THE INTEGRATION OF STRUCTURAL OPTIMIZATION IN THE GENERAL DESIGN PROCESS FOR AIRCRAFT

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Abstract

Formal mathematical optimization methods have been developed during the past 10 to 15 years for the structural design of aircraft. Together with reliable analysis programme like finite element methods they provide powerful tools for the structural design. They are efficient in at least two ways:

- producing designs that meet all specified requirements at minimum weight in one step;
- relieving the engineer from a time consuming search for modifications that give better results, they allow more creative design modifications.

MBB has developed a powerful optimization code called MBB-LAGRANGE which uses mathematical programming and gradients to fulfill different constraints simultaneously.

A method for solving large linear equation systems by an iterative method is described to show the effort which went into the program formulating the physical problem in a very efficient mathematical way.

Some examples depicting the successful application of the MBB-LAGRANGE code are presented.

The paper closes with an outlook how the optimization problem could be enlarged to include also shape and size of airplanes.

INTRODUCTION

To improve or modify a design, a process, a procedure, or any given task into a "better" direction, is referred to as "optimization". This is often done by experience, parametric investigations, iterative procedures, by experimental testing and modifications, or based on empirical data. This approach usually leads to better results but nobody can tell how far away the optimum still is or even where it is. A more efficient way to perform this task is provided by a special branch of applied mathematics, called optimization. This kind of optimization changes the chosen variables in a design problem in a way to achieve the best value for an objective while not violating defined constraints that represent the boundaries of the design space.

This formal optimization was rather early introduced in economics or chemical engineering due to the linearity of the problems, as described by Ashley in an excellent overview paper on the aeronautical use of optimization [1]. In order to use the potential of mathematical optimization, it is necessary to describe the physical nature of the problem in a way that allows the use of optimization algorithms.

In structural design, finite element methods together with modern computers have provided tools that allow to analyse complex structures with high accuracy. These were main essentials to initiate development and application of optimization programs for structural design since 1970. Approximately at the same time, composite materials were introduced in aerospace design. They offer an infinite variety to combine their highly anisotropic elastic properties for any specific combination of design requirements. For a more efficient use of these materials, optimization programs are required to handle the complexity of the problem, especially if additional requirements besides strength are involved in the problem [2]. During the last decade considerable effort has been spent to develop modern structural optimization procedures, using efficient mathematical optimization algorithms as well as optimality criteria which satisfy all requirements simultanously and find optimal values of the design variables by direct computation. The increasing emphasis of aeroelastic considerations is shown in fig. 1, which was taken from [3].

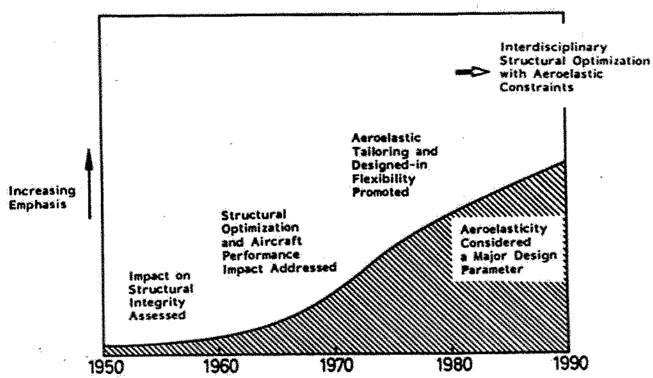


Fig. 1 Evolution of aeroelastic considerations in fighter aircraft design

1. STRUCTURAL OPTIMIZATION IN THE GENERAL DATA FLOW

The use of structural optimization tools during the preliminary design stage of an advanced aircraft gives the following potential improvements:

- satisfies the requirements of new aircrafts
- minimizes the objective (weight)
- increases the quality of products
- shortenes the development phase
- increases chances of the company in competition

In order to do this, an appropriate mathematical programming procedure has to be embedded in the general data flow, which is depicted in fig. 2 and fig. 3 taken from [4].

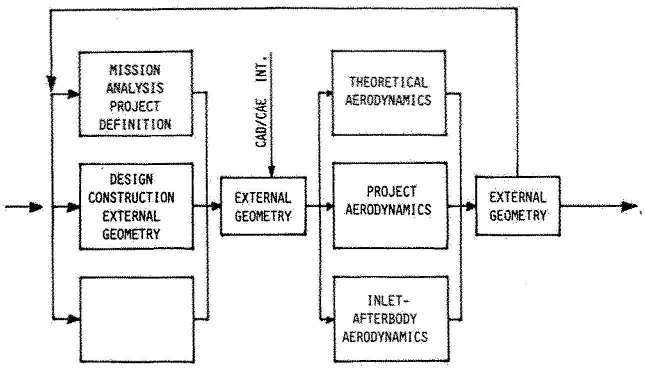


Fig. 2 External geometry in data flow

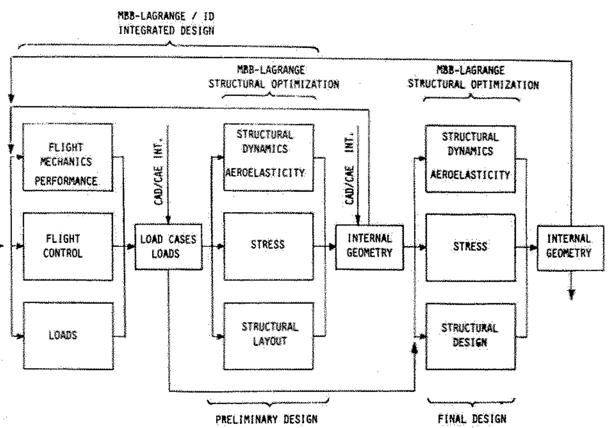


Fig. 3 General data flow

These figures show a typical flow of geometric, aerodynamic, structural and other data which are used during the design phase of an aircraft. The improved productivity is a result of the integrating effects of the structural optimization. Shorter time of development is realised and fewer data transfers go wrong.

