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STRUCTRUAL OPTIMIZATION - A NEED FOR PRESENT AND FUTURE HELICOPTER DEVELOPMENT

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Structural Optimization - A Need for Present and Future Helicopter Development

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Abstract

Structural optimization in modern helicopter industry has become a necessary tool to improve the economy and comfort for present and future developments. Increasing requirements for manufacturing costs, safety, weight and lifetime will be the goal for further optimization of components and system optimization with multi-objectives.

The used basic optimization tools will be structured in 3 different fields of work:
Helicopters of the new generation will show a very high portion of structural components made of fiber composites. To take the best advantage of these materials, methods of structural optimization at panel level, already in early design phase, are the tools to choose the best fiber orientations and laminate thicknesses.
Optimization on special components like elastomeric dampers and bearings are also necessary to increase lifetime and effectiveness of damping and antivibration equipment while design restrictions e.g. dimensions, weight or damage tolerance are defined as constraints.
To achieve the optimal design of a complete structure all special requirements must be fulfilled, that means that all constraints e.g. stress, strain, dynamic response or displacements have to be in a feasible range. Optimization on structural level will be shown by an example calculated with MBB-LAGRANGE computer code.

Introduction

In the process of designing helicopter structures, methods of structural optimization are of great advantages. These methods allow to generate a design, which is optimal with respect to an objective function and which fulfils given design constraints. As a helicopter is a flying vehicle, in most cases the objective function will be the weight, but in special cases also other objective functions are useful. So, e.g. for drive shafts with constant weight, the distance between two bearings can be maximized or the distance between the shear center and the center of gravity of a rotor blade cross section can be minimized.
In this paper optimization is shown on an elastomeric radial bearing component. Replacing classical bearings in helicopter rotor system, elastomeric bearings have to fulfil all necessary design requirement and have to guarantee practical mission range. Life time of this elastomeric components will become a critical factor, especially for commercial use. The presented example shows a usable way for optimizing life time of a elastomeric bearing.
In the field of structural optimization, there exist

two principle approaches: First the whole structure can globally be optimized by using one of the large computer codes, based on the finite element theory (e.g. MBB-LAGRANGE, MSC-NASTRAN, etc.). Second it can be useful too, to investigate special components or parts of structures by means of smaller computer codes. In contrast to the first approach, the second will be called optimization at panel level.

In this paper the use of both approaches will be shown at examples of composite structures. It is shown that both methods do not compete with each other but they complement each other.

Methods of structural optimization at panel level can be used already in early design phases, when exact geometry and the type of construction is not yet known. In this phase principle studies on the geometry and type of construction are efficiently done by the use of small computer codes. OLGA is one of these small codes for the optimization of fiber reinforced laminates at panel level. Single layer thicknesses and fiber orientation angles are varied in such a way that optimal stiff and light laminates are achieved under consideration of certain design constraints [1].

The given example for this phase shows the optimization of a laminated panel (determination of the layer thicknesses and layer angles) due to special thermal requirements.

In later design phases the global structural optimization is performed by using the larger codes based on finite element methods. With those methods the whole structural design is checked and the last overall design changes are determined in order to meet all requirements. As example the optimization of a helicopter tail boom is given. For this structures the first eigenfrequency and the sandwich face sheet wrinkling are essential design constraints.

Structural Optimization at Panel Level

The panel level optimization code OLGA (Optimierung von Laminaten mit geschichtetem Aufbau, which means: optimization of laminates with a layered structure), based on the classical laminate theory (CLT), uses different numerical optimizers, e.g. method of the interior penalty function or method of sequential quadratic programming. With the program system OLGA it is possible to determine the optimal lay-up for any laminate (figure 1) under nearly any design constraints.

