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From Structural Optimization to Multidisciplinary & Multilevel Optimization

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***Abstract*:.** *We present the state of the art of optimization techniques used through the design process of our aircraft, focusing on the airframe studies.*
We begin by recalling the main features of our ***multilevel design process*** *from global to detail, with the presentation of* ***"Definition Models"*** *and* ***"Analysis Models"*** *used at each level.*
In this context we show the present place of mathematical optimizers at each level, used mainly both for design sizing, and for creating natural links between levels of definition (condensation of sized details via Lagrange Multipliers). Then we evoke the main axes of R&D : ***adaptation of CAD/CAE tools*** *for easy handling of Design Variables, generalization of the* ***Feature Modeling*** *techniques to analysis/sizing, strategies of* ***Multilevel/Multidisciplinary Optimization****, mathematical techniques for* ***Robustness Analysis****.*
We conclude by noting the present maturity of environment for the generalization of mathematical optimization techniques through the whole aircraft design process.

1. Introduction

Mathematical optimization methods have been used at Dassault Aviation since the mid 70ies for design of military aircraft.
They have been the most developed and industrially practized in the domain of structural sizing where they have reached rapidly an appreciable level of multidisciplinarity with the simultaneous consideration of design constraints from mechanical strength and stiffness, static aeroelasticity and flutter, vibrations, ...(see ref. 1, 2, 3.).
Mathematical optimization have also found appreciable application in other fields, in particular :

- Optimization of aerodynamic shape (drag, flow separation constraints, see ref. 4.).
- Tuning of Flight Control System parameters for flexible aircraft.

Hereafter we present a reflection on the generalization of these mathematical optimizations to support the aircraft design ; this reflection cannot be separated from the consideration of the whole design process of aircraft. This leads to analysing the multilevel/multidisciplinary organization of this process to identify the present and potential places and types of mathematical optimization steps.
The presentation focusses mainly around the branch of airframe studies, yet it can be easily generalized to other skill process.

2. Multilevel/multidisciplinary Organization of design process

These types of organization have been more or less explicitly formalized by all aircraft manufacturers to face the complexity of our product design ; it consists in a progressive definition of the product, by levels, from global to detail which is symbolized on plate 1.

Multilevel Organization of Design

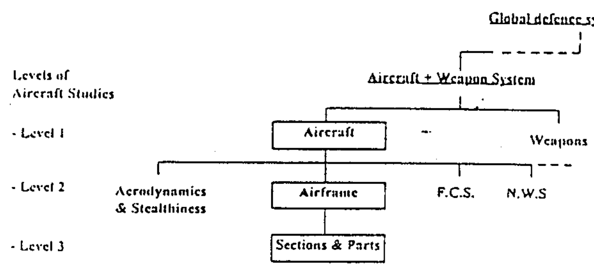

Plate 1

In this organization, the airframe studies are spread on 3 levels :

- level 1 : **"Aircraft"** design
- level 2 : **"Global Structure"** design
(global studies in other disciplines as : Aerodynamics, Stealthiness, Flight Control System, Navigation and Weapon System, ..., are placed on the same level).

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- level 3 : **"Detail design"** of sections and parts.

At each level a **"Product Digital Model"** is built which can be conventionally decomposed in :

- one **"Definition Model"**, describing the considered product/subproduct with the ad-hoc fineness
- several **"Analysis Models"** allowing to demontrate that the defined product meets its requirements.

The design process is made of study iterations :

- at each level, for sizing and comparizons of alternative solutions
- between levels mainly for validations or calibrations of analysis models or data
- through several disciplines at the same level in case of strong design coupling

We briefly present the types of "Definition Models" and "Analysis Models" handled at each level of the branch of structure studies.

- **Level 1 ("Global Aircraft" Design)**

- **Definition model**

It corresponds to a list of few hundreds of design variables gathering :

. Classical global definition parameters as Architecture typology and associated main geometrical characteristics (ex : wing span, chord, relative thickness, ...)
. Global characteristics (performances and demands) of subsystems / equip-ments (e.g. engines, sensors, ...)
. "Intermediate" performances (e.g. structural weight and other components of weight breakdown, fuel volume, electrical / hydraulical power break-down,...)
. Aircraft performances (e.g. range, payloads, take off length, ..., eventually cost).

The part of the design variables corresponding to geometrical informations can be automatically visualized via a specific **"feature modeler"** calling our general C.A.D. tool CATIA (see plate 2).

