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Concurrent Engineering in Design of Aircraft Structures

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This article focuses on the idea of concurrent engineering on the complete aircraft development process, from conceptual design to manufacturing. Three examples are presented to show important aspects of an integrated design philosophy: 1) a strategy to include the handling qualities of a fighter aircraft into the structural design, 2) an integrated design optimization study for an aircraft fin, and 3) a design for a manufacturing approach with an integrated tape-laying system. Finally, some remarks on economic aspects are outlined.

I. Introduction

THE introduction of technological innovation into aircraft structures usually is not a continuous process, in most cases there are technology pushes, as there has been the change from wood to laminated wood, to metal, to composite, and maybe to smart materials and smart structures in the future. There are two main reasons for these technology jumps:

1) The lifetimes of aircraft usually are 25 to 40 yr, and it is the exception to introduce new structural technologies into existing designs due to cost and airworthiness reasons.

2) The development of new materials and introduction into structures is itself a process which lasts 10–20 yr.

Therefore, it is important to start the development of a new aircraft design and to have a fully matured structural technology available that can be introduced without risk into the design.

In the past, the major technological pushes in new materials and structures have been driven by the weight-saving potential due to higher specific strength of new materials. The introduction of new materials was promoted by material and structural design engineers and, as the weight saving potential has been so big, the question of manufacturing costs could be easily answered in favor of the new technologies, especially in military aircraft designs, where the increase in performance often ruled out the cost aspects. But this has changed dramatically in recent years.

The ability to build lightweight structures will always be a dominant factor for flying articles, and therefore, all possibilities of finding optimum designs must be available such as 1) mathematical optimization codes in preliminary design stages including tailoring for composite materials, 2) load alleviation and active vibration control to reduce loads and reserve factors, and 3) efficient codes for analyzing structures that are all interconnected.

Airlines and air forces have to consider life cycle costs of aircraft and, therefore, the fly-away-price of the aircraft structure is only one factor within the life-cycle costs.

Consequently, the aspect of design-to-cost, to manufacture, to assembly, to reliability, and to supportability have become key issues already in the conceptual design phases of new aircraft.

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The implications of these requirements for technological innovations in the field of aircraft structures are as follows:

1) Manufacturing and assembly technology should be fully developed at the start of the design phase. This includes the aspects of reproducibility, quality assurance, health hazards, and the question of advanced production techniques. But most important will be, whether the design-to-cost data have been developed and justified well enough to allow the introduction of new technologies at a reasonable risk.

2) The aspects of reliability and supportability have to be covered from the very beginning. The problem is to make qualified forecasts for a lifetime of 25–40 yr on the acceptability of materials to environmental degradation, because "real life" tests are not possible due to time constraints.

3) Also, the issues of material qualification, development of design allowables, and design methods have to be addressed before the start of the design phase. This requirement is no longer as dominant as it was in the past.

The management of technological innovation has to take into account concurrent engineering aspects as never before. The challenges, which have to be addressed, are to foresee the most promising features in the development of new materials with respect to advanced aircraft concepts, and to start a well-timed concurrent engineering action promoting the most critical research issues for the implementation of advanced technologies into new aircraft designs.

The time span between new aircraft projects is becoming larger and larger, and flying demonstrators will be of increasing importance in the future. This approach to assure the airworthiness of new technologies and to develop at least a limited amount of in-service experience for new concepts will promote the introduction of technological innovations into the design of new aircraft.

II. Linked Geometry-Based Design and Manufacturing Process for Composite Aircraft Structures

In recent years, composite materials have gained an important role in airplane construction. Due to their superior lightweight structural characteristics, especially carbon fiber reinforced plastic materials (CFRP) can save more than 40% of weight in a modern fighter aircraft design. On the other hand, using these new materials can result in a considerable reduction of parts compared to traditional metallic designs.

A linked geometry-based design and manufacturing process for composite aircraft structures, as has been developed at Deutsche Aerospace (DASA), is shown in Fig. 1. This process covers four essential phases.

A. Conceptual Design

During this phase, the basic aircraft configuration is defined. Starting with technical concepts, determined by the

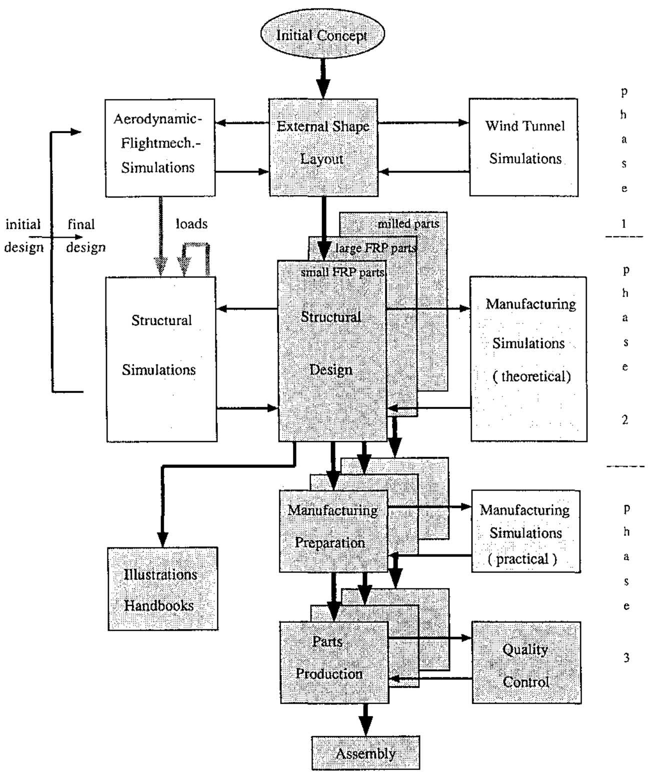

Fig. 1 Aircraft process from design to manufacturing (aircraft structure only).