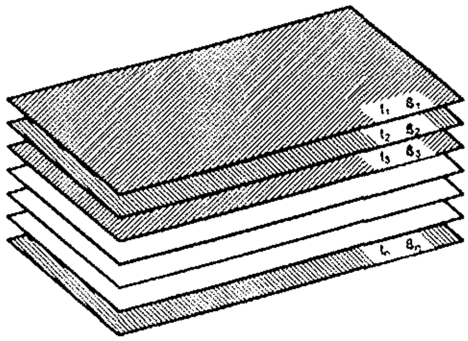

Figure 1: Geometry of general laminate

As design variables of the panel problem the thickness t_i and the fiber orientation angle β_i of any different layer of the laminate can be chosen. The vector of the design variables $\{x\}$ has following form:

$$\{\mathbf{x}\} = \{t_i, \ldots, t_k, \beta_i, \ldots, \beta_k\}$$

For laminates with n layers the vector $\{\mathbf{x}\}$ can contain up to n layer thicknesses and n fiber orientation angles. Layer thicknesses and fiber angles respectively can be linked together to reduce the number of design variables or to get a special type of laminate lay-up (e.g. symmetric or an orthotropic laminate). The linking is accomplished by the linking matrix [L], which connects the design variable set $\{\mathbf{x}\}$ with the real laminate thickness t_i and fiber orientation angles β_i:

$$\{t_i, \ldots, t_n, \beta_i, \ldots, \beta_n\} = [\mathbf{L}]\{\mathbf{x}\}$$

The quantity to be optimized is called the objective function. This function $f(t_i,\beta_i)$ is given as an explicit function of the design variables. In OLGA it is possible to take any result of the classical laminate theory (e.g. weight and stiffnesses, etc.) which can be maxi- or minimized. An example with maximum Young's moduli optimization is shown later. It is also possible to combine some different results to a new function, which then will be optimized.

The design constraints can be any result of the laminate theory, especially the laminate strength (stresses in the single layers and factors of safety respectively, evaluated by application of a proper failure criterion, e.g. Tsai-Wu), the laminate stiffness or the temperature expansion of the laminate. Unlimited loadcases (depends on computer hardware) can be considered to the optimization loop. The panel can be used with tension and pressure loads. Also available are combinations of shear loads n_{xy}, moments m_x, m_y, m_{xy} and temperature loads ΔT.
In addition to the standard output of the classical laminate theory extensions for the treatment of face sheet wrinkling of sandwich structures, local and global stability of rectangular plates with different boundary conditions is available.
Figure 2 shows the structure of OLGA. The modular FORTRAN code allows it to make easily extensions, like additional objective functions or design constraints.

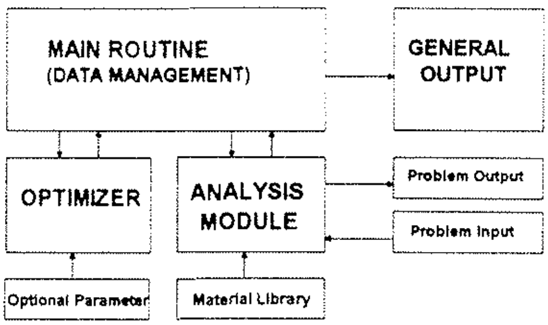

Figure 2: Structure of OLGA

The input data for OLGA consists of dataset Problem-Input which contains all necessary data to describe the physical problem and a special control parameter file for the selected optimizer. Their values should be modified moderately to improve convergence.
The basis of the analysis module is the classical laminate theory, detail descripted in e.g. [3], [4] and [5], which shows the material law of a general laminate in the form

$$\begin{bmatrix} n \\ m \end{bmatrix} = \begin{bmatrix} A & B \\ B & C \end{bmatrix} \left[\begin{bmatrix} \varepsilon_0 \\ \kappa_0 \end{bmatrix} - \begin{bmatrix} \alpha_t \\ 0 \end{bmatrix} \Delta T \right].$$

