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STRUCTURAL OPTIMIZATION OF AIRCRAFTS
PRACTICE AND TRENDS

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ABSTRACT

After a general presentation of the CATIA-ELFINI tool, developed by DASSAULT, where C.A.D., structural analysis and optimization are fully embedded, we focus on a detailed description of the optimization algorithm. We show the special features of optimization with composite materials.

We present two relevant examples of both structural and aeroelastic optimization on carbon structures of a wing and a fin.

We describe the new organization of design resulting from use of optimization technics.

We recall technics neighbouring optimization as model adjustment and computation with uncertain data.

We conclude by presenting further developments.

1 - INTRODUCTION

The structural optimization technics is a routine process at Dassault since the late seventies. It has been applied for all project from Mirage 2000 to Rafale.

In the past, design of structure was achieved with the "fully stress design" process (F.S.D.) made of iterations of drawing and analyses with reinforcement where the structure is not sufficiently strong and lightening when there are strength margins. Yet with only strength of material constraints on metallic structure it has been demonstrated (see reference 1) that this approach was neither optimum (maximization of stresses is not equivalent to weight minimization) nor efficient for design process. Practically designer is completely unable to intuitate any solution when constraints due to flexibility are involved such as eigen frequencies, aerodistorsion, flutter, and with ply disposal of composite materials.

Therefore we consider that, to-day, the use of mathematical optimization tool is compulsory for the design of aircraft.

We have built the structural optimization tool inside the Dassault software CATIA-ELFINI, it includes :

- the well-known C.A.D. tool CATIA, which gives us geometry and mesh generation
- static finite element analysis for linear and non linear problems
- static aeroelasticity, calculation and management of loads
- linear dynamics : eigen modes calculation, harmonic and transient responses
- non linear dynamics : impact and crash analysis, landing gear and aircraft interaction
- unsteady aeroelasticity, flutter, coupling with flight control system
- fatigue and crack propagation analyses
- heat transfer and thermo elastic coupling
- acoustic and elastoacoustic coupling.

The optimization monitor covers most of theses branches.

The system works on request either in a interactive or in a batch mode, and use a common data base managed automatically.

Some of the main common characteristics of branches are :

- topological dialogue for mesh and every data generation. All properties as connectivities between nodes and elements, geometry connection with CATIA surface element characteristics, etc.., are described by block of constant properties in a space of indices referring node and element. The process leads to very clean meshes for all types of structure from the whole aircraft meshes to tridimensional analyse of fitting details (plates 1 and 2)

GENERAL MESH OF COMBAT AIRCRAFT

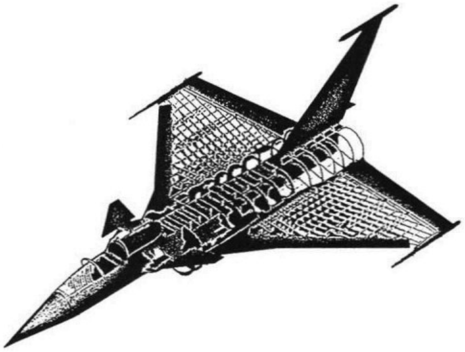


PLATE 1

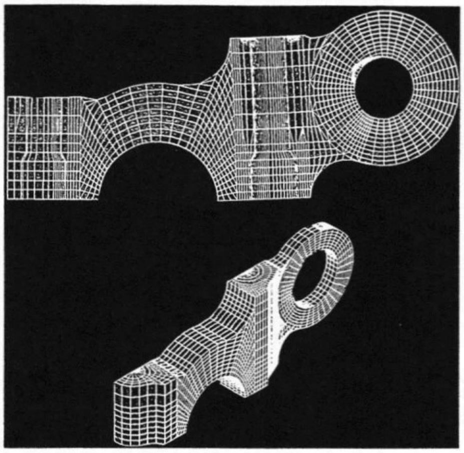


PLATE 2

LANDING GEAR FITTING ANALYSIS

- very wide possibilities of visualization of inputs and outputs, a lot of "wire frame" and "pixel" type of picture for displacement stresses, failure criteria and for optimization design variable, active constraints and safety margin plot (see § 2 Final Touches)

- advanced mathematical solution : the solution of linear problems is run by a very powerful variant of the Frontal Gauss method, which makes relatively trifling the computer time for classical linear problems (about 1' of CPU on IBM 3090-VF for a complete aircraft calculation, see plate 1).