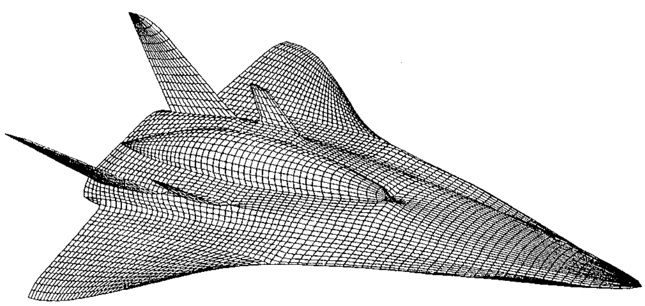

Fig. 2 Typical surface mesh on a hypersonic vehicle for CFD-computations.

requirements of the customer (e.g., airplane performance, flight qualities, standards, and a lot of other demands), estimation formulas and data sheets are used to find a initial aircraft concept that fulfills most of the requirements.

B. External Shape Layout and Structural Design

This phase is characterized by the use of more sophisticated analysis tools such as finite element methods (FEM) and computational fluid dynamics (CFD). Moreover, with the application of multidisciplinary design optimization (MDO) in the preliminary steps of this design stage, it is possible to reduce the number of iteration steps advancing to the detailed design. Thus, the influences of different disciplines (e.g., structural mechanics, aerodynamics, flight mechanics), can be considered simultaneously.

For the geometry-based data flow during these phases, the following principles have turned out to lead to an optimal process: CAE-computations (e.g., aerodynamics, structures) are based on three-dimensional CAD-geometry design (CATIA): 1) direct use of the CAD-model-description for the CAE-model (e.g., mesh for CFD-computation, Fig. 2); or 2) transfer of the CAD-design-model to a standard preprocessor (PATRAN) for FEM-, and heat-transfer calculations; and 3) using standard postprocessor for visualization of results.

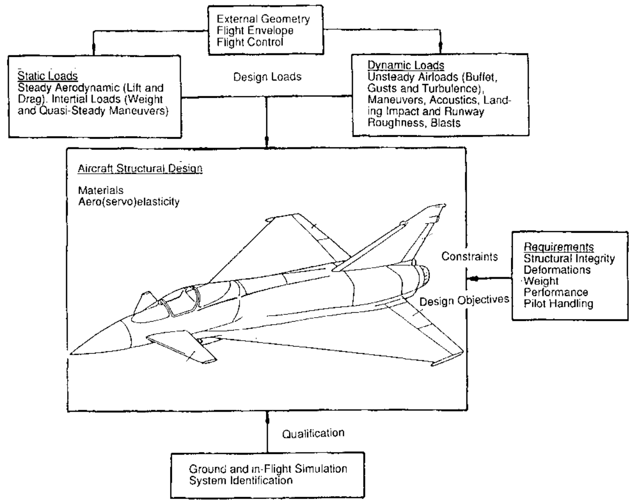

Fig. 3 Scenario of modern high-performance aircraft structural design.

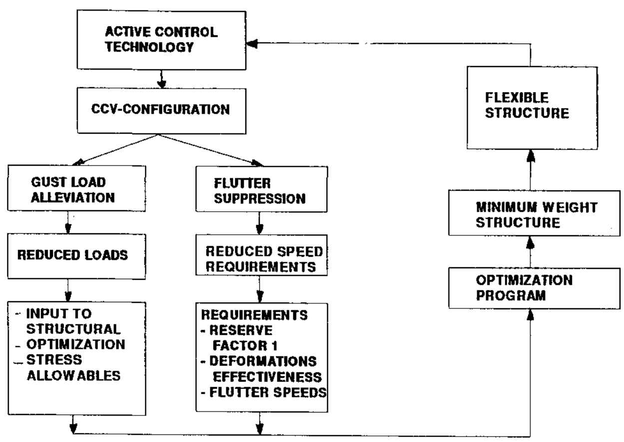

Fig. 4 Strategy to connect with active control.

C. Manufacturing Process

The manufacturing process for the composite aircraft structures of today is characterized by the change of traditional manual methods to more mechanized and automated processes. The necessary guidelines include the following: 1) automatic manufacturing of models with milling machines, 2) automatic manufacturing of moulds with tape laying machines, 3) automatic manufacturing of composite parts with tape laying machines, 4) computer integrated quality control, and 5) automatic electronic testing of cured parts.

All are based on the three-dimensional geometry data coming from upstream in the design process.

III. Multidisciplinary Design Optimization

In the past, the design of structures was an intensive process through several steps of modifications and analyses to comply with requirements for performance, strength, stability, stiffness, and weight.

During the past decade, mathematical optimization methods have been integrated into analysis programs to design structures for defined requirements in one calculation at minimal weight. Especially the use of composite materials, offering a broad scale of "tailoring" their strength and stiffness properties in an optimal combination, requires these tools to use their full potential.

Rather than running the design process through different disciplines in structural design such as flight mechanics, generation of loads, stress analysis, local and global buckling, mass calculation, dynamics, flutter/dynamic response, and static aeroelastic analysis, with the structural optimization program MBB-Lagrange, which has been developed in 1984, it is now possible to simultaneously fulfill these constraints or use them as objective functions. Mathematical optimization algorithms, finite element methods for structures, and panel methods for aerodynamics build up the basis for optimization calculations with a high rate of generality and efficiency.[1,2]

Figures 3 and 4 show the aircraft structural design scenario and strategies to exploit structures that are part of the concurrent engineering philosophy.

In the following chapters are some selected examples that show important aspects of an integrated design philosophy.