At the present time the development of new airplanes is influenced by new techniques, such as flutter suppression, CCV-configuration, gust load alleviation etc, see fig. 4. In addition to stress, displacement, aeroelastic and dynamic constraints an integrated design involves all these techniques and the optimization procedures must be extended for these new constraints. Even at the very moment a reliable optimization code is the basis, which allows parametric investigations and weight penalties to be evaluated.

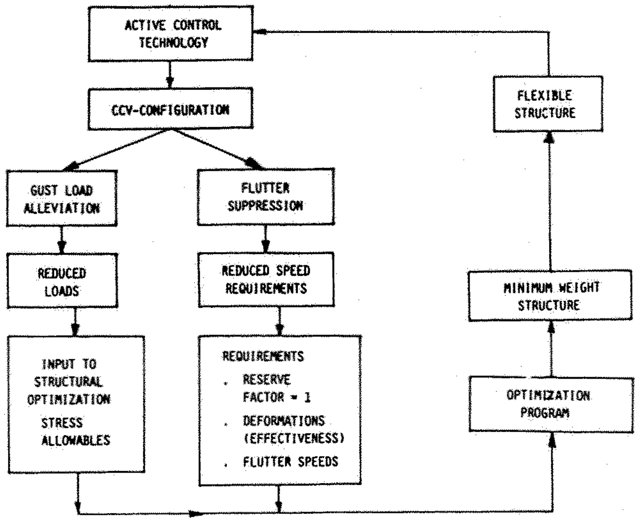


Fig. 4 New technologies of recent aircraft

2. STRUCTURAL OPTIMIZATION AT MBB

MBB has developed its own structural optimization system called

MBB-LAGRANGE

The performance and requirements/constraints of this new program system are shown below:

- <u>REQUIREMENTS</u>

  Finite Element Structure

- <u>STRUCTURE VARIABLES</u> $x \in \mathbb{R}^m$
  - Skin Thickness
  - Balance Masses
  - Fibre Directions
  - Grid Point Coordinates

- <u>CONSTRAINTS</u> $G_j(x) \geq 0,\ j \in \mathbb{N}$
  - Min./Max. - Variable
  - Stresses
  - Strains
  - Deformations
  - Flutter Speed

- o Divergence Speed
- o Aeroelastic Efficiencies
- o Eigen Frequencies
- o Element Stability
- o Dynamic Response
- o Weight

o **MULTIOBJECTIVE FUNCTION** $f(x) \rightarrow$ Min.

Vector Optimization = "Trade Off" Studies of Convex Combination of Objectives

The program architecture is organized due to the concept of H. A. Eschenauer [5] with the main parts optimization algorithm, optimization model and structural analysis including sensitivity analysis.

The corresponding optimization models are based on the general nonlinear programming problem according to [5]. The design variables $\underline{x}$ are cross sectional areas of trusses and beams, wall thicknesses of membrane and shell elements, laminate thicknesses for every single layer in composite elements or nodal coordinates for geometry optimization problems. The constraints in form of inequalities may be any limitation of displacements, stresses, strains, buckling loads, aeroelastic efficiencies, flutter speed, divergence speed, natural frequencies, dynamic response and design variables [6].

In the case of scalar optimization, the objective function $f(\underline{x})$ often includes the structural weight or another linear combination of the design variables. However, it is also possible to define one of the constraint functions as objective and to introduce the weight as constraint at the same time. If vector optimization problems are under consideration, then optimization strategies $p[\underline{f}(\underline{x})]$ according to [5] ensure the transformation to scalar substitute problems.

It is necessary to provide several different optimization algorithms, because there is no known single algorithm which is adapted to every type of problem. The following algorithms are implemented in LAGRANGE:

- IBF : Inverse Barrier Function,
- MOM : Method of Multipliers,
- SLP : Sequential Linear Programming,
- SRM : Stress Ratio Method,
- RQP1, RQP2 : Recursive Quadratic Programming,
- GRG : Generalized Reduced Gradients.

The structural and sensitivity analysis are based on finite element methods (FEM). Static, buckling, dynamic, aeroelastic and flutter moduls have been incorporated. It is possible, to treat homogeneous materials with isotropic, orthotropic or anisotropic behaviour as well as fiber reinforced composite materials. The element library contains the types: truss, beam, membrane (3, 4, 8 nodes), shell (3, 4 nodes) and volume elements. In addition, shell structures can be analyzed with a special transfer procedure. This transfer matrix procedure transforms the transfer matrices to a stiffness matrix that can be assembled together with the remaining finite element stiffness matrices. This mixed procedure allows very efficient analyses of large shell structures with complex boundary conditions.

The program architecture of MBB-LAGRANGE, shown in fig. 5, has a modular set up with defined interfaces. While the modules INPUT and RESULT are used to enter data or to process the results, the real optimization calculations takes place in the DESIGN module. There we have a strong separation between optimization and analysis. The "mathematics" is mostly located in the part optimization algorithm. The "physics", that stands for the structural response and its derivatives, are realized in the analysis and gradient module. The link of both is the optimization model.