  For 3D massive problems (plate 2) the use of conjugate gradient technics allows to keep the same level of performance, taking into account the contact non linearities.

  For geometric non linear problems (membrane effects, post-buckling, snap through, etc...) an original algorithm called "preconditioned B.F.G.S. with exact line search" has been developed (Ref. 3 and 4). This algorithm benefits directly from the biquadratic character of total potential. It can handle the most severe snap-through conditions (see plate 3 : calculation of post buckling of curved stiffened panel in carbon epoxy material).

  We must underline the strong practical interest of the post buckling analysis, which allows to design thin composite skin buckling before ultimate load.

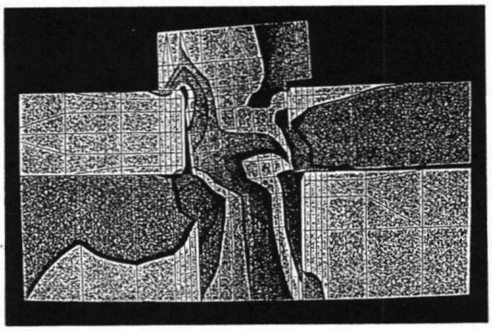


PLATE 3

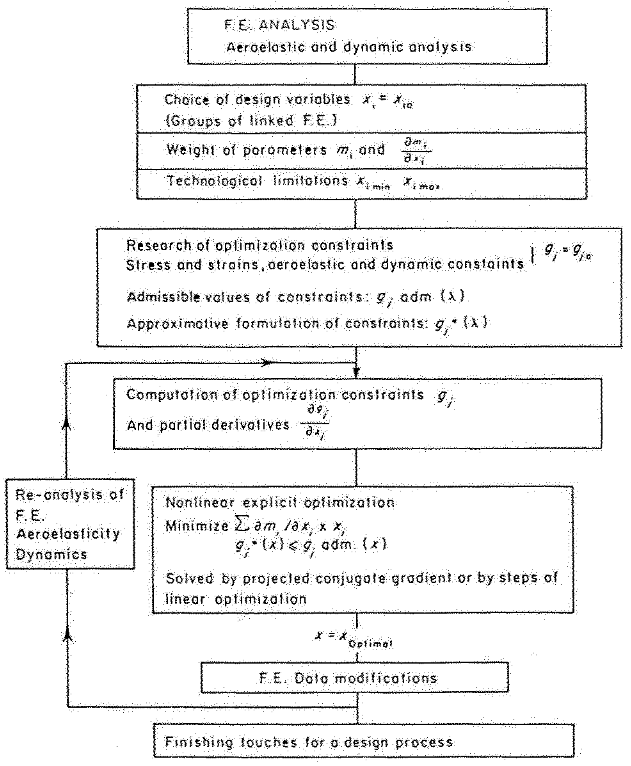
BOLT FATENING

We are going to present a more detailed view of :

- the optimization technics which is mainly used to set the general dimensioning of the structure. It is supported by F.E. models of the whole aircraft which are elaborated only from the rough definition of external shape and internal architecture, the result of this optimization being the starting point of detail drawing,
- the checking analyses which comes with detail drawings,
- the organization for drawing and analysis which results from necessities of composite design and present possibilities of computer tools.

2 - THE OPTIMIZATION METHOD

We have described it in several papers (Ref. 1 and 2) ; now we present the operational tool as it was used for "Rafale" design ; the organization is iterative with the flow-chart below.