Level 1 : Global Aricraft Definition

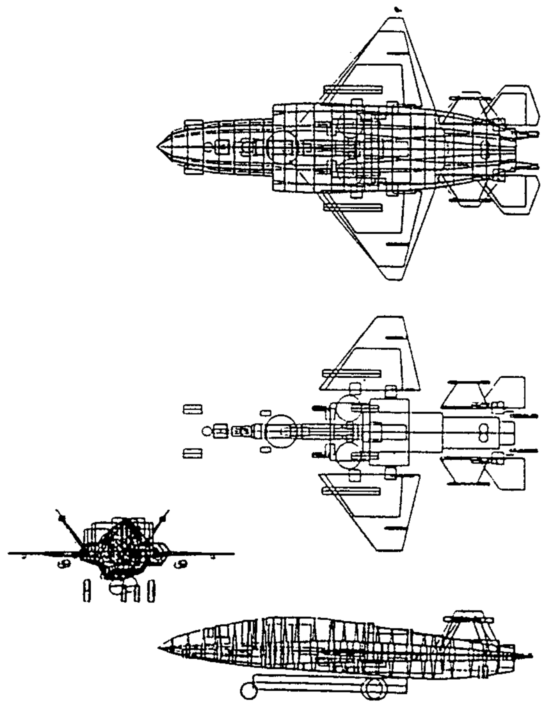

Plate 2

- **Analysis Models**

At level 1 analysis models correspond to **behaviour models**, most often formalized by explicit mathematical formulae linking Design Variables corresponding to approximate evaluations of "intermediate" and global aircraft performances.
These behaviour models (and the corresponding subsystem data) must be validated and calibrated on the results of level 2 detail sizing.

At this stage the structure subsystem is only represented by few architecture and shape data and by the behaviour model of structural weight (function of shape arguments, maneuver domain, operational weight, for a given architecture typology).

The sizing at level 1 consists in finding a set of Design Variables satisfying both aircraft performance requirements, presumed subsystems characteristics and performances, and all the equations representing analysis models. In § 2 below, we show and discuss how it amounts to a canonical mathematical optimization problem.

- **Level 2** (Global Structural Design)

- Definition Model

Today it corresponds to a C.A.D. drawing of the general structural lay-out and of main equipment arrangement, under the form of CATIA objects with attributes indicating selected technological principles (materials, types of stiffening, ...).

An example of Level 2 structural model is presented plate 3 (Hermes Shuttle). Although the definition Design Variables of level 2 models are not explicit, we can notice that the number of hidden implicit Design Variables (see Feature Modeling in § 5) is at least two orders of magnitude greater than in level 1 model.

Level 2 : Global Airframe Definition

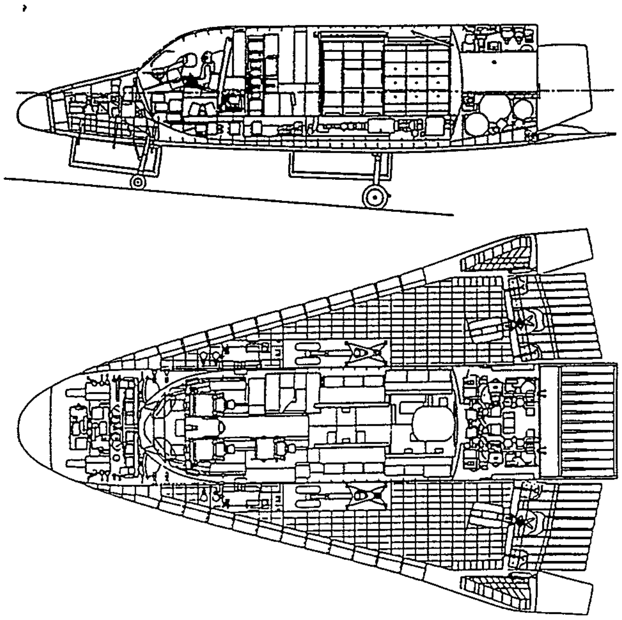

Plate 3

- Analysis Models

Here the main model element is the **Global Finite Element Model** of the whole aircraft (see plates 4, 5, 6) supporting global analysis of :

. Static aeroelasticity and flutter (see ref. 1, 2, 3),

. Flight and Ground loads,

. Internal loads and average structural strength.

These analyses include interactions between structures F.C.S., aerodynamics and sensors.