IV. Examples

A. Care-Free Handling and Maneuver Load Control

Maneuver loads must be screened and flight parameters must be restricted (still fulfilling the necessary requirements). Such an approach also allows a reduction of the reserve factor and, hence, weight savings.[3]

A fighter aircraft is presented as an example. All its primary flight control surfaces are interfaced and controlled in their motion through the flight control system (FCS), and the pilot commands maneuvers with his stick and pedals. The way maneuvers are flown is completely different from stable command augmented airplanes, using one control surface only, and design loads depend very much on the FCS.

The primary control surfaces are 1) inboard flaperons, 2) outboard flaperons, 3) foreplane, and 4) the rudder.

Inboard-outboard flaperons and/or foreplane can therefore be used for trimming and controlling the longitudinal aircraft motion, and it depends on the allocation of stick inputs to these control surfaces.

Figure 5 shows an example of how much the foreplane and wing trailing-edge flap loads and moments can be affected by an appropriate choice of the initial trim contribution. This applies for the subsonic region, where the aircraft is unstable longitudinally, as well as for the supersonic region, where the aircraft is stable.

If the foreplane/flap schedule is only chosen from a handling and performance point of view, one may run into problems with the design loads on both surfaces, as one gains advantages on both surfaces by choosing an optimum loads concept.

Figure 6 illustrates the problem, that MIL-SPEC requirements no longer represent generally usable structural design conditions for a carefree handling aircraft. It can be seen that the MIL-triangular stick displacement initiates a full g maneuver with associated high positive and negative pitch rates and operationally unacceptable acceleration rates resulting in high inertia loads for the pilot. The carefree handling aircraft on the right side of the diagram is controlled to its maximum g by a full back stick, and it can be seen that both the maximum g-rate as well as the pitch rate are cut down extremely to operationally meaningful levels by the control system.

The examples show clearly that the aerodynamic loads produced by maneuvers depend on carefully chosen control laws/trim programs of the flight control system.

Real time simulations with measured aerodynamic derivatives, aeroelastic efficiencies, and optimized control laws must be performed and maximum response parameters selected from the histories. These response parameters are expressed as accelerations and rates about all axes at all altitudes. After considering aircraft weight, c.g., and fuel state, the actual design loads are derived. They are dependent on the FCS design and—for the flying aircraft—on performance. Two conclusions are as follows.

1) Unstable aircraft are completely dependent upon the integrity of the flight control system.

2) The applied loads are also dependent upon the flight control system. Therefore, the design loads cannot be exceeded and the ultimate factor can therefore be reduced to 1.4 or less, which gives a mass saving of about 3% of structural mass (about 120 kg).

B. Integrated Fin Design Using Implicit Function Theorem

The finite element model is shown in Fig. 7. The following chapter is focused on findings and results of an integrated design optimization study for an aircraft fin.[4] The basic flight mechanics design requirement for a vertical fin is to provide a specified control power inside the whole flight envelope with a minimum weight structure.

A method proposed by Sobieski[5] using implicit function theorem presents a practical way of performing the sensitivity analysis of internally coupled systems.[5]

The unit side load p depends on the aerodynamic derivative c_β, on the surface area S and the aeroelastic efficiency η, a reduction factor for the aerodynamic derivative due to structural deformations.

The formulation of the state variable equations for our fin is a more generalized form, and we get the following equations:

flight mechanics

$$p = c_\beta \cdot \eta \cdot S$$

aerodynamics

$$c_\beta = f_A(\lambda, \Lambda)$$

structure/aeroelastics

$$\eta = f_S(\lambda, \Lambda, S, t)$$

The internal coupling of the system is given by the first equation. The state variables c_β and η are not internally coupled.

For our first approach to an integrated design analysis, we have selected three aerodynamic design variables: 1) taper ratio λ, 2) aspect ratio Λ, and surface area S. Structural design variables are a selected set of element sizes t. After the selection of state variables and design variables for our fin problem we can formulate the system sensitivity equations (see Fig. 8).

The coefficients of the equations are the negative partial derivatives of the state variables p, c_β, and η. The unknown terms on the left side are the total derivatives of state variables and design variables. The partial derivatives of the state variables and design variables that will be provided by the individual disciplines are on the right side of the system sensitivity equations.

The right side of our total system sensitivity equation represents partial state variable sensitivities with respect to the independent design variables. Each discipline that contributes to the analysis is able to prepare its partial sensitivities independently. A practical way to compute sensitivity derivatives is the finite difference technique. The panel method calculation will be repeated for a slightly changed design parameter. The user must decide carefully about the range of design parameter changes, because if the change is too small the numerical uncertainties may become important. If the difference is too large, nonlinearities may cause significant errors. The range in which accuracy of finite differencing is acceptable becomes problem-dependent. For our sensitivity analysis using the finite difference method, we have chosen a 10% perturbation magnitude on the aerodynamic design variables (Fig. 9).

The 10% increase of taper ratio has caused a reduction of approximately 2% efficiency and 1.23-kg structure weight. The design variable with the strongest influence to the aeroelastic efficiency is the aspect ratio. A 10% increase of aspect ratio would cause a 6.3% decrease in aeroelastic efficiency. The partial derivative for the surface area increase presents a small reduction of 1% in efficiency and a considerable weight penalty.

