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COMPUTER-AIDED CONCEPTUAL AIRCRAFT CONFIGURATION DEVELOPEMENT BY AN INTEGRATED OPTIMIZATION APPROACH

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Abstract

The objective of the conceptual design phase is the development of the aircraft configuration which is most efficient for a given specification. To numerically assist this procedure a CAE-system is presented which, as main attributes, handles arbitrary analysis and synthesis methods as modules in a method library, applies an always consistent and complete computer internal modelling of geometry and performance, and controls the design processing through a design management system as a central user interface. To point out the potential of this open program architecture, and, in particular, the modelling approach chosen an aerodynamic analysis of complete aircraft configurations is discussed. Furthermore, it can be shown that paralleling the multivariate optimization with the design synthesis leads to a more efficient strategy than the conventional successive procedure. With this integrated optimization approach a comparative concept evaluation can be performed.

1 Introduction

Designing a new commercial aircraft requires comprehensive concept studies. This Conceptual Phase, the first part of the Configuration Development Phase, is much more governed by consideration of global characteristics, comparative parameter studies and sensitivity studies than the following Preliminary and Detail Design Phase where the analysis level is significantly higher.

The comparative evaluation of different concepts requires even in this early design stage the careful analysis of aerodynamics, structure, propulsion, weight & balance, stability & control, performance, and economics. Due to their strong interaction these disciplines must be properly interfaced leading to the integration in a synthesis process which has to be iterative because the resulting variational problem is of very high order and does not have a closed solution[1].

At the beginning of the design process the design specifications lead to the definition of several initial baseline designs[2] which are consolidated iteratively through successive analysis. The non-deterministic character of the design process offers a large spectrum of potential configurations so that experience and judgement of the design engineer play a dominant role in the decision making.

The main intention of the concept phase is the parametric variation of as many design values as possible to obtain the most promising concept with respect to a merit function. To be able to handle the resulting computational effort the mathematical model must be adapted to the design level and, independent of this level, the particular analysis methods which cover the spectrum from statistical weight approaches to more sophisticated CFD-methods, have to be methodically consistent. On the other hand, the favoured design concepts have to be consolidated through sensitivity studies and multivariate optimization of selected non-restricted design variables[3]. Here, care has to be taken that due to a continuous decrease of configuration changes during the synthesis procedure a refined set of methods has to be provided. Hence, it appears necessary to find a reasonable compromise between required analysis accuracy and resulting computational effort.

Consequently, the primary goal in developing a program system for this design synthesis in the first configuration development phase should be to retain the flexibility and transparency of the classical design process. That is in contrast to some new investigations on the feasibility of expert systems in aircraft design which show that knowledge based strategies by means of inferential methods are becoming increasingly significant. Thus, at the Cranfield Institute of Technology[4] studies on a knowledge based wing design in the conceptual phase were performed within the ESPRIT program. It becomes obvious that the iterative design process which is characterized by strong interdependencies and ambiguous decision structures makes high demands on program flow control and knowledge base. The program system developed at MIT[5,6] models geometry and performance of the aircraft through design variables linked by functional interrelations which are automatically sequenced according to the actual design task. The input of geometry information occurs at a menu-oriented graphical interface which allows the aircraft geometry to be interactively modified. A more general system environment was developed at NLR[7] to use knowledge based expert systems for designing arbitrary technical objects. Besides pure knowledge handling this system enables the use of external program libraries for analysis calculations. The implementation of an intelligent aircraft design system is intended.

In the present investigation, a non-inferential procedure for knowledge processing and storing was preferred to take into account a more engineering-oriented approach. Due to the numerous considerably different design tasks in conceptual design this can only be achieved with an approach which allows the selection of suitable analysis modules from a Methods Library. This library can be extended at any time by the design engineer. That requires an open program structure which enforces a clear separation of flow control, analysis modules and object representation. Consequently, the absence of a central program structure shifts the consistent and always complete computer-internal modelling of geometry and performance of the aircraft into the focus of the design system.

Hence, the geometry and performance models are the essentials of this paper. They allow the continuous adaption of the analysis level during the consolidating process and are prerequisites for an efficient aerodynamic analysis and for the integration of the optimization in the design synthesis. It is the computer-internal modelling which distinguishes this concept from other program systems also basing on the classical, engineering-oriented design strategy. The CAD-system ADAS[8] of the TU Delft which uses the commercial graphics system MEDUSA applies a highly developed analysis level which now will be extended to the application of more sophisticated CFD-methods and supersonic design. A system which also uses an engineering approach is the integrated program system for the conceptual design of short haul commuter aircraft developed at Loughborough University of Technology[9]. The program enables simultaneous optimization of the parameters describing the flight profile and the main design values with respect to suited merit functions. Finally, at the TU Braunschweig a 2-stage program system[10] for conceptual design was developed which includes a FEM-weight determination and also an optimization module but which does not offer the possibility of selecting problem-specific analysis methods.