- Cost function

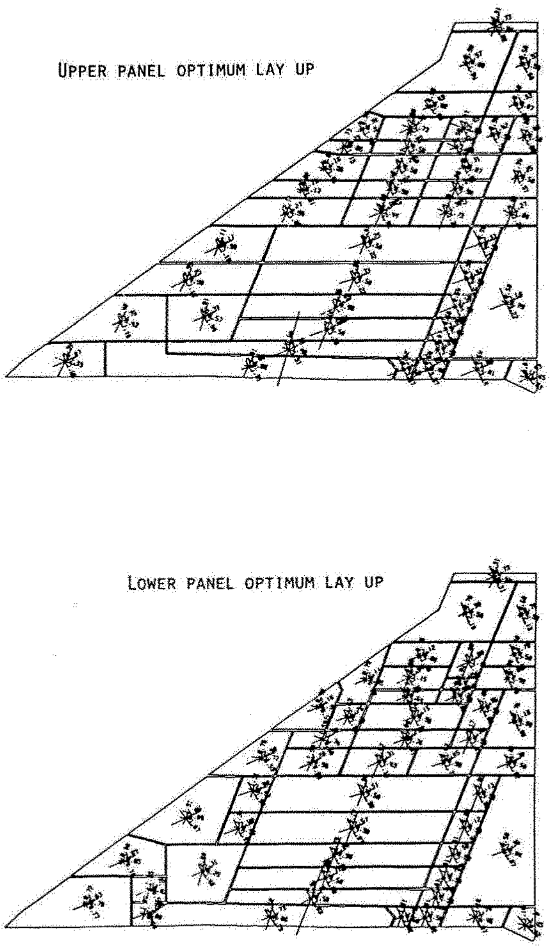
The current goal in optimization is weight minimization. Nevertheless, in some cases, weight can be taken as a constraint, the objective being maximization of safety margin.

- Design variables

The characterization of the optimization design variables is made on groups of Finite Elements (plate 4). The choice of these variables partly takes into account manufacturing constraints and tooling rules for metallic material.

OPTIMIZATION OF A CARBON-EPOXY WING

PANEL DESIGN VARIABLES


UPPER PANEL OPTIMUM LAY UP

LOWER PANEL OPTIMUM LAY UP

PLATE 4

For a composite material, the design variables are the number of plies in each direction for each group.

The number of design variables often reaches 500, which can act simultaneously over several analysis models.

FINITE ELEMENT ANALYSIS

Displacement computation :

$$X = [K]^{-1} F$$

Strength, stress computation :

$$\sigma = [\frac{\partial \sigma}{\partial X}] X$$

OPTIMIZATION CONSTRAINT DERIVATION

Displacement derivation :

$$\Delta X = - [K]^{-1} [[\Delta K] X - \Delta F]$$

Strength, stress derivation :

$$\Delta \sigma = - [\frac{\partial \sigma}{\partial X}] [K]^{-1} [[\Delta K] X - \Delta F] \quad (1)$$

$$\Delta \sigma = - [[K]^{-1} [\frac{\partial \sigma}{\partial X}]^{t}] [[\Delta K] X - \Delta F] \quad (2)$$

(1) number of resolutions equal number of load cases

(2) number of resolutions equal number of constraint operators

Table 1

- Constraints and "sensitivities"

Constraints inequations come from the different analysis branches of ELFINI, we can consider simultaneously :

. Various failure criteria (including composite materials), computed from static stresses for all the dimensioning cases of loads
. Local buckling criteria
. Limited displacements
. Aeroelastic variation of aerodynamic derivatives
. Dynamic natural frequencies
. Flutter speed and aeroelastic dynamic damping
. Various technological constraints (as minimum values of design variables, and limitations of the thickness variation between adjacent design variables).

The constraints considered during the same optimization can come from several analysis models (ex : symmetric and anti-symmetric F.E. aircraft model, local buckling analysis by Rayleigh-Ritz method, local refined F.E. analysis , different external store configurations for dynamic and flutter, variation of shape due to control surface deflections, etc.).