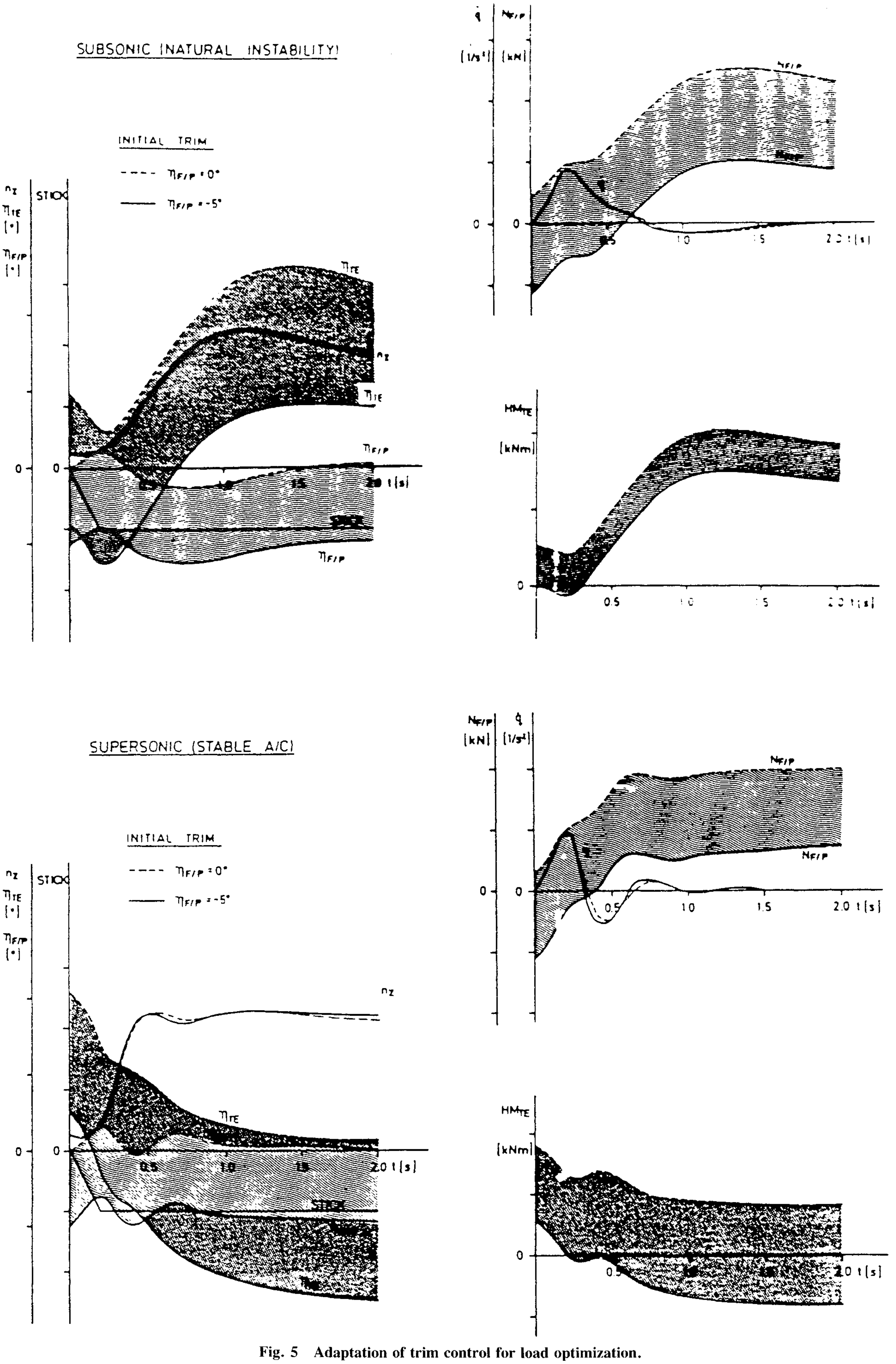

Fig. 5 Adaptation of trim control for load optimization.

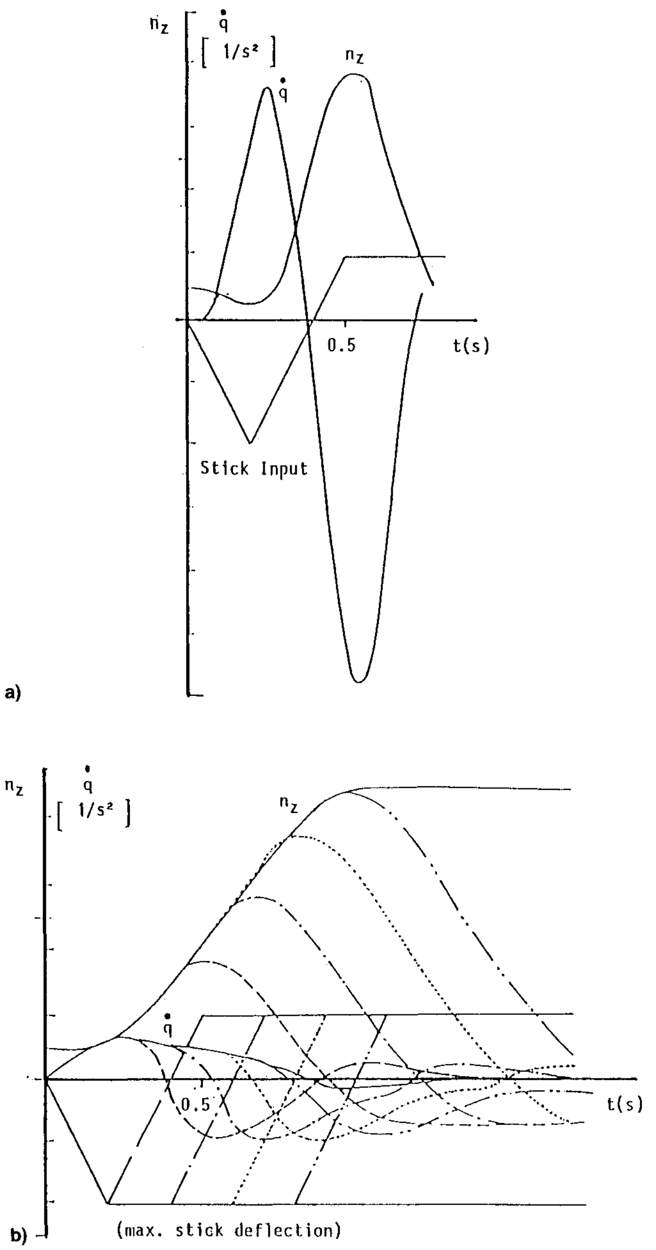

Fig. 6 Comparison of a) MIL-SPEC and b) carefree handling maneuvers.