Global Finite Element Model : Hermes Shuttle

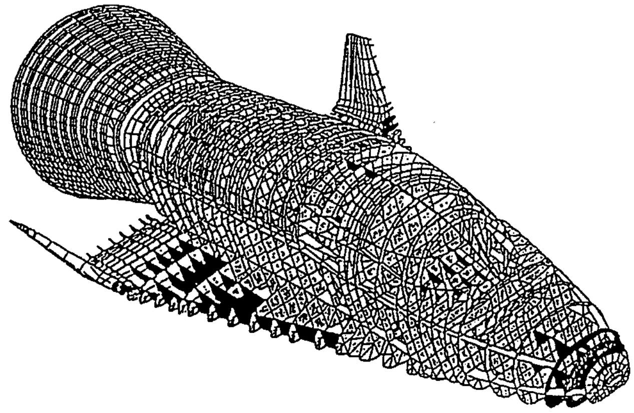

Plate 4

Level 2 : Global Finite Element Model - Combat Aircraft

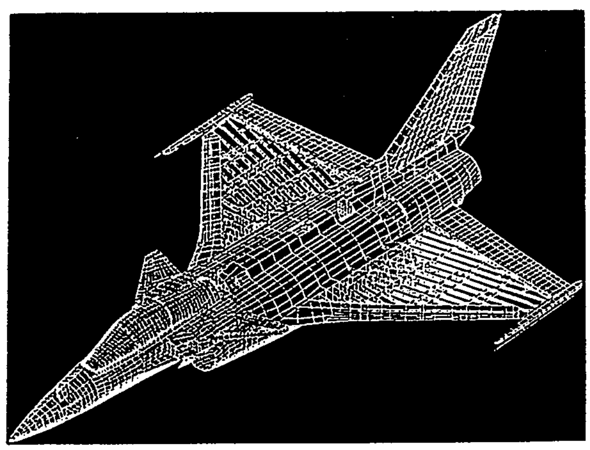

Plate 5

Aeroelastic Deformation - Mach 0,9

9 g load factor (x5)

Roll 260°/s (x8)

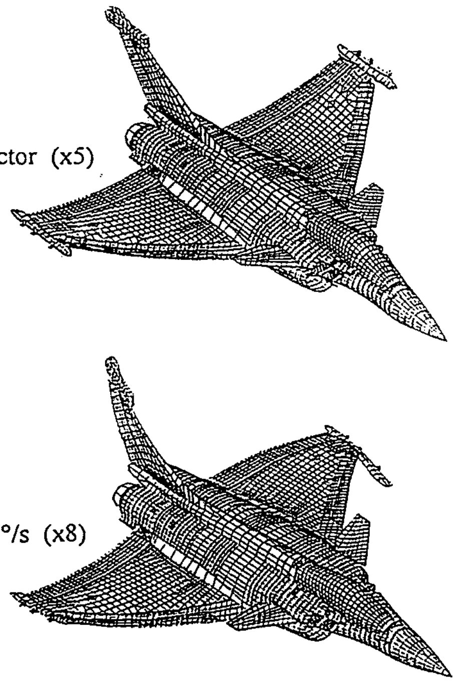

Plate 6

- **Level 3** (Detail Design of sections and parts)

- **Definition Model**

At this level, it is the CATIA Digital Mock-Up, assembly of 3D solid representation of all parts and of all equipments, including wires, pipes and mounting (see plate 7), the definition fineness must be relevant both to support demonstration of detail design requirements (→ Verification File) and to provide definition informations for manufacturing and all downstream activities (procurement, support, ...).

We remark that the number of implicit hidden Design Variables still multiplies by two orders of magnitude in comparison with level 2 definition.

- **Analysis Models**

At level 3 structural analysis models became sophisticated local non linear Finite Elements models, coupled with the global F.E. model of the aircraft by a technique of model nesting ("Super Element" technique, or load/ displacements boundary conditions), main types of analyses are :

- **2.5 D** (bending elements)
  Large displacements, post buckling, plasticity analysis with "bolt by bolt" meshes (mesh step ~ ½ fastener step),
- **3 D** detailed fitting and fastener analyses with plasticity and contact effect,
- **Dammage tolerance** analyses (crack propagation on 2.5 D or 3 D models),
- **Dynamic impact analyses,**

see plate 8

Very often these detailed numerical models must be associated with **experimental models** (partial and material elementary tests) for calibration of strength criteria (strength criteria in fastening area remain the weak point of the structural analysis chain).