We call "sensitivities" the derivatives of constraints in function of design variables. The principle of ELFINI optimization is to compute these derivatives by a correct mathematical process. It can easily be demonstrated, (see table 1 and references 1 and 2) that the computation of derivatives of static stresses, displacements, and aeroelastic coefficients is equivalent to solutions with "dummy" case of loads.

The number of this dummy case of loads is :

- number of loading case x number of design variables if formula 1 of table 1 is used
- number of constraints if formula 2 is used.

For practical problems this number of dummy case of load reaches currently several thousands, and their resolution does the main part of computer cost of optimization.

When constraints are eigenvalue or are directly related to eigenvalue (e.g. eigen frequency, linear buckling load, divergence or flutter speed, aeroelasticity damping) the cost of their derivation is neglectible (see tables 2 and 3 and references 1 and 2). But we must underline that these derivations need a far more accurate calculation of eigenvectors than those needed for eigenvalue analysis only. Within the same range of ideas, we have noticed that it was very difficult to compute with proper accuracy derivations of solution of problems treated with the classical modal basis reduction (e.g. dynamic response, aeroelasticity), practically it would be necessary to compute the correct mathematical derivative of vectors. This is mainly why we have developed an approach of static aeroelasticity without basis troncature effect (see ref. 1), it leads to a mathematically exact and low cost calculation of derivatives.

DERIVATION OF EIGEN VALUES

ANALYSIS

- eigen modes : V_i
- eigen values : ω_i

$$[[K] - \omega^2_i [M]] V_i = 0$$

SENSIVITY ANALYSIS OF EIGEN VALUES

$$\Delta [V_i^t [[K] - \omega^2_i [M]] V_i] = 0$$

$$2 V_i^t [[K] - \omega^2_i [M]] \Delta V_i +$$

$$V_i^t [[\Delta K] - \omega^2_i [\Delta M]] +$$

$$\Delta \omega^2_i V_i^t [M]] V_i = 0$$

$$\Delta \omega_i = \frac{V_i^t [[\Delta K] - \omega^2_i [\Delta M]] V_i}{2 \omega_i V_i^t [M] V_i}$$

Table 2

- Mathematical optimization

Starting from the analysis and derivation of constraints, we use an explicit non linear approximation of the constraints in terms of the design variables, mainly the formulation in inverse variables. Taking as new variables inverses of design variables, it leads to minimize an homographic function (weight) subject to linear inequations. This problem is easily solved by projected conjugate gradient algorithm. The cost of the mathematical optimization step is low.

The mathematical optimization step gives a prediction of the optimum, from which we start new iterations.

The number of iterations, needed to get the global convergence, ranges from 3 to 5 (see plate 4).

The cost of all the iterations of optimization ranges about 8 to 15 times the cost of the analysis.

- Final touches

Generally the theoretical optimum obtained from the optimization algorithm needs some modifications, since it does not often represent a realistic design. Starting from the table of constraints derivatives, the final touches consist in examining interactively the effect of small modifications, directly given by the designer during the drawing. The program instantaneously shows the picture of new safety margin and violated constraints (see plate 6).

We can also interactively rerun the mathematical optimization step after changing assigned value of constraints.

3 - SPECIAL FEATURES OF OPTIMIZATION WITH COMPOSITE MATERIAL

The organization described above is well suited for a composite material with the addition of following specificities.

- Failure criteria analysis and derivation

Inside the optimization loop we use failure criteria of the "Tsaï-Hill" family as :

$$C = \sqrt{\left(\frac{\sigma_x{}^2}{\sigma_{xad}{}^2} + S_1 * \frac{\sigma_Y{}^2}{\sigma_{yad}{}^2} + S_2 * \frac{\tau_{xY}{}^2}{\tau_{xyad}{}^2} - S_3 * \frac{\sigma_x \sigma_Y}{\sigma_{xad}{}^2}\right)}$$

with

σ_x, σ_y and τ_{xy} : stress tensor components

σ_{xad} , σ_{yad} , τ_{xyad} and $S_i = 0$ or 1 : criteria parameters

Arguments of criteria are adapted to each situation (eg : tension, compression, bending, holed panel, etc...), by calibration on more sophisticated criteria and on test results.