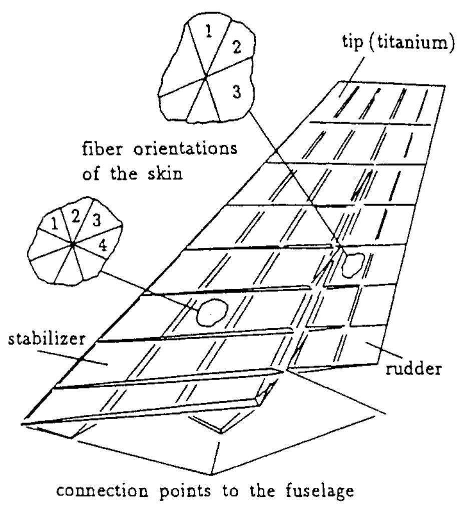

Fig. 7 Analysis model of the fin.

STATE VARIABLES — TOTAL DERIVATIVES — PARTIAL SENSITIVITIES

FLIGHT-MECHANICS / AERODYNAMICS / STRUCTURE / AEROELASTICS

$$\begin{bmatrix} I & -\frac{\partial p}{\partial c_\beta} & -\frac{\partial p}{\partial \eta} \\ -\frac{\partial c_\beta}{\partial p} & I & -\frac{\partial c_\beta}{\partial \eta} \\ -\frac{\partial \eta}{\partial p} & -\frac{\partial \eta}{\partial c_\beta} & I \end{bmatrix} \begin{bmatrix} \frac{dp}{d\lambda} & \frac{dp}{d\Lambda} & \frac{dp}{dS} & \frac{dp}{d\underline{t}} \\ \frac{dc_\beta}{d\lambda} & \frac{dc_\beta}{d\Lambda} & \frac{dc_\beta}{dS} & \frac{dc_\beta}{d\underline{t}} \\ \frac{d\eta}{d\lambda} & \frac{d\eta}{d\Lambda} & \frac{d\eta}{dS} & \frac{d\eta}{d\underline{t}} \end{bmatrix} = \begin{bmatrix} \frac{\partial p}{\partial \lambda} & \frac{\partial p}{\partial \Lambda} & \frac{\partial p}{\partial S} & \frac{\partial p}{\partial \underline{t}} \\ \frac{\partial c_\beta}{\partial \lambda} & \frac{\partial c_\beta}{\partial \Lambda} & \frac{\partial c_\beta}{\partial S} & \frac{\partial c_\beta}{\partial \underline{t}} \\ \frac{\partial \eta}{\partial \lambda} & \frac{\partial \eta}{\partial \Lambda} & \frac{\partial \eta}{\partial S} & \frac{\partial \eta}{\partial \underline{t}} \end{bmatrix}$$

DESIGN VARIABLES λ Λ S $\underline{t}$

Fig. 8 System sensitivity equations.

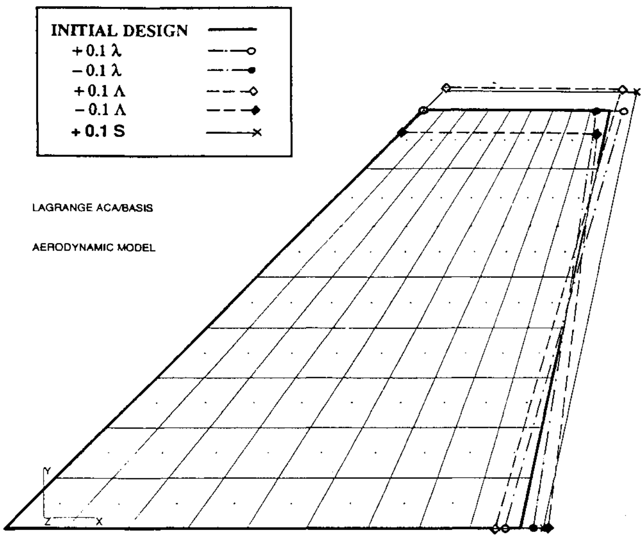

Fig. 9 Aerodynamic shape differences.

At that point of our integrated fin design study, we have to formulate the influence of the structural design variables. How strong is the influence of the element sizing variables? There is a possibility of using the already existing structural optimization module. After a structural weight optimization study we obtained the partial weight sensitivities that are given in Fig. 10 for comparison.

The state variable p is plotted for all finite difference sensitivities of the design variables λ, Λ, S, and for the optimized element sizes t. The strong impact of element sizes to structure weight is obvious.

The initial fin design was the basis for our sensitivity analysis, and after the structural optimization we found the minimum weight solution for the initial aerodynamic shape. For this configuration we got a lateral load p_0 and a structure weight w_0, which will be now the reference values for further design studies. The integrated design study allows additional aerodynamic design variables, and we want to find out if there might be solutions with a higher p and the same weight w_0, or solutions with a lower weight w and the same lateral load p_0.