The material law is calculated from the data of the unidirectional layers and the information about the laminate lay-up (layer thickness and fiber orientation angle). With use of this material law the stresses and factor of safety against fiber failure and interlaminar failure can be determined. More detailed information about OLGA, modules used theory and program description can be seen in [1].
The given example shows the optimization of a layered structure with thermal expansion and design constraints. Design variables are fiber orientation angle α and layer thickness t. Fiber orientation is given between $10° \le \alpha \le 90°$ (α_{min}= 10° as lower bound for production restriction) and the boundaries for fiber thickness is set to $0.01 \le t_{\pm\alpha} \le 4.00$ [mm]. Used material is fiber M40A with 60 Vol%.

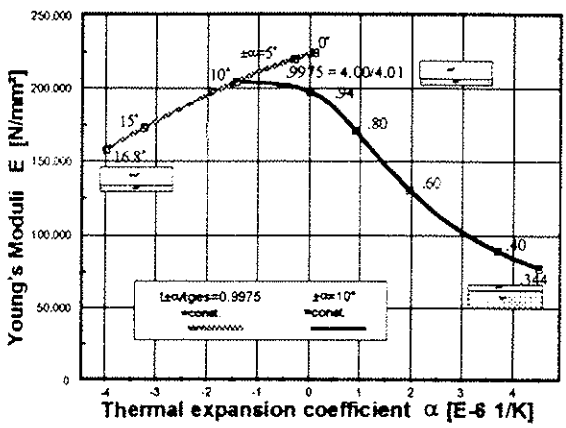

Figure 3: OLGA optimization example

The objective function is maximum Young's moduli. To show optimization results the given thermal expansion coefficient α is varied between $\pm 4.0 \cdot 10^{-4}$ 1/K for this example. Figure 3 shows the maximum Young's moduli at the boundary of design constraints with 200500 N/mm² at $\alpha = -1.5 \cdot 10^{-4}$ 1/K.

Component Optimization

Modern helicopter rotor systems have to fulfil requirements e.g. system simplification, weight reduction and easy maintenance by better safety, reliability and lifetime. One decisive way is to use an elastomeric bearing rotor system. This paper shows the method to get a elastomeric bearing with maximum life time constrained by construction space and stiffness requirements. Figure 4 shows component reduction at Eurocopter TIGER rotor hub with elastomeric bearings.

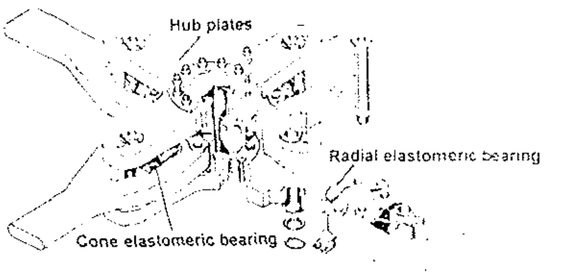

Figure 4: TIGER rotor hub with bearings

Sizing of thin layered elastomeric bearings is carried out in three design steps. Figure 5 shows this principal phases. Predesign with material selection, determination of required bearing envelope and estimation of stiffness and life limits. The used design tools are material data sheets and analytical/empirical material behaviour equations. More detailed information to calculate material data and material constants can be seen in [4], [5] and [6].

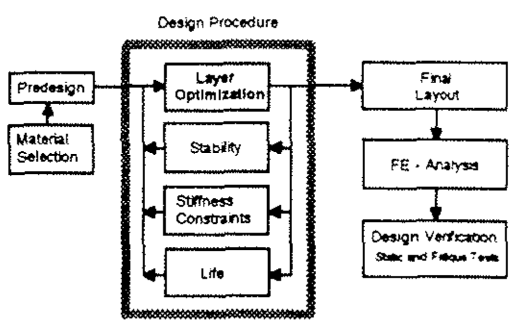

Figure 5: Design procedure

To describe the optimization problem, stress and strain distribution in thin elastomeric layers are derived by the asymptotic theory of thin elastomeric layers. Calculation of spring rates and local strains for different load directions by means of finite element programs is to tedious in this design stage because of the large number of design variables. Using DIRICHLET's boundary problem

