded profile without reinforcements is a function of the circumscribed diameter d_B and the matrix material. Reinforcements increase the minimum wall thickness because the reinforcing elements have to be pulled by the matrix material during the extrusion process. The ratio between web and flange thickness and the number of reinforcing elements are input parameters for the manufacturing effort model for extrusion molding. The output of this model is a nondimensional effort value between zero (very low manufacturing effort) and one (high manufacturing effort).

In figure 6 three Pareto fronts (set of all optimal compromises between conflicting objectives) for different design optimization cases with varying constraints in manufacturing effort are shown. Each point is an optimal design, which means, that no design with a lower mass can be found for a given deformation. The ‘ultimate’ design would be placed at the lower left corner of the diagram. If high manufacturing effort is tolerated, aluminum profiles with carbon fiber reinforcements are optimal (material costs are neglected). Parts with less then 2 kg mass can be achieved with magnesium - carbon fiber combinations. Four to six reinforcing elements are located in the flanges, and the web and flange thicknesses are quite different leading to lower mass but higher manufacturing cost.

7. Conclusions

The simultaneous consideration of structural, vibro-acoustic and manufacturing aspects for optimisation of CFRP fuselage structures in MDO techniques has been demonstrated. Since completeness of the optimisation model is essential, techniques to include qualitative knowledge are found very helpful.

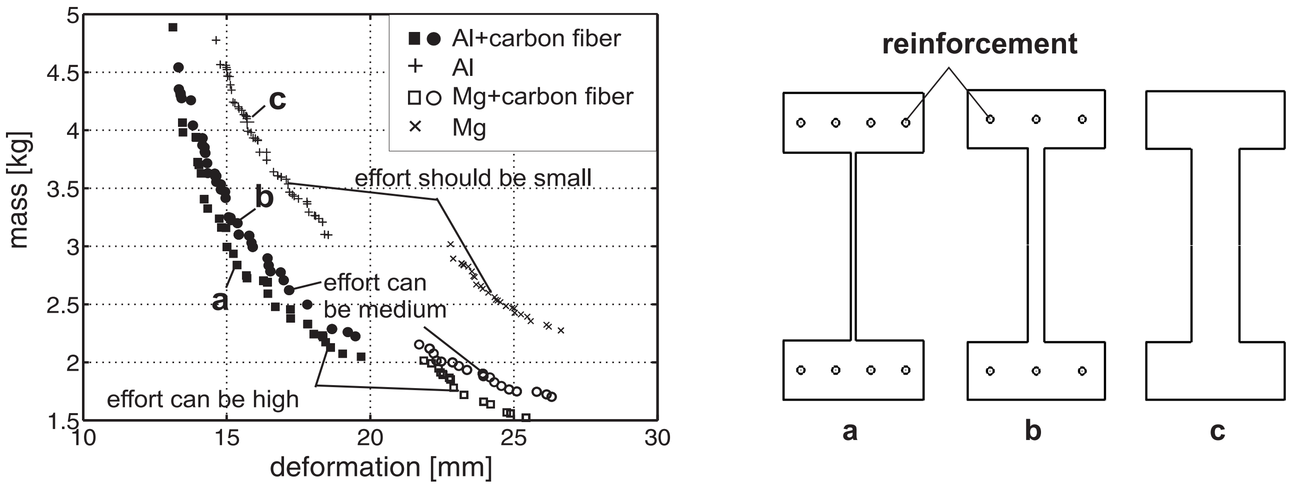

Fig.6. Optimization results for the I-section beam: on the left side Pareto fronts for different manufacturing effort restrictions; resulting into different designs given on the right side

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