To gain more knowledge about the influence of structural optimization, we performed for each aerodynamic partial sensitivity model a structural optimization with an aeroelastic fin efficiency requirement of 80%. The best integrated design solution resulted in a 10% reduction of aspect ratio. In this case, the lateral unit load will be slightly increased and the weight is reduced by 7.5%. These examples show that state variables are coupled, and using parametric studies will be very time-consuming in finding an optimum solution.

Therefore, we need an optimization module that will be provided at each iteration step with the appropriate models for structure and aerodynamics with which to perform the sensitivity analysis.

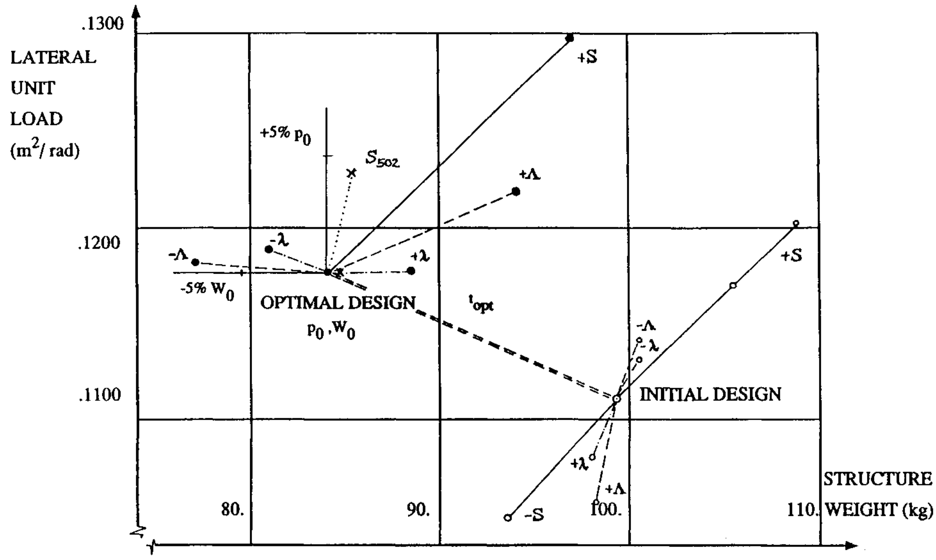

Fig. 10 Summary of partial sensitivities.

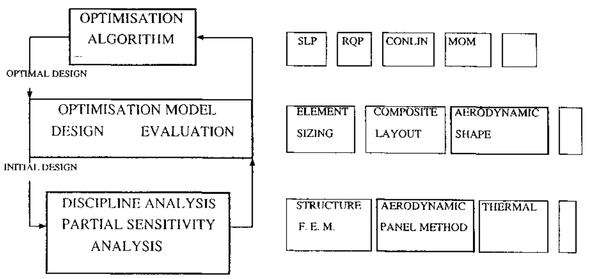

Fig. 11 Open architecture for general optimization in MBB-Lagrange.

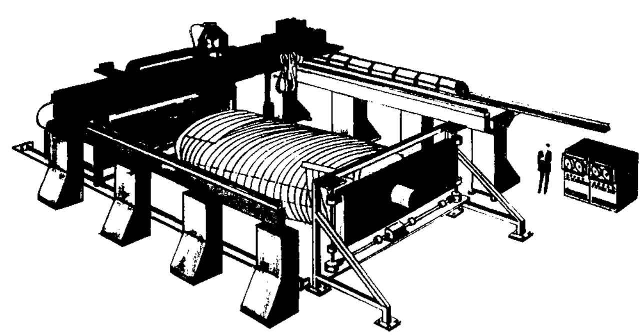

Fig. 12 Tape placement machine (Gantry-type).

After we have formulated the total derivatives, an optimization module that performs the necessary steps with design variables other than structure element sizing is necessary.

A rough scheme of such modular software is shown in Fig. 11.

C. Design for Manufacture (DFM)

A major objective of the design for manufacture approach is the integration of manufacturing informations into the product design and analysis process design. Knowledge about the potential and restrictions of the manufacturing system leads to manufacturable designs with a minimal number of iteration steps between design, analysis, and manufacturing.

For this reason, DASA is developing an integrated hardware and software system for the design of automatic production of complex nondevelopable CFC-structures.

This "integrated tape laying system" (ITLS) is completely integrated in the CAD-system CATIA. The outcoming data can be used directly to run the CNC-control of the tape-laying machine on the shop floor (Fig. 12).

The graphical interactive system allows the designer the automatic generation of tape paths for CFC-prepreg-tapes and the simultaneous analysis (e.g., with FEM-program NASTRAN) of the designed structure.[6]

By using the latest development of MBB-Lagrange within this design iteration is not only possible to define design variables, but also sizing parameters. These are 1) cross-sectional area of elements, 2) thickness of elements, 3) laminate thickness of composite elements, 4) balance masses, 5) coordinates of nodes (under development), and 6) fiber orientation (within the limitations of the tape-laying machine).

The fin structure, already shown in Fig. 7, was used for optimization of the fiber orientation angles. For this concept study[7] 1862 constraints were defined: 1) stress limitation (isotropic elements 119/loadcase), 2) limitation of failure safety (composite elements 252/loadcase), 3) aeroelastic efficiencies—fin (0.8), 4) Ma = 1.8 (750 kt)—rudder (0.5), and 5) flutter speed—530 m/s.

The problem consists of 102 sizing design variables (one independent design variable for every layer in every element).

The sizing optimum results in a weight of 42.3 kg (= 100%) for the variable skin weight.

By introducing the ply angles as additional design variables it is possible to define a lot of other design models. In Fig. 13 the results are presented.

The strong influence of the ply angles to the optimum weight is obvious. Allowing every ply angle in each element results in a minimum weight design of 25.3 kg. This weight is the theoretical lower limit and it will not be manufacturable, but it shows the potential of weight saving, including fiber orientation as design variables. But it is also obvious that the manufacturing requirements (e.g., minimum steering—radii) has to be considered.