$$-\Delta\Theta(\alpha_1, \alpha_2; \xi) + \sigma\Theta(\alpha_1, \alpha_2; \xi) = (\alpha_1, \alpha_2; \xi),$$

with $(\alpha_1, \alpha_2; \xi) \in \Omega$

to solve the HELMHOLTZ's differential equation with the boundary condition

$$\Theta(\alpha_1, \alpha_2; \xi) = 0. \quad \text{for all unbonded surfaces,}$$

we get the general form of solution for relative volume deformation Θ with

$$\Theta(\alpha_1, \alpha_2; \xi) = \Theta_0(\alpha_1, \alpha_2; \xi) + \Theta_1(\alpha_1, \alpha_2; \xi) \cos\varphi.$$

α_1, α_2 are surface coordinates of the elastomeric layers, ξ is stiffness, Ω is the surface respectively design space, φ describes the circumference angles. To solve this boundary problem, classical numerical procedures e.g. variation principles, shooting method or finite difference equations can be used.

The mathematical formulation for life optimization of the elastomeric/shim packages is given by the objective function L with

$$\max\{L_1(\mathbf{x})\}, \quad \mathbf{x} = (G_1, \ldots, G_N; t_{E,1}, \ldots, t_{E,N}).$$

to describe the maximum life for one single elastomeric layer. Shear moduli G and layer thickness t are design variables. If individual length l of the elastomeric layers is allowed, $l_E, \ldots, l_{EN}$ will be optional. To get maximum life for the whole system, life of

$$L_2(\mathbf{x}) = L_3(\mathbf{x}) = \ldots = L_N(\mathbf{x}) = L_1(\mathbf{x})$$

must be maximum for all. Constraints, essentially stiffness requirements K for

$$K_T(\mathbf{x}) = 1/((1/K_{T,i})) \leq K_{T,max},$$
$$K_R(\mathbf{x}) = 1/((1/K_{R,i})) \geq K_{R,min} \text{ and}$$

$$G_{min} \leq G_i \leq G_{max}, \quad t_{min} \leq t_i \leq t_{max}$$

describe the optimization problem. Material data have to be given with an analytical or numerical description of failure surfaces and S-N curves. Additional formulations of a damage accumulation model for multiaxial loading should be included.

N, the number of layers is given. Actual it is

intended to expand theory and program code to allow N as design variable, too.
As an appropriate numerical optimization algorithm for the non-linear constrained optimization problem are non-linear simplex techniques, generic algorithm respectively evolution strategies.
For phase three, final layout, a finite element analysis of the complete bearing have to be done. Structural analysis of elastomeric/shim package will be carried out with MARC from Analysis Research Corporation MSC/NASTRAN resp. ANSYS from Swanson Analysis System, Inc.
Main topic of interest are static analysis and life prediction for elastomeric layers and shims, stiffness and stability of elastomer/shim package and interface load distribution to the inner and outer housings. Thermal and viscoelastic analysis of internal heat - build up through cyclic loading , thermal and residual stress due to manufacturing, environmental temperature and internal heat generation have to be checked.
Figure 6 shows an elastomeric bearing example for design study during development phase.

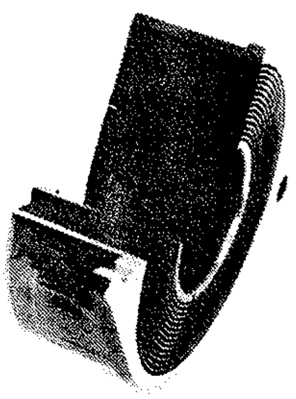

Figure 6: Optimized radial elastomeric bearing

Structural Level Optimization

The method of structural optimization deals with the problem to find the optimal layout for a whole aircraft structure. Structural optimization in this paper is restricted to fiber composite structures and to the optimization code LAGRANGE, which has been developed by former MBB (today a part of DASA) and the Research Laboratory for Applied Structural Optimization at University of Siegen since 1984. The principal concept to deal with optimization problems in design process is shown in figure 7.