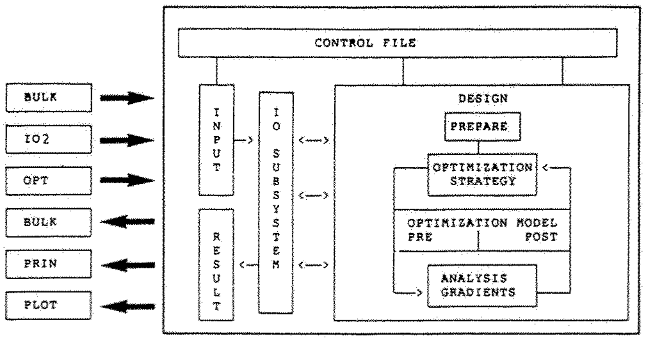


Fig. 5 Program architecture of MBB-LAGRANGE

An interactive user exit with an integrated knowledge based system supports all phases of optimization runs. Further possibilities like the automatic preparation of batch procedures for different hardware systems and like the automatic linking dependent on the problem size ensure a high user comfort. Standard interfaces enable the integration in the CAE-environment (NASTRAN, I-DEAS, PATRAN). Especially the graphical input of some optimization data saves a lot of time and is really helpful, e.g. variable linking, buckling fields and displacement constraints.

In order to illustrate the tremendous effort which had to be spent to achieve good mathematical descriptions of the structure whilst still being able to simultaneously fulfill several boundary conditions the derivation of the static aeroelastic module is shown.

3. ITERATIVE SOLUTION OF LARGE LINEAR EQUATION SYSTEMS FOR STATIC AEROELASTIC PROBLEMS

There is a tendency in structural analysis towards systems with increasing numbers of elements and degrees of freedom. This is caused by the technological demand for exact descriptions of local structural details, and it is possible with nowadays computer sizes and costs [7].

For this reason, the aerodynamic models and solution methods for aeroelastic problems are adapted to finite element methods. That means solutions in the structural system. But in contrast to pure static problems, the aerodynamic loads matrix is almost fully populated and unsymmetric. A direct solution method is no longer efficient in storage size and computing time, and should be replaced by an iterative method.

When the mathematical method for LAGRANGE was selected the driving considerations were

- low computer storage space
- low time consumption
- applicability for various problems

3.1 Description of the Problem

In static aeroelastic problems, the aerodynamic load depends on the deformation of the structure. The load vector is composed of a part that depends on the solution and one that is independent of it. Thus, the problem can be expressed as a static equilibrium system with n degrees of freedom.

$$K \cdot u = b_o + b(u) \qquad (1)$$

with $K \in \mathbb{R}^{n \times n}$; $u, b_o, b \in \mathbb{R}^n$

K is an n x n stiffness matrix that is symmetric, positive definite, sky line organized, and a CHOLESKY-factorization is possible. This decomposition can be performed with vectorized algorithms to save time and space. That means, that during the iterations equation systems with new right sides are solved.

In aeroelasticity the aerodynamic influence can often be expressed in linear relations [11]. Therefore, the vector b(u) can be expressed as

$$b(u) = C \cdot u \quad ; \quad C \in \mathbb{R}^{n \times n} \qquad (2)$$

This matrix C contains all physical properties, like the dynamic pressure, and all required transformations from the aerodynamic to the structural sytem. Using equation (2), equation (1) can be rewritten as.

$$(K - C)\, u = b_o \qquad (3)$$

If the difference K-C is regular, equation (3) can be solved. Because the direct solution of (3) as well as the calculation of C is not favourable, an other approach is required.

An iteration process for the solution of (3) is defined in (4), where an additional relaxation process is introduced to improve convergence:

$$Ku^{(m+1)} = \omega C u^{(m)} + (1-\omega)\, Ku^{(m)} + \omega \cdot b_o \qquad (4)$$

This equation corresponds with the following eigenvalue problem [7]:

$$(\omega C + (1-\omega)\, K - \lambda_t(\omega)\, K\,)\, w = o \qquad (5)$$

The convergence of the iteration strongly depends on the dominant eigenvalues $\lambda_t(\omega)$. The eigenvalue $\lambda_{ti}(\omega)$ is derived by the transformation

$$\lambda_{ti}(\omega) = \lambda_i \cdot \omega - \omega + 1, \quad \Lambda_{i=1,\ldots n} \qquad (6)$$

where λ_i are the eigenvalues of the untransformed case ($\omega = 1$). Because the maxtrix C is unsymmetric, real and conjugate complex eigenvalues λ_i and λ_{ti} appear. The eigenvector w remains unchanged by the transformation. Some possible graphs of λ_t versus ω are plotted in Fig. 6. An approach for finding optimal values of w (for small λ_t) is also indicated in this figure.