For this reason a development was initiated that includes these manufacturing data as additional constraints into the optimization model.[8] It will be possible in the near future to have the optimization as the "driving part" in the complete composite design process. The data flow for this integrated process, including the ITLS-system, is shown in Fig. 14.

The potentials of such a high integrated soft- and hardware system can be summarized by the following: 1) minimal number of design and analysis iterations, 2) no iterations between design and manufacturing process, 3) minimum weight designs, 4) manufacturable designs, 5) no possible hardware changes within an iteration process, 6) minimal failure potentials, 7) save quality control, and 8) protection of health against hazardous composite materials.

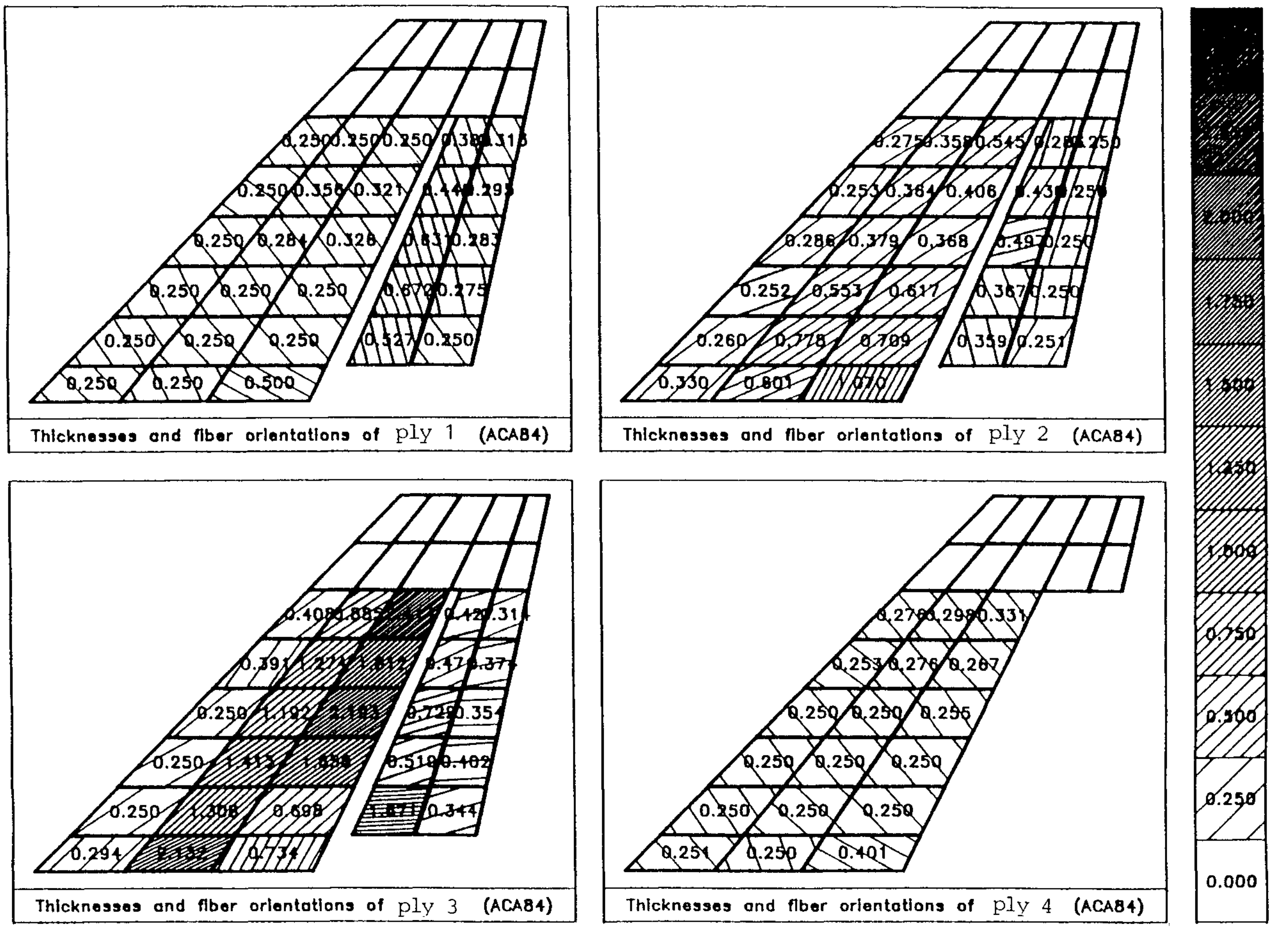

Fig. 13 Optimization results of the fin.