Due to the fact that, at a given point, the final failure mode is not known beforehand, it is necessary to handle constraints on all potential failure modes simultaneously.

This is achieved at a relatively low cost if the derivation is performed in two steps :

- compute strain tensor and its derivative by formula 1 of table 1 (3 components common to all plies with membrane assumption),
- starting from strain tensor and material Hook law, calculate ply by ply failure criteria and their derivatives.

- Local buckling criteria

Even if optimization can handle directly global buckling, for management and cost effectiveness it is generally preferable to calculate and to derivate local buckling criteria with the following post-processing analysis :

- On the general finite element model, calculation and derivation of stress flows of structural meshes,
- Local buckling load factors and their derivatives calculation by a Rayleigh Ritz method (see table 3).

Sizes of meshes for local buckling analyses are independent from their representation in the global F.E. model, and they can be tuned to be suited to the actual stiffening.

LOCAL BUCKLING ANALYSIS
BY RAYLEIGH-RITZ METHOD

RAYLEIGH-RITZ MODEL

External load fluxes : $\Phi = \begin{matrix} \Phi_{x0} \\ \Phi_{y0} \\ \Phi_{xy0} \end{matrix} = \rho\, \Phi_0$

Normal deflection :

$w = \sum a_{mn}\, x^i.x^j.L\,(x,y) \qquad V = \begin{matrix} a_{11} \\ \dots \\ a_{mn} \end{matrix}$

BUCKLING FACTORS

Buckling initiation : $W_1 = W_2$

W_1 = Bending elastic energy
W_2 = Membrane work of external loads ($W_2 = \rho\, U_2$)

$W_1 = \rho\, U_2$

$\min \rho = W_1 / U_2 \iff \partial W_1/\partial V - \rho\, \partial U_2/\partial V = 0$

$[\, K - \rho\, G\,]\, V = 0$

DERIVATION OF BUCKLING FACTORS

$$\rho = - \frac{V^t.K(\lambda).V}{V^t.G(\Phi).V}$$

$$\frac{\partial \rho}{\partial \lambda} = - \frac{V^t.\partial K/\partial \lambda.\ V}{V^t.G(\Phi).\ V} + \rho\, \frac{V^t.\partial G/\partial \Phi.\partial \Phi/\partial \lambda.V}{V^t.G(\Phi).V}$$

Table 3

In the optimization loop, stacking sequences are not taken into account (assumption of material homogeneity through panel thickness), this for the sake of algorithm simplicity, and due to difficulties to express lays covering and stacking constraints in drawing.

The order of buckling modes can change between iterations ; this can cause a non convergence of iterations if all potential buckling modes are not controled simultaneously (see reference 2).

- Design constraints

These constraints express the fact that results of optimization must correspond to a real drawing of composite panel, which must be made of stacked layers with special rules for easy manufacturing.

Design constraints are handled at two levels :

. Inside the optimization loop, as by placing constraints checking a minimum number or a given minimum proportion of plies in each direction, or a maximum slope of thickness (constraints corresponding to linear inequalities on design variable),
. After mathematical convergence, by automatic thicknesses rounding off to get a whole number of plies, and by a special half interactive program which transforms the stacking of plies by area, which are the rough output of optimization, into a proper cut out of layers.

4 - EXAMPLE OF APPLICATION OF OPTIMIZATION OF CARBON EPOXY STRUCTURE

We present two significant examples of optimization calculation of carbon epoxy parts for a combat aircraft.

- Optimization of a combat aircraft wing

We resume here the configuration of the optimization of a carbon epoxy Delta Wing box, corresponding to the mesh presented on plate 2, with the design variable patch of plate 4.