Level 3 : Digital Mock-Up

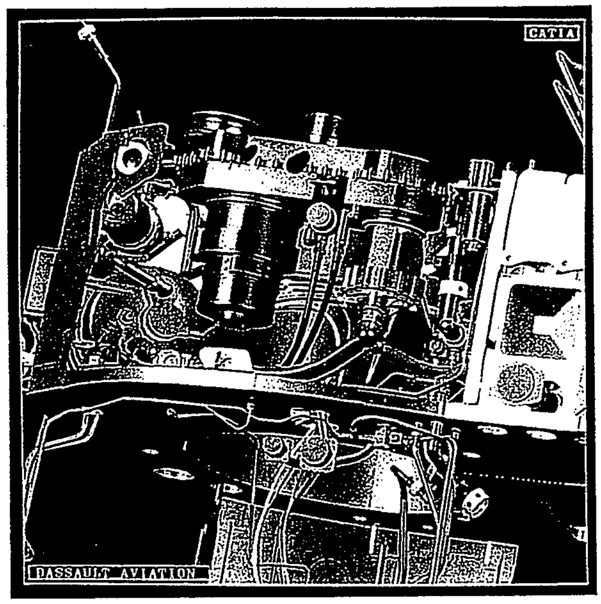

Plate 7

Level 3 : Detail Finite Element-Analysis

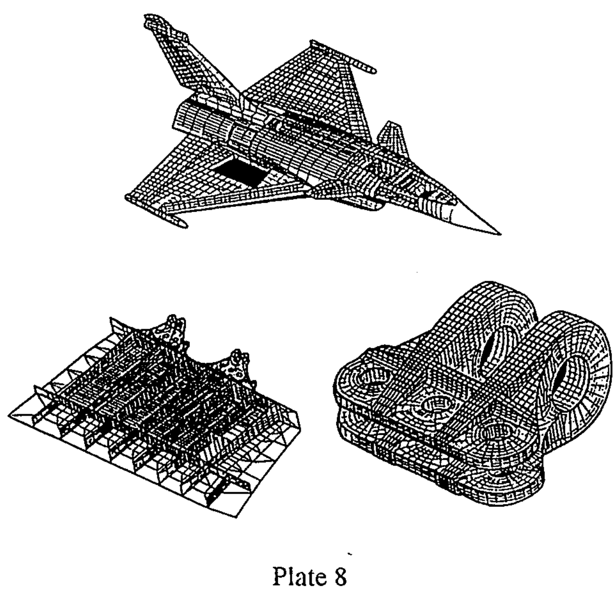

Plate 8

3. Sizing with mathematical Optimizers

Presently the use of mathematical optimization techniques inside the whole design process remains partial.
At every levels "Architecture" choices remain driven by engineer intuition and experience, mathematical optimization appears essentially for "sizing" within the frame of given topologies.

- **At level 1** the organization of the definition model with formalized Design Variables linked by explicit mathematical formulae allow the direct use of classical mathematical optimization packages (c.f. ref. 5) for complete or partial "presizing".
In the practical cases where we are more interested in finding possibilities of solutions within the field allowed by design constraints, than in maximizing any objective function, we use a technique of constraint propagation in subdefinite domain (see principles in ref. 6).
The main point at this stage is the flexibility of the tool which can be run for hundreds of hypothesis sets (influences of aircraft requirements, subsystem performances, robustness analyses, ...), input and output of design problem can be interchanged.

- **At level 2**, ordinarly we use the optimization monitor of our ELFINI tool.
It runs on the global Finite Element Model connected with aeroelasticity, loads and strength analyses, its main features are :
. cost function : mass (most often)
. design variables (few hundreds to few thousands) : Sections, thicknesses, number of plies in each direction for composite material, for group of associated Finite Elements.
We have recently added geometric shape parameters :
- constraints (few thousands to few hundreds of thousands) :
  . local strains, stresses, strength criteria, internal loads,
  . buckling criteria,
  . static aeroelasticity effects (→ flight qualities),
  . dynamic responses,
  . flutter margins,
  . ...

see plate 9.