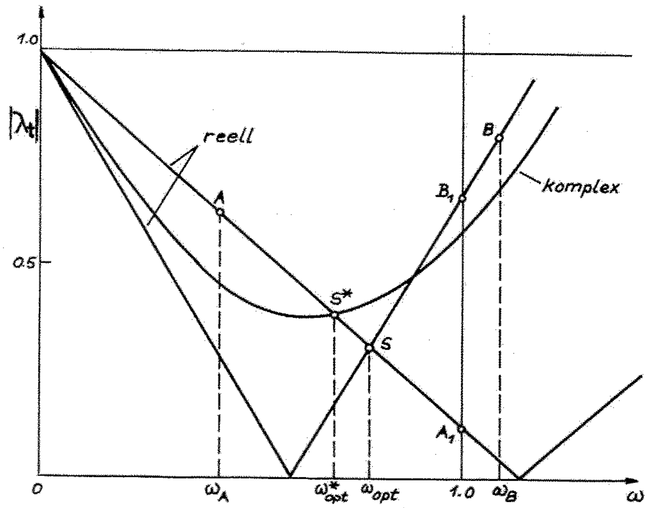


Fig. 6 Dominant eigenvalues as a function of the transformation variable ω

An explicit calculation of eigenvalues and -vectors is impossible in most cases. But it can be shown, that the flow of the iteration allows to deduct for dominant eigenvalues. This is completely described in [7]. If the matrix for all eigenvectors of equation (5) is regular, the solution u and the initial solution $u^{(o)}$ can be expressed as linear combinations of eigenvectors.

$$u = W \cdot d \qquad (7)$$

$$u^{(o)} = W\, d^{(o)};\ u^{(o)} \neq u;\ W \in \mathbb{C}^{n \times n}; d, d^{(o)} \in \mathbb{C}^n \qquad (8)$$

Introduced into (4), this yields an approximation after step m

$$u^{(m)} = u - \sum_{k=1}^{n} \lambda^m_{tk} \cdot (d_k - d_k^{(o)})\, w_k \qquad (9)$$

The values λ_{tk}, d_k, $d_k^{(o)}$, and the eigenvector w_k do not depend on the number of iterations m. For a chosen approximation $u^{(o)}$ the iteration process is determined. The summation terms in equation (9) vanish for $m \to \infty$, if

$$|\lambda_{tk}| < 1 \; ; \; \forall_{k=1,\dots n} \qquad (10)$$

This allows to extract the difference of two consequente iteration steps:

$$\Delta u^{(m+1)} = u^{(m+1)} - u^{(m)}$$

$$= \sum_{k=1}^{n} \lambda^m_{tk} \cdot z_k \; ; \; z_k \in \mathbb{C}^n \qquad (11)$$

where

$$z_k = (1 - \lambda_{tk}) \, (d_k - d_k^{(o)}) \, w_k \qquad (12)$$

Equation (11) can be used to analyse the iteration. For the following considerations, it is assumed that eigenvalues are in a descending order, and non-dominant eigenvalues do not affect $\Delta u^{(m+1)}$ for sufficiently high values of m. This leads to three main cases:

a) One single dominant eigenvalue exists for a certain ω in this case.

Equation (11) is used for any components j to form:

$$\lambda_{t1} = \Delta u_j^{(m+2)} \, / \, \Delta u_j^{(m+1)} \qquad (13)$$

The eigenvalue can be transformed back with equation (6). If point S in Fig. 6 is only determined by real dominant eigenvalues, a proper selection of ω allows to find points A and B.

For $\omega = \omega_{opt}$ two dominant eigenvalues will appear with different signs.

b) In this case, one additional iteration is used for equation

$$\Delta u_j^{(m+3)} = \lambda_{t1}^2 \; \Delta u_j^{(m+1)} ; \; \forall_{j=1\dots n} \qquad (14)$$

to obtain the two eigenvalues λ_{t1} and $\lambda_{t2} = -\lambda_{t1}$ for any component j. If equation (13) is used for all iteration steps, case b will deliver a sequence of alternating identical values, depending on m even or odd.

c) In the case of a conjugate complex pair of eigenvalues, their extraction is much more difficult.

The real difference $\Delta u^{(m)}$ in this case is the sum of two complex products with changing real parts.

$$\Delta u^{(m)} = \lambda_1^{\,m} \; z_1 + \lambda_1^{*m} \; z_1^* + 0 \; (\lambda_3^{\,m}) \qquad (15)$$

Assuming that only one pair of conjugate complex eigenvalues is dominant, the substitution

$$\lambda_1 = \lambda' + i \cdot \lambda'' \; , \; \lambda_1^* = \lambda' - i\lambda'' \qquad (16)$$

is used to derive the following relations:

$$\Delta u^{(m+2)} = 2 \, \lambda' \Delta u^{(m+1)} - (\lambda'^2 + \lambda''^2) \; \Delta u^{(m)} \qquad (17)$$

$$\Delta u^{(m+3)} = 2 \, \lambda' \Delta u^{(m+2)} - (\lambda'^2 + \lambda''^2) \; \Delta u^{(m+1)} \qquad (18)$$

The only problem here is to determine that a sequence of this type of values exists after m steps.

To perform iterations for several values of ω for the optimal case with a preselected accuracy is an acceptable compromise in this case.

In the case of optimization the required calculation of gradients leads to a solution of the transposed problem in static aeroelasticity:

$$K \cdot y = C^T y + f \quad ; y, f \subset R^n \qquad (19)$$

with many right hand sides f. Analog equation (11) the following expression is formed:

$$\Delta y^{(m+1)} = \sum_{k=1}^{n} \lambda^m_{tk} \quad s_k \qquad (20)$$

Vector s_k is obtained by the corresponding left eigenvectors.

Although the eigenvalues of the transposed problem are the same as in the untransformed case, the iteration can show a different course - especially during the first steps - because of $z_k \neq s_k$. This can cause a difference in the required number of iterations for the same accuracy.

These three cases show that solutions can always be found in automated procedures and restarts are not necessary.