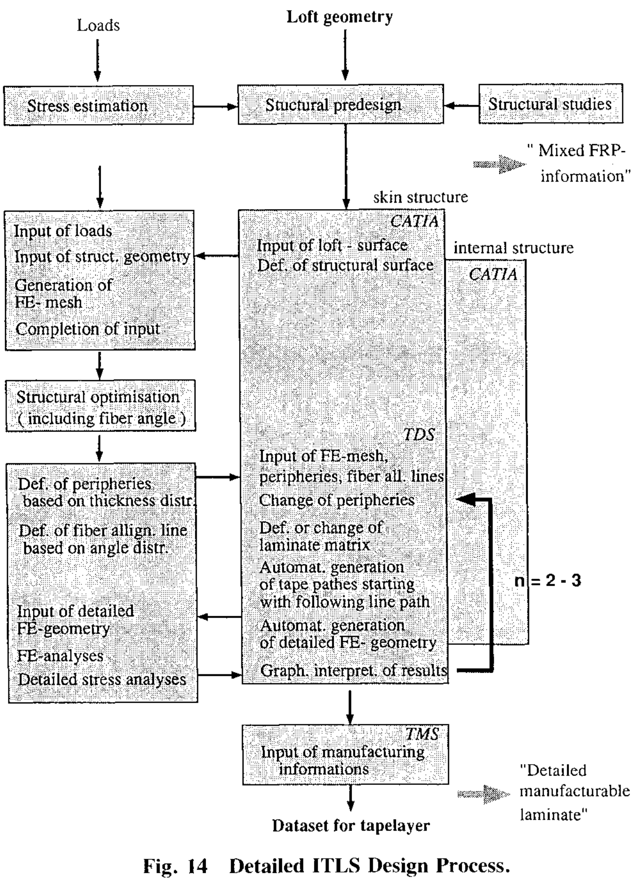

Fig. 14 Detailed ITLS Design Process.

V. Conclusions

Several activities are presently going on at DASA that all are meshed in the idea of concurrent engineering, where the main goal is to move manufacturing and supporting considerations into the design process. Also, the design process itself must be streamlined in the context of getting all engineering disciplines integrated and all necessary computer codes interconnected. The role of multidisciplinary design optimization will be much more emphasized in the future.

While the idea is simple, integrating the technologies is a major multidisciplinary challenge. In Fig. 15 it is shown how much concurrent engineering is needed for integration.

Design-to-cost is also a major aspect for new projects.

Design-to-cost capabilities require several conditions, which should be available or evaluated at each company such as the following.

1) Develop a series of technical promising designs to the same detail of design within a project (do not compare first drafts with final designs).

2) Provide an established and proven data base on cost figures for different manufacturing routes. The problem is to have well-supported data for new manufacturing technologies available in time to be useful.

3) For a well-detailed design it would be best to have tools available that are able to model manufacturing processes and produce exact cost figures.

4) Last, but not least, design-to-cost has to consider recurring and nonrecurring costs. This means, that infrastructure, machines generally of existing plants, or even investments in new production plants and production lines have to be accounted for.

There will be considerable amounts of engineering efforts necessary, and also the development of software has to be

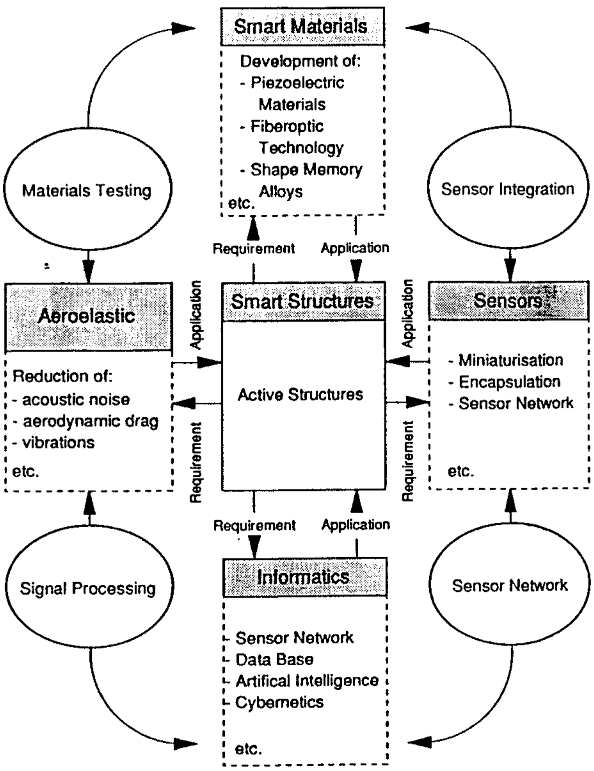

Fig. 15 Concurrent engineering for active, smart structures.

accelerated. Companies wanting to make competitive products in the years to come have to invest now for the future.

References

[1]Kneppe, G., "MBB-LAGRANGE—Structural Optimization for Space and Aircraft Structures," MBB-Rept. S/PUB/406, June 1990.

[2]Krammer, J., "Practical Architecture of Design Optimization Software for Aircraft Structures Taking the MBB-LAGRANGE Code as an Example," AGARD Lecture Series 186, May 1992.

[3]Sensburg, O., Bartsch, O., and Bergmann, H., "Reduction of the Ultimate Factor by Applying a Maximum Load Concept," *Journal of Aircraft*, Vol. 24, No. 11, 1987, pp. 759–767.

[4]Schneider, G., Krammer, J., and Hörnlein, H. R. E. M., "First Approach to an Integrated Fin Design," 72nd Meeting of the Structures and Materials Panel of AGARD, MBB-Rept. S/PUB/448, Bath, England, UK, April–May 1991.

[5]Sobieszczanski-Sobieski, J., "Sensitivity of Complex, Internally Coupled Systems," *AIAA Journal*, Vol. 28, No. 1, 1990 pp. 153–160.

[6]Berchtold, G., and Klenner, J., "The Integrated Design and Manufacturing of Composite Structures for Aircraft Using an Advanced Tape Laying Technology," DGLR-Jahrestagung 1992, Bremen, Germany, Sept.–Oct. 1992.

[7]Eschenauer, H., Schuhmacher, G., and Hartzheim, W., "Multidisciplinary Design of Composite Aircraft Structures by LAGRANGE," *Computers and Structures*, Vol. 44, No. 4, 1992, pp. 877–893.

[8]Eschenauer, H., Schuhmacher, G., and Krammer, J., "Constructive Design Models for Multidisciplinary Optimization of Fiber Composite Structures," 4th AIAA/USAF/NASA/OA/Symposium on Multidisciplinary Analysis and Optimization, Cleveland, OH, Sept. 1992.