Optimization of a Carbon Epoxy wing
(except from reference 3)

Optimum Lay-up (Upper panel)

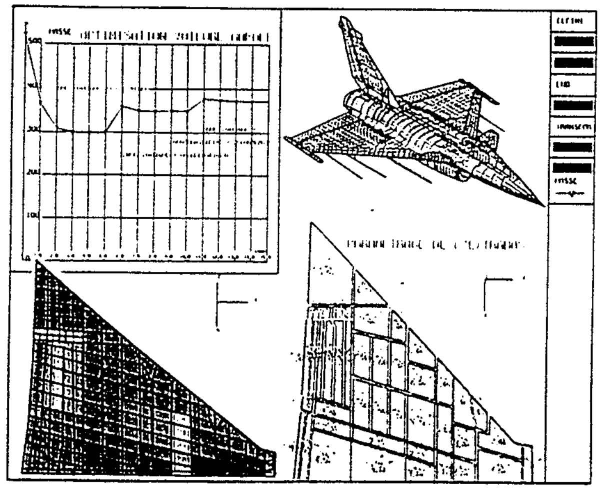

Plate 9

The optimization algorithm is resumed plate 10, it uses a classical approach of "feasible direction" method with linearized inverse approximation of constraints, it converges between 3 to 5 interations where computer consuming step are constraints calculations (resulting often from several F.E. analyses) and "exact" sensitivity analyses (see details in ref. 1, 2, 3.).

In addition for a practical use, we must dispose of a weight correction data base giving :
- ratios actual weight/F.E. weight, in function of technological solutions of design,
- half empirical models for masses of fittings non represented in global F.E. models.

Added to the optimum mass and sizing the optimizer give directly the sensitivity analysis of "cost of requirement" via the "Lagrange Multipliers" of active constraints. In this way, we deliver for the level 1 model the tangent behaviour model of structural weight in function of global shape, maneuver domain and total weight, the principle of optimality allowing the elimination of the hundreds of level 2 internal sizing design variables.

Structural Optimization Algorithm

- DESIGN VARIABLES $\lambda = \lambda_o$
- MASS ANALYSIS $M(\lambda) = mo + \Sigma\, mi\, \lambda_i$
- F.E./AEROELASTICITY ANALYSES
  → CONSTRAINTS $\sigma(\lambda)$
- SENSITIVITY ANALYSIS
  → $\delta\sigma / \delta\lambda$
- MATHEMATICAL OPTIMIZATION ON INVERSE APPROXIMATION
  $\alpha_i = 1/\lambda_i$
  $M(\alpha) = m_o + \Sigma\, m_i / \alpha_i$ minimum
  $\sigma_{jo} + \Sigma\, (\delta\sigma_j / \delta\alpha)\, \alpha_i \leq \sigma j$ available
  → α opt → λ opt (approximate)
  (projected conjugate gradient)

CONVERGENCE REACHED BETWEEN 3 TO 5 MAIN ITERATIONS
COST ~ 10 TIMES THE ANALYSIS COST

Plate 10

Special features of these tools allowing low cost and short time analyses/optimization are :

- the direct link between CATIA and ELFINI, via the mesh generator
- the reduction of input data volume resulting from the use of optimization techniques ; structural sizing becomes a result of calculation instead of being an input
- availability, with the ELFINI system, of historical record of the whole analyses/optimization process, so :
  - project iterations can be replayed only with the input of modified data
  - standard parametric models of CATIA structural objects and of corresponding analysis/optimization chain can be prepared in advance (facilities of CATIA-ELFINI "topological" mesh generator allow to follow easily actual shape of parametrized standard drawings)
- intrisic performances of ELFINI algorithms reinforced by the presently available computer power.

With such tools and a suited organization, sizing of any proposed airframe configuration during preliminary project studies can be extremely rapid and the objectivity of comparisons between alternative solutions is guaranteed by mathematical optimization. **The outcome is an implicitly fully conceived airframe design.** Performances of airframe interacting with other subsystems (e.g. aeroelastic behaviour) are correctly estimated. Weight and cost of structure can be precisely established.

- **At level 3** detailed drawings are initiated from considerations of stress flows and average sizing resulting from level 2 studies.

In theory, detail sizing could be processed by the same types of F.E. optimization techniques as for level 2 sizing, but it remains practical obstacles :

- present weakness of shape parametrization for **assemblies of parts** with today available C.A.D. tools and still more if we consider links with analyses.
- The heaviness of non linear local analyses and of their connections with physical tests, which send laborious systematic iterations between design and analyses.

It results today that level 3 analyses are more often used for "checking" than for real sizing optimization.

4. Axes of Research and Development

The trend is to extend progressively the use of mathematical optimization techniques among all levels and all disciplines of the design process, we mention here the main axes with corresponding difficulties to resolve.