As an example, a realistic structure was investigated with different values for ω. Fig. 7 shows the iterations for ω = 0.5, 0.7, 1.0 and ω_{opt} = 0.667. Graph 1 for ω = 1.0 shows convergence for the eigenvalue λ_{min}, but the solution itself did not converge because $\lambda_{min} < -1$ violates the convergence condition. A check with ω = 0.7, no. 2, yields λ_{min} again after the backward transformation. For ω = 0.5 the maximal eigenvalue λ_{max} is obtained, no. 3. With ω_{opt} the sequence of alternating identical values of case b was obtained. All iterations show a progress during the initial steps that is different from the dominant values because of the contributions of the non-dominant eigenvalues and eigenvectors.

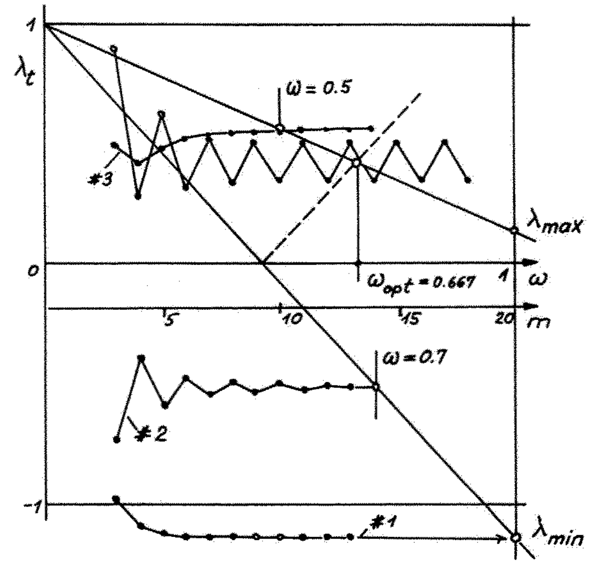


Fig. 7 Dominant eigenvalues vs. ω and results of iterations for individual steps m

4. APPLICATIONS

4.1 Heat Flux and Frequency Optimization of a Satellite Structure

For spacecraft structures usually two different operating phases are most decisive. During launching phase the dynamic loads dominate. On the other hand the following mission in orbit is characterized by thermal effects. Thus an objective conflict occurs, because none of the possible designs permits a simultaneous optimal fulfillment of dynamic and thermal objectives. Here, vector optimization methods are suitable for determining an unique optimal compromise solution.

The ISO-satellite, the European infrared space observatory, will be used to explore cosmic infrared radiation (Fig. 8).

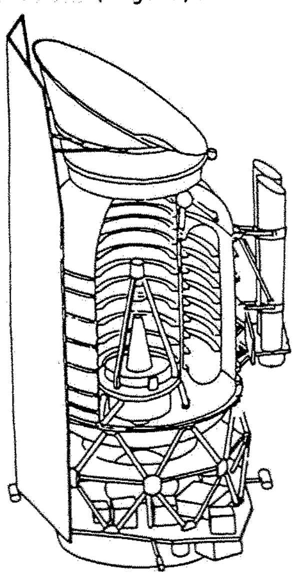


Fig. 8 Infrared space observatory satellite (ISO)

In order to maximize the lifetime of the satellite, the heat flux from the outer to the inner structure, which contains a cooling mechanism for a special sensor, shall achieve a minimum value. Secondly, the natural frequency of the dominant axial vibration mode is to be maximized.

The objective function vector $\underline{f}(\underline{x})$ includes the heat flux $\Phi(\underline{x})$ and the frequency $\omega_A(\underline{x})$:

$$\underline{f}(\underline{x}) = \begin{bmatrix} f_1(\underline{x}) \\ f_2(\underline{x}) \end{bmatrix} = \begin{bmatrix} \Phi(\underline{x}) \\ -\omega_A(\underline{x}) \end{bmatrix} \tag{21}$$

$$\text{where max. } \omega_A(\underline{x}) = -\min\,[-\omega_A(\underline{x})] \tag{22}$$

In the sketch of the structural model (Fig. 9), it can be seen, that the inner and outer structure are linked by means of a spatial frame work and sus pensions.

The cross sectional areas of the supporting frame work are defined as the design availables (Fig. 9). As previous studies have shown, the heat flux Φ can be treated as a linear function of these design variables. Corresponding checks for the initial and optimal designs confirm this approach.

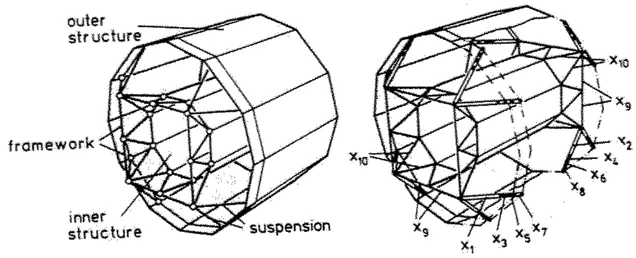


Fig. 9 Finite element model and design variables of the ISO satellite

$$\Phi(\underline{x}) \sim c_o + \sum_{i=1}^{n} c_i\, x_i \tag{23}$$

and

$$\frac{\partial \Phi}{\partial x_i} \sim c_i \tag{24}$$

where the coefficients c_o and c_i are calculated in advance by a heat transfer program.