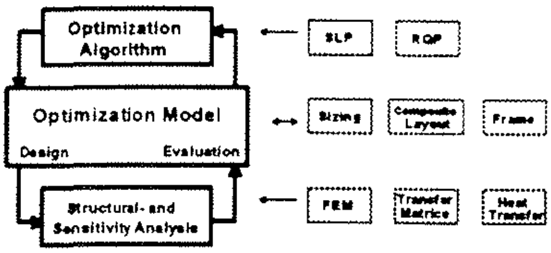

Figure 7: Program modules of LAGRANGE

In an iterative loop the optimization module changes the chosen design variables in a way to achieve the best design value for an objective function, not violating defined constraints which present the boundaries of design space. With initially given start up values, normally the present design state, an structural analysis will be done. The whole model has to be a finite element structure comparable to FE-codes e.g. MSC/NASTRAN or ANSYS. As an great advantage of an optimization code, immediately can be shown if any given constraints are violating the current design. The next step in optimization process is the sensitivity analysis of the structure. The gradient for the objective function $f(\mathbf{x})$ and the constraint function $g_j(\mathbf{x})$ with respect to the design variables $\mathbf{x}_i$

$$\frac{\partial g_i}{\partial \mathbf{x}} \quad \text{and} \quad \frac{\partial f}{\partial \mathbf{x}} \quad \text{with} \quad x = \{t_1, \ldots, t_N, \beta_1, \ldots \beta_N\}$$

must be delivered. LAGRANGE is able to calculate the sensitivity analysis by analytical formulations. For large problems this analytical formulation is essential for solving and to avoid numerical instabilities. As design constraints displacements, strain, stresses. buckling, flutter, eigenfrequencies, transient and frequency response, aeroelastic efficiencies, sandwich wrinkling, manufacturing constraints, etc. are available. The next step in the optimization loop is carried out by the module optimization algorithm. This module calculates the new design variables which adjust the optimization criterias. It is possible to use several different optimization algorithm like inverse barrier functions (BF), method of multipliers (MOM), sequential linear

programming (SLP) or recursive quadratic programming (RQP), etc., because the optimizer is normally problem sensitive, too. More details of LAGRANGE and optimization examples are given in [7], [8] and [9].
The following example shows optimization with LAGRANGE on Eurocopter TIGER tail boom.

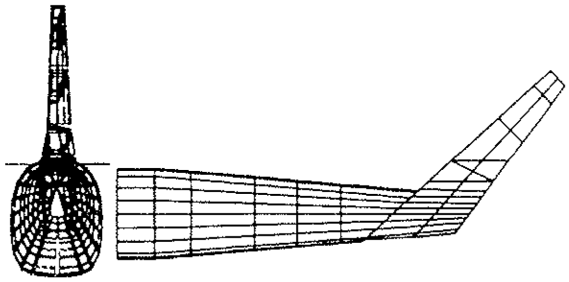

Figure 8: TIGER tail boom

The whole tail boom inclusive the rudder is designed in Kevlar/carbon fiber reinforced plastic with NOMEX honeycomb sandwich [10]. For FE-idealisation CBAR and CQUAD elements are used. Design variables are the layer thickness t for 1064 elements. Fiber angles β will not be changed due to manufacturing restrictions. Optimization part is the whole tail boom and rudder with sandwich shells, webs and spars. As design constraints material strength, local compressive strength, deformations, eigenfrequencies, sandwich, global and flange buckling are given. Design objective is minimum weight. The whole system could be described with 319 nodes and 1064 elements which yield to 1800 DOF. 4 loadcases with aerodynamically and mass loads for flight and landing conditions have been defined. 1064 structural variables and 56 design variables are results in 1840 constraints. For solution sequential linear programming has been used.