We had used two analysis models for static and aeroelasticity with the survey of flutter on three external load configurations.

	MODEL 1	MODEL 2
F.E. models	wing model with a representation of other part of the aircraft by super element technique (3544 DOF) symmetric and antisymmetric analysis	complete plane 13003 DOF symmetric and antisymmetric analysis
Design Variable	476 Design Variable (Number of plies in 4 directions)	
Static cases of loads	24 cases of loads combined from symmetric and antisymmetric	0
Failure criteria	476 failure criteria equivalent "Tsaï-Hill criteria"	
Buckling criteria	144 critical buckling factor issued from 77 local buckling analyses of composite plates by Rayleigh Ritz method	0
Static aeroelastic constraint	0	7 control surface efficiencies and minimal roll speed
Flutter		5 flutter speeds and 60 aeroelastic dampings corresponding to 3 external load configuration
Technological constraint	374 constraints on composite lay-up (thickness shape, maximum and minimum ratio between each ply direction)	

On plate 5, we present the history of convergence in weight. Drawing constraints and flutter constraints have been successively introduced later in order to see their influence. The optimum values of design variables are presented plate 4.

We present on the table above weight sensitivities of wing panels to typical project hypothesis obtained by optimization.

OPTIMIZATION OF CARBON EPOXY WING
HISTORY OF CONVERGENCE

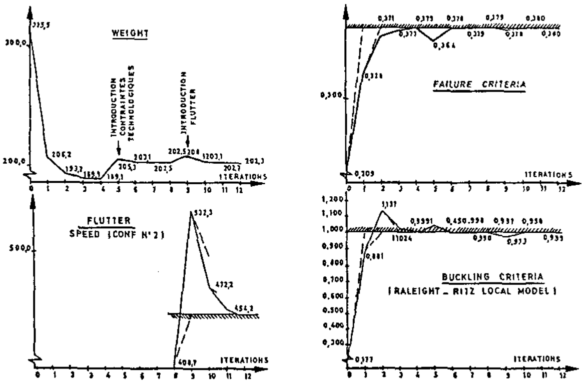


PLATE 5

Design Hypothesis		weight (ratio)
1	Composite material Strength of material constraints only, rough from computer optimization	1.
2	+ Aeroelasticity constraint	1.19
3	+ Aeroelasticity + Technological constraints	1.25
4	Weight from final detailed drawing (review by checking analyses)	1.36
5	Aluminium alloys solution Strength of material + Aeroelasticity (comparable with 3)	2.10

OPTIMIZATION OF CARBON EPOXY FIN

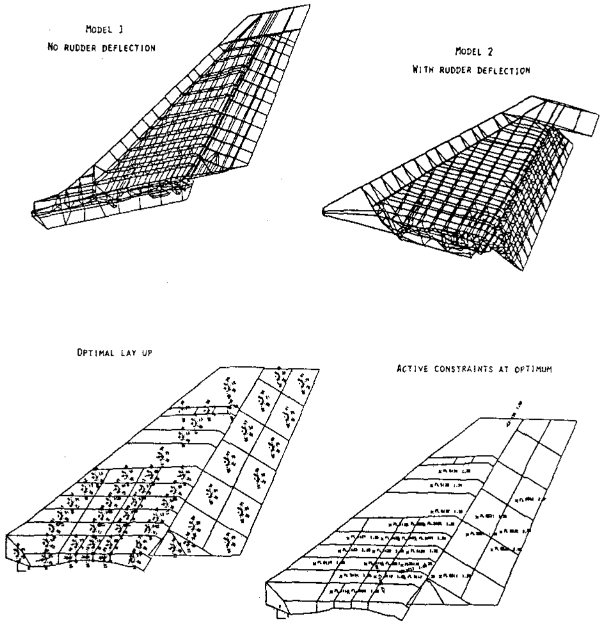


PLATE 6

- Optimum design of a vertical fin

The lay out of the box and the rudder in carbon epoxy are optimized considering static cases of load for two rudder deflection cases, and constraints on rudder aeroelastic efficiencies and dynamic frequencies, see plate 6.