The natural frequency ω_A results from eigenvalue problems of a finite element model (212 elements and 672 degrees of freedom):

$$[\underline{K}(\underline{x}) - \omega_k^2(\underline{x})\underline{M}(x)]\,\underline{q}_k\,(\underline{x}) = \underline{0} \tag{25}$$

with $\underline{K}$ and $\underline{M}$ as stiffness and mass matrices and $\underline{q}_k$ the eigenvector solution, associated with the eigenvalues ω^2. Since the connection between the axial mode duct the sequence of the corresponding eigenvalue ω_A in the frequency spectrum ω_k ($k = 1 \ldots n_f$) can change during the optimization process, it has to be checked within every iteration and, if required, it needs to be adapted [8].

The derivatives of the natural frequency ω_A are as follows

$$\frac{\partial \omega_A}{\partial x_i} = \frac{1}{2\omega_A} q_A^T \left[\frac{\partial K}{\partial x_i} - \omega_A^2 \cdot \frac{\partial M}{\partial x_i} \right] q_A \qquad (26)$$

By means of a constraint-oriented transformation (trade-off) this vector optimization problem VOP is reduced to a scala optimization problem SOP [9]. The heat flux Φ is minimized as main objective and the frequency ω_A has to achieve different constraint levels to get different functional efficient solutions. For this optimization problem with one dominant constraint the recursive quadratic programming algorithm RQP shows good efficiency [5].

The initial design has a nondimensional heat flux of $\Phi = 1.0$ and a nondimensional frequency of $\omega_A = 1.0$. Dependent on the selection of appropriate constraint levels for the frequency, one gets different optimal compromise solutions. The functional efficient boundary (Fig. 10) delivers a good foundation for the selection of a final design. Here the design with $\Phi = 0.99$ and $\omega_A = 1.08$ is chosen [9].

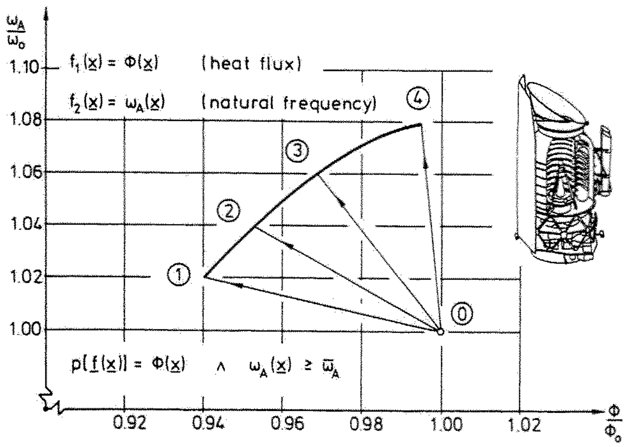


Fig. 10 Boundary of functional efficient solutions for the ISO satellite

4.2 Design of a Carbon Fiber Wing

The wing structure for the experimental aircraft X-31A was optimized with LAGRANGE. In this case, optimization was beneficial for two main objectives of the program: a low cost approach and a very short time for development and design. Besides a design for minimum weight another requirement was a high flutter margin to reduce efforts and costs for flutter wind tunnel and flight tests. Although flutter did not affect the design, it could be surveyed simultaneously during optimization. Static aeroelastic effectiveness was also investigated during the design process.

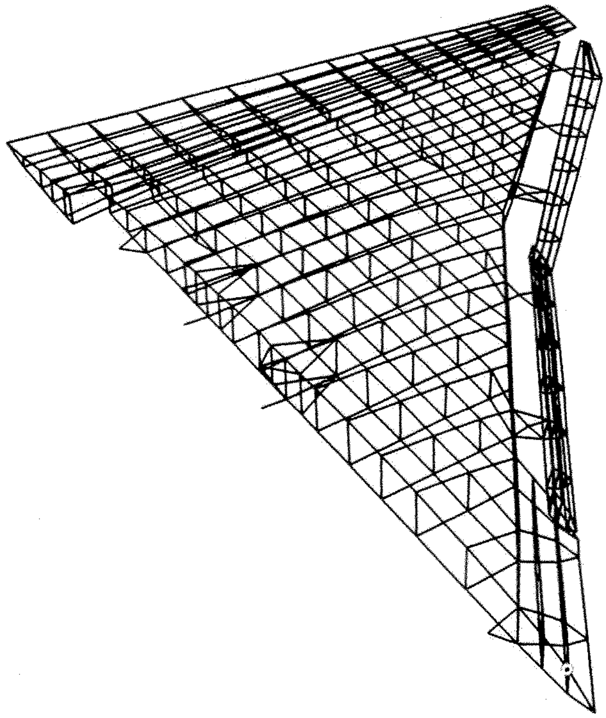


Fig. 11 Finite element model of the X-31 wing

A finite element model of the wing is depicted in Fig. 11. It has 1764 elements and 1871 degrees of freedom. The optimized skin thicknesses were then translated into design drawings with small modifications. As an example, the upper wing skin weight of 53 kg from an initial design (pre-optimized with another program) could be reduced to 44 kg in the FEM, which resulted in 45 kg in the actual design. The final design meets the target weight and has a margin of 100% in airspeed for flutter.

4.3 Aeroelastic Tailoring of a Fin made of Composite Material

An aircraft fin has to fulfill quite different design requirements with a similar priority and the final design requires the evaluation of many off-design point studies [10].

The design of aerodynamic surfaces such as wing, fin, foreplane and tailplane needs two major design steps:

First, the aerodynamic design to define the overall geometry like area, span, aspect ratio, taper ratio and profil.

Second, the structural design to develope the internal structural arrangement of skin, ribs, stringers, spars, rudder support, rudder actuation, attachments, equipment systems.