- **Handling of design variables directly from C.A.D. definition models**, particularly the shape design variables ; the problem is not scientific, it is to obtain an efficient software organization ensuring the facility of data exchange from appropriate C.A.D. models to F.E. meshes, F.E. analysis, strength criteria analysis, ..., and also supporting the transmission of sensitivity analyses along the calculation chain. It is a prerequisite for the industrial application both of multidisciplinary optimization and of level 3 detailed design optimization (see below).

- **Generalization of the feature modeling technique**, from design definition to analyses and optimization. The presently emerging technique of feature modeling gives a semantic description of parts and assemblies of parts (sections) with a minimum of words and numbers which are natural design variables. This principle can be generalized with the **connection to design features** of :

- critical analysis points, and other "design drivers",
- corresponding "availables",
- calculation process, with **the automatic run of analysis chain** (e.g. : mesh, loads, F.E. analyses, local post processing, ..., edition of verification files),
- **sizing** via mathematical optimization.

By regrouping all inputs/outputs of each analysis chain links in a single vector, we find again, both the concept of generalized design variable as in the present organization of our level 1 model, and all the possibilities to exchange on demand inputs and output in the sizing process.

- **Multidisciplinary/Multilevel optimization**

These techniques can become mature thanks to progresses of numerical analysis in all disciplines and to previously evoked explicitation of generalized design variables at all design levels linked by analysis/sensitivity tools.

The development is progressive with the gradual connection of optimizers of each discipline. Our first priority is the coupling of structural optimization with aerodynamic shape optimization (ex. : European Cooperation M.D.O.).

The main mathematical problems to solve are :

- Availability of "affordable" sensitivity analysis in all disciplines (present success in C.F.D.).
- **Multidisciplinary optimization strategy,** between two families of approach :
  - **"Isolevel" approach** (generalization of our present approach of ELFINI), with the same set of design variable running on all coupled disciplines and iterations of :
    - separate analyses in each disciplines
    - mathematical optimization on approximate "~ tangent" formulation of objective and constraints.
  - **"Multilevel approach"**
    With, for instance, iterations of :
    - condensation of disciplinary (level 2) optimizations, via Lagrange multipliers of constraints feeding level 1 behaviour models.
    - optimization on level 1 behaviour models, with many possible variants for construction of behaviour models (see below).
- **Handling of architecture modifications**

The problem is still largely open meeting a part of the Artificial Intelligence difficulties. It comes from handling both continuous (size) and discrete (architecture types) design variables, discrete design variables controling the topology of the optimization problem (ex. : technology choices for subpart make specific design variables and constraints to appear).

- **Improving of construction of subproduct behaviour models**, by combination of several approaches :
  - Interpolation between data base of "checked points" (obtained via subproduct level sizing, ..., data from existing subproducts),
  - Taking advantage of sensitivity analysis to subproduct requirements (via Lagrange multipliers),
  - Ad hoc model formulations increasing interpolation/extrapolation capabilities in function of mathematical / physical / enginee-ring considerations,
  - "Optimization" of calibration point map via Tagushi like methods,
  - Arbitrary models (or complements of models) built via adapted neural network identifi-cations (!)

We find here globally the problematics of mathematical model identification.

- **Mathematical optimizations tools for robustness analysis**

They correspond to the analysis of project risks completing the classical failure probability analyses of the system by fault tree methods.

The idea consists in using mathematical optimization techniques to find the worst design points ("pessima") inside the space of variable, random or ill known parameters ; this associated with classical optimization in function of other design parameters.

We have already tested this approach for flutter analysis.

The prolongation of this technique could be the calculation of the solution probability in function of probability densities of design variables.

5. Conclusions

In spite of above remaining developments it is now an environment maturity for the generalization of sizing with mathematical optimization techniques through the whole design process of aircraft ; the main features of these new environments are :

- The arrival of a new generation of C.A.D./C.A.E. software frame, integrating a generalized notion of feature modeling with all products definition/requirements characteristics gathered in a single table of design variables linked explicitly by a chain of analysis models.

- The maturity of numerical analyses (including sensitivity analyses) in most disciplines, including C.F.D..
- The understanding of the building of behaviour model of subproducts and of their links with the optimum sizing of these subproducts via Lagrange Multipliers.
- The availability of a large choice of mathematical optimization algorithms ("convex", "genetic", "simulated annea-ling", ...) which use remains affordable if they are run with simple "tangent" or "behaviour" models.

But the most important now is the present maturity in the designer spirit, coming from more than 20 years of experience and demonstration of evident interest of structural sizing with mathematical optimizers.

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