The exact configuration of this optimization follows :

	MODEL 1	MODEL 2
F.E. models	Fin model (1800 DOF) with a super element of the whole aircraft	Fin model with a deflected rudder
Design Variables	237 Design Variable on the number of lay, spars and ribs flanges (area) and web (thickness)	
Static Load cases	3	1
Failure criteria	190 failure criteria on composite materials with holes	190
Buckling criteria	98 buckling criteria computed from Rayleigh Ritz models for panel buckling analysis	82
Displacements	1 on the step between box and rudder	0
Aeroelasticity	8 constraints on fin and rudder yaw efficiencies for two Mach number	0
Dynamic	Frequencies of 1st flexion mode and rudder mode	0
Technology	107 constraints on plies distributions and on minimum distance between lay interruptions	

5 - CHECKING ANALYSIS

It must be understood that, if optimization tool is essential to reach rationally a good general drawing, the result must be justified in detail with more complex analyses than those which can be handled inside the optimization loop. The most typical of these checking analyses are the following :

- Effect of local loads (e.g. fuel tank pressures, vibration, thermal load, etc.)
- Local fatigue analysis
- Damage tolerance analysis
- Detailed local analysis of holed composite panel (e.g. point stress analysis)
- Post buckling analysis

Design constraints corresponding to these details checking analyses have been simplified to be handled by general optimization. These simplified assumptions must be validated by local checking analysis.

Effects of calibration of these constraints can be examined with Lagrange multiplier of active constraints (handled interactively by "Final Touches" modules) or by replay of Mathematical optimization step.

6 - ORGANIZATION OF DESIGN PROCESS

Now we have the following organization for design of composite structures, from the preliminary project to the delivery of manufacturing drawings :

. *Start from a CATIA drawing of only external* shape and a brief definition of internal architecture

. Elaborate, by CATIA-MESH, a first simple general F.E. mesh of the whole aircraft (10-30000 D.O.F.) with approximate cross sections and thicknesses (see plate 2). The model is adjusted with simple cases of load

. Static aeroelasticity and loads, which give the envelope cases of loads and show the latent problems of aeroelasticity

. Examination of internal load fields and stresses for selection of "strength of material" constraints in optimization

. Dynamic modes computation with the various external store configurations, flutter problem recognition

. First run of optimization

. Drawings of the structure supported by :
  - interactive test of authoritative modifications of results of optimization to make drawing easier, this with the final touches module,
  - changes and additions of constraints,
  - critical examination of "cost of requirements", directly obtained from "Lagrange multipliers" of optimization. It allows to appreciate the influence of safety margin on certain criteria (e.g. : composite materials),
  - detail checking analyses supported by methods described above in § 5. They are performed taking proper boundary conditions in the Finite Element model of the whole aircraft via a super Element technics. Detail checking analyses must validate the simplified criteria used for mathematical optimization ; otherwise optimization must be replayed with calibrated criteria.

Although a single run of optimization in production last no more than a few C.P.U. hours, for the Rafale design the optimization job have remained inside the computer more than six months, in order to examine detail analysis effects, the influence of the choice of constraints and alternative designs.

7 - NEIGHBOUR OF OPTIMIZATION : IDENTIFICATION AND COMPUTATION WITH UNCERTAIN DATA

The solution of these problems can be considered thanks to possibilities of elaboration of sensitivity table.

- Model adjustement

A typical example of these technics is the adjustement of F.E. dynamic model to measured natural modes ; the unknowns are design variables of local thickness and mass, modal deformation and frequencies ; the modal equation appears as an equality constraint, the objective is to minimize a "distance" from measured to computed mode ; the method don't need the knowledge of connection between computed and measured modes.