The final design must fulfill the following design requirements with minimum weight:

- Static strength to withstand design loads
- Aeroelastic efficiencies for performance
- No flutter inside of the flight envelope
- Manufacturing constraints, min. and max. gauges

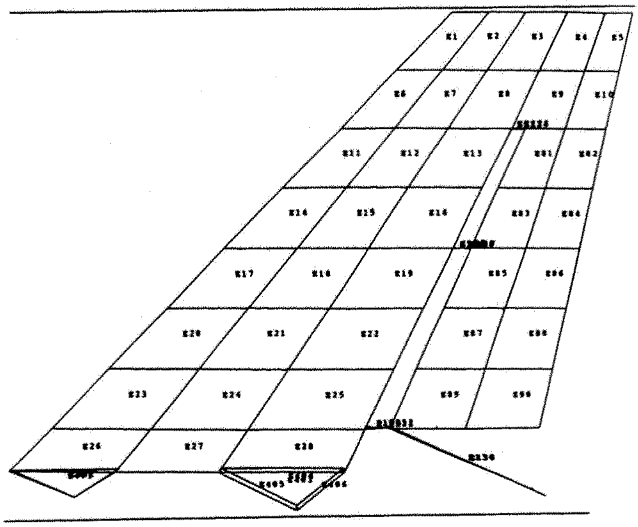


Fig. 12 Fin structural model with skin element numbers

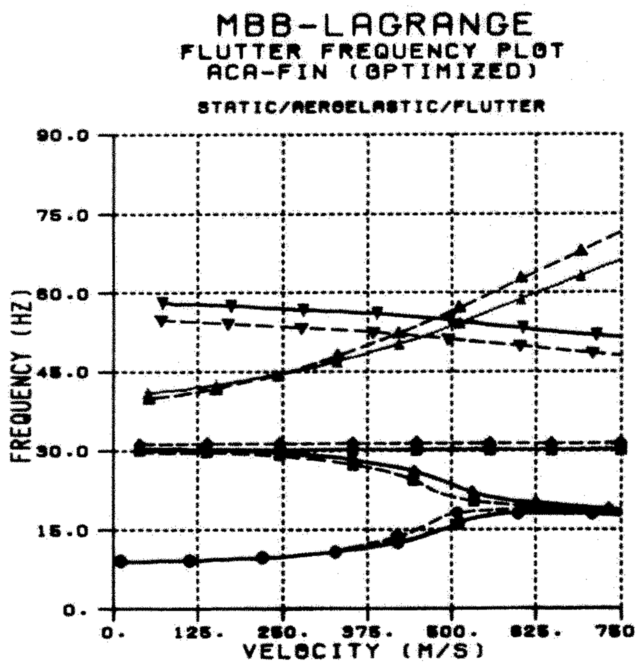
It is quite clear that such a design requires an interactive coupling of the above mentioned two design steps. A structural model of the investigated fin is shown in Fig. 12. A comparison of initial design analysis results and design constraints is given in the following table:

	DESIGN CONSTRAINT	INITIAL DESIGN	VIOLATION
STRENGTH	Strain allowables Tension $\leq .0037$ Comparison $\leq -.0028$	Load case 2 Element 18 Element 22	 -.123 -.228
AEROELASTICS Ma 1.8/750KTS	Efficiencies FIN .8 RUDDER .5	 .753 .441	 -.059 -.118
FLUTTER Ma 1.2/S.L.	Flutterspeed VF = 530 m/sec	495 m/sec	-.066

The frequency versus speed behaviour for the optimized/initial structure is given in Fig. 13. The corresponding damping is plotted in Fig. 14. The results of the optimization procedure are shown in Table 1.

The flutter speed is increased to 530 m/sec and aeroelastic efficiencies are increased 8% for the the fin and for the rudder by 13%. The structural weight is reduced by 7%.

Skin thicknesses for the different carbon fibre layers of the optimum structurl design are presented in Figs. 15-18.



Initial Design: -------- V_{FL} = 495 m/s

Optimized Design: ________ V_{FL} = 530 m/s

Fig. 13 Flutter analysis frequency plot for initial and optimized design

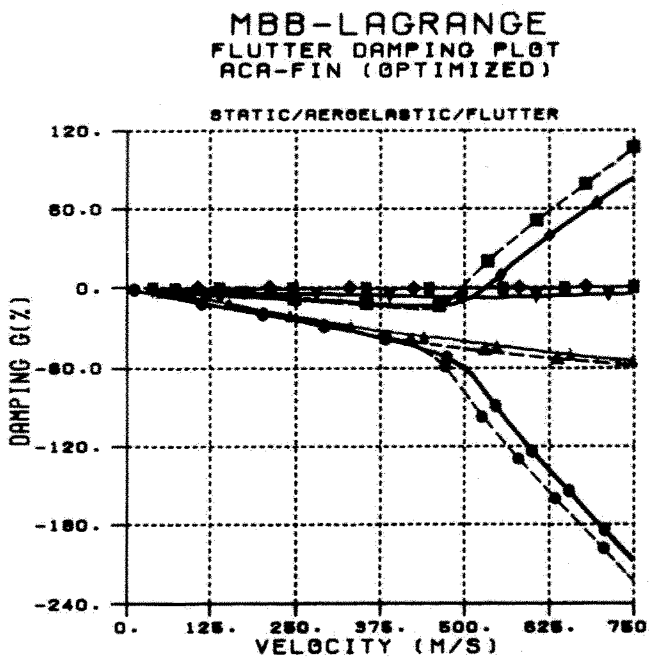


Fig. 14 Flutter analysis damping plot for initial and optimized design

DESIGN	INITIAL CONSTRAINT	VIOLATED DESIGN	OPTIMAL
WEIGHT [kg]			
Structure	99.4		92.9
Non Structure	53.6		53.6
Total	153.		146.5
STRENGTH	Loadcase 2 Element		
	18 - .123 22 - .224	-.123 -.228	
EIGEN-FREQUENCY [Hz]	f1 = 8.90 f2 = 29.83 f3 = 31.16* f4 = 39.97 f5 = 54.86		9.20 30.21(x=1.) 30.61 41.08 58.31
FLUTTER FREQUENCY	fF = 21.22		22.0
SPEED [m/s]	VF = 495.	-.066	530.
AERO-ELASTICS FIN RUDDER	.753 .441	-.059 -.118	.814 .500