Ex.	mass [kg]	1. Ω [Hz]	ΔM [kg]	Remarks
0	71.6	5.15	0	Reference
1	65.6	4.95	-6.0	Static only
2	66.2	5.15	-5.4	Static+dynamic
3	98.9	6.50	+27.3	Static+dynamic
4	89.9	6.50	+18.3	add. Stringers

Table 1: Optimization results

Optimization results are shown in table 1. The used basic model (named 0) with initial values shows an eigenfrequency of 5.15 Hz. With static optimization only (ex. 1) weight will be reduced by 6 kg but with decreasing eigenfrequency. With full static and dynamic optimization weight will be reduced by 5.4 kg. Calculation example 3 and 4 shows additional weight, caused by higher eigenfrequency requirements. Example 4 shows less additional weight then ex. 3, because stiffness, resp. material has been added at discrete stringers and not to a greater shell area.

Conclusion

The present optimization examples show the possibilities to design and improve components and structural elements of aircrafts.
Most elements of a helicopter have special requirements and thus the objective functions and restrains will be different too. It is also shown that the engineer has to use various tools for different design phases to get best design results. Extensive calculations will result in design improvements which are necessary for future developments. System optimization with multi-objectives will be used for the increasing requirements for manufacturing costs, safety, weight and lifetime.

References

[1] Rapp, H.;
New Computer Codes for the Structural Analysis of Composite Helicopter Structures. Forum Proceedings of the 16th European Rotorcraft Forum, Paper No II.4.4, 18th - 20th Sept., Glasgow, UK, 1990.

[2] Tsai, S. W., Hahn, T. H.;
Introduction to Composite Materials.
Technomic Publishing Co., Westport Conn., 1980.

[3] Nagendra, S., Haftka, R. T., Gürdal, Z.;
Stacking Sequence Optimization of Simply Supported Laminates with Stability and Strain Constraints.
AIAA Journal, Vol. 30, No. 8, August 1992, pp. 2132-2137.

[4] Hausmann, G.;
Gummi - Metall - Verbindungen.
Vortrag Elastomerverarbeitung, 12. VDI-Jahrestagung, 7. - 9. Febr., Braunschweig, Germany, 1994.

[5] Hopf, A.;
Eine KQ - Methode für komplexwertige Daten zur Ermittlung der Gedächtnisfunktion viskoelastischer Materialien.
Diplomarbeit Technische Universität München, Institut für Angewandte Mathematik und Statistik, Germany, 1993.

[6] Spitzenpfeil, C.;
Numerische Parameterbestimmung mit Hilfe von Optimierungsmethoden am Beispiel des ODGEN-Modells für hyperelastische Werkstoffe.
Diplomarbeit Fachhochschule Würzburg - Schweinfurt, Germany, 1993.

[7] Dobler, W., Erl, P., Rapp, H.;
Optimization of Sandwich Structures with Respect to local Instabilities with MBB-LAGRANGE.
NATO/DFG Advanced Study Institute, Optimization of Large Structural Systems, Sept. 23 - Oct. 4, Berchtesgarden, Germany, 1991.

[8] Eschenauer, H. A., Schuhmacher, G., Hartzheim, W.;
Multidisciplinary Optimization of Fiber Composite Aircraft Structures.
NATO/DFG Advanced Study Institute, Optimization of Large Structural Systems, Sept. 23 - Oct. 4, Berchtesgarden, Germany, 1991.

[9] MBB-LAGRANGE,
MBB-LAGRANGE - User Manual, Version LAG09; MBB-DASA Documentation.

[10] Schranner, R., Dufour, G.;
System Design for the Tiger Helicopter.
16th European Rotorcraft Forum, 18th - 21th Sept., Glasgow, UK, 1990.