- Computation with uncertain data

Sometimes, at the start of any problems, we have an imprecise knowledge of data ; the idea of computation with uncertain data is to search the "worst" point in the uncertain design variable space.

The problem is solved by two approaches :

. find the "worst" possible point by minimization of a safety margin function inside the authorized space of design variable variations,

. if it exists a possibility of failure, compute the probability of failure, starting from probability density of design variables.

Now we have started to apply these ideas on flutter and vibro-acoustic analysis of preliminary projects.

8 - FURTHER LEVELS OF OPTIMIZATION

The general tendency is to introduce progressively all the "arguments" of structural design in the optimization loop.

The next steps of development follows :

- Optimization with "bending" design variables

It doesn't give rise to any theoretical difficulties ; the relative complication comes from the non linear dependance of stiffness, neutral surface and constraints on design variables, which complicates program writing.

- Optimization with post-buckling analysis

It is one of the most important lack of the present operational optimization. Now we get round the difficulty, by an empiric adjustment of the load level of linear buckling ; we only verify results of optimization by post-buckling analysis.

The correct solution is not a lot more intricate than that of bending case ; it can easily be demonstrated that the derivation cost is almost that of linear problem ("dummy" cases of load at the final equilibrium state).

- Shape optimization

It is needed by a lot of practical problems of varying difficulty (shape of stiffeners, pressurised vessels, fitting, etc.).

The main difficulty is to express design variables and "topological" constraints.

For the above problems, many authors and ourselves have elaborated specimen programs running on academic cases, but to have a really operational tool, it is necessary to introduce geometric design variables and the associated "topological" constraints at the level of CAD system, this need important investments.

- Optimization in heat transfer problems

One of the necessity of Hermes project has been to put thermal analysis at same level of sophistication as structural analysis ; immediately after we have met the need for a thermal optimization tool.

The general arrangement of thermal optimization is the same as in structural optimization, the complications are in the transient and highly non linear character of thermal problems.

Fortunately it can be demonstrated that temperature derivation needs the solution of the same differential linear equation system for all design variables and, integrated at the same time as the analysis, it doesn't need additional factorization. Therefore the cost of derivatives is relatively lower than that of static elasticity problem.

Jointly we develop heat transfer identification process and also computation with uncertain data, particularly needed by the random or badly known character of a lot of data.

- Multidisciplinary interactions

For a combat aircraft, the idea should be to optimize at the same time : structure, cut out of control surfaces, actuators and hydraulic power, parameters of electrical flight control system, and aerodynamic shape.

For the moment this state of grace is not yet reached, but tendency is to apply optimization to each discipline and to proceed in relation to the other matters by "fixed point method" or by simplification of interactions. So starting from Lagrange multipliers issued from the optimization of each discipline, it is possible to "condense" their interactions ; for instance, as far as structure is concerned, we can easily give the weight cost of requirements of other disciplines (exchange rate between structure weight and roll speed, profile relative thickness, etc.).

9 - CONCLUSION

The tendency would be to include more and more detailed analyses inside the mathematical optimization loop. This evolution is hindered by the difficulties of the task.

The tool described above represents the achievement of the first level of structural optimization, where geometry is given and mass and stiffness matrices are linear functions of design variables.

Significant progress is not easy. It corresponds to including inside optimization :

- "bending" design variables
- non linear and post-buckling analysis, rules of effective width
- stacking order of plies and constraints on layers cut out of composite material
- shape optimization, which is also implicitly necessary in the above functionalities.

Independently from their theoretical difficulty these developments need a higher level of integration of F.E. optimization with C.A.D. ; in particular the architecture of C.A.D. system must support the description of design variables and of drawing constraints.

Another promising field of research is to use technics of artificial intelligence to pilot the design, it seems to be one mean to manage optimization with discontinuous evolution of design variables. Presently we have started the development of this technics at the level of check sizing of carbon fiber panels. It rests on a knowledge basis composed of rules, referring technological constraints and methods of calculations.

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