* (x=1.)

Table 1: Optimization Results

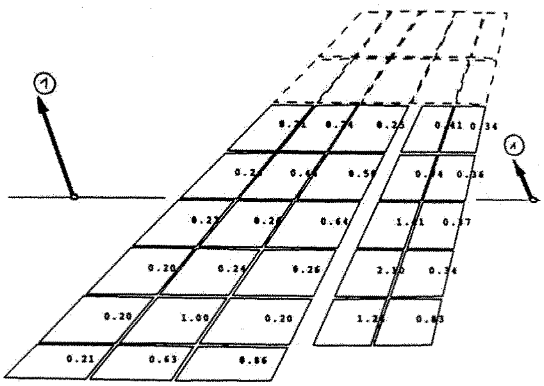


Fig. 15 Aeroelastic design: skin thickness for layer 1

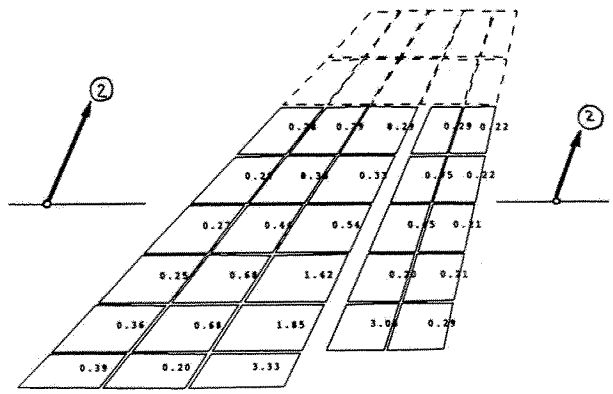


Fig. 16 Aeroelastic design: skin thickness for layer 2

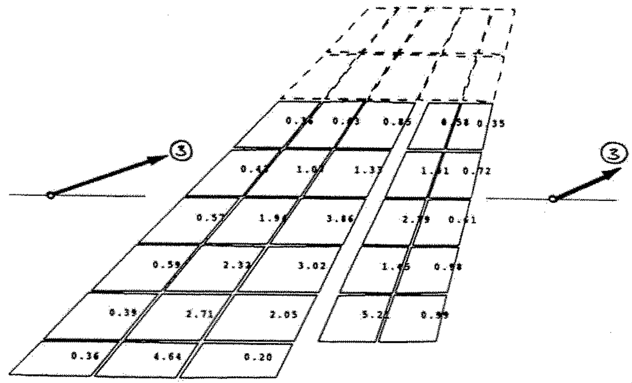


Fig. 17 Aeroelastic design: skin thickness for layer 3

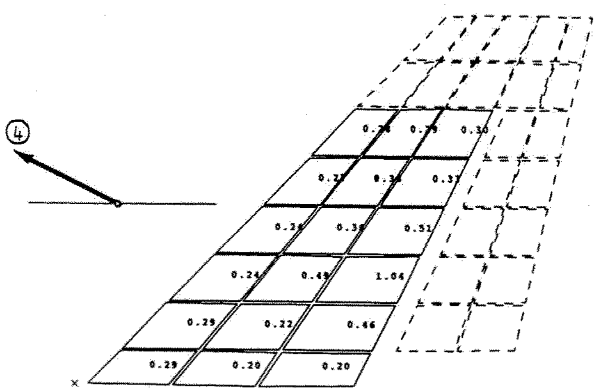


Fig. 18 Aeroelastic design: skin thickness for layer 4

Look Ahead

Further development of MBB-LAGRANGE will be concentrated on the introduction of additional analysis options, computing cost reducing approximation procedures, and new structural constraints including:

- Heat transfer and thermal stresses
- New routines for buckling and global stability
- Dynamic Response
- Effect of FCS on structural phenomena
- Geometry optimization (fiber direction, position of spars)
- Effect of changed loads throughout optimization
- Integration of new disciplines
- Combination of different objective functions
- New optimization routines

For the future, it is a challenge in aerospace engineering to combine design variables, requirements, objectives, and constraints from different disciplines in one optimization program. But it can not be expected and is not desired that there will be one program only for the optimal design of aircraft.

An initial preliminary design should in fact include as many disciplines as possibles. But at the same time, this task must remain in a not too detailed and complex level to allow the investigation of a great number of designs and to answer questions concerning essential changes of design requirements in a relatively short period of time.

After this, the individual disciplines should use their own programs and methods to find the optimum in a more detailed model, without forgetting the neighbour areas.

The preliminary design program could in parallel serve as a tool to integrate the results from detail designs.

Large efforts will be required to reduce the enormous computational costs by the development of efficient methods for cross sensitivity calculations and for approximate optimization procedures.

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