After discussion of the concept and structure of the design system CAPDA the main chapters of this paper concentrate on the computer-internal modelling concept for geometry and performance and on the resulting potentials of this approach which are mainly an extended aerodynamic analysis and an optimization strategy integrated in the design synthesis.

2 The Design System CAPDA

2.1 Concept and Structure

The computer-aided procedure for the conceptual design of aircraft (CAPDA)[11] allows the evaluation of various competing configurations and assists the design engineer in deciding which solution to analyse more closely in the following design phases. The complexity of the design process requires specific demands regarding the concept and realization of a CAE system for the configuration development of aircraft. These demands include the following items:

- In accordance with the interdisciplinary character of design problems the analysis and synthesis methods should be handled as modules in a Methods Library.
- The sequencing of programs for application to specific tasks such as Design Synthesis, Parameter Studies, Configuration Optimizations or Pre/Postprocessing should be supported by a comfortable user interface.
- The computer-internal modelling of aircraft geometry and performance must match the increasing amount of information resulting from the advancing design process and at all times must provide a consistent and complete representation of the aircraft.
- Independent of a specific application, the computer-internal representation of geometry and performance information must constantly be accessible over standardized interfaces.

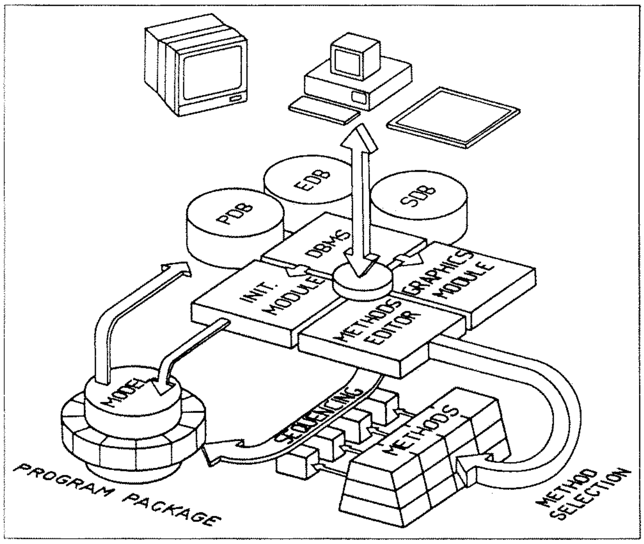

Fig. 1 CAPDA. Concept and structure.

These demands led to the definition of the program structure for the design system CAPDA shown in figure 1.

2.2 The Design Management System

The Design Management System, figure 2, is a central user-interface that handles all control and administrative functions necessary for the processing of a design problem, thus allowing access to all capabilities of the CAD-system without previous experience being a prerequisite. On the basis of an extensive information and documentation

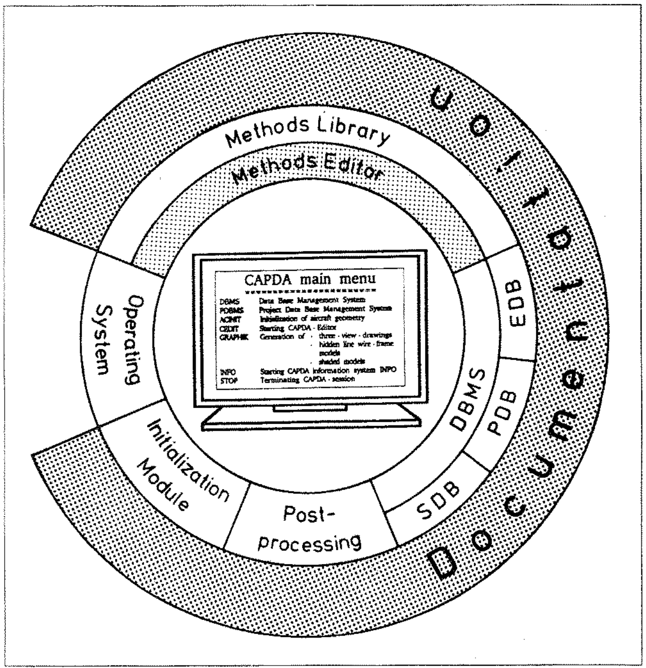

Fig. 2 Design Management System. User interface.

system the design engineer is guided through the entire design process: from the initialization of the aircraft geometry over the selection and sequencing of the analysis-methods through the Methods Editor up to the execution of the resulting program and presentation of the results. By applying the philosophy of an open design environment the CAD-system can be adjusted to the requirements of actual design problems through the integration of additional user-specific methods in the Methods Library. This is supported by further system information and by direct access to all commands of the operating system.

All necessary data for the design process are stored in three data bases: the Statistics Data Base (SDB) which contains mainly geometry information of existing aircraft, the Project Data Base (PDB) in which designed aircraft are stored, and the Empirical Data Base (EDB) which contains information on airfoils and powerplants. The user has access to these data bases via the Data Base Management System (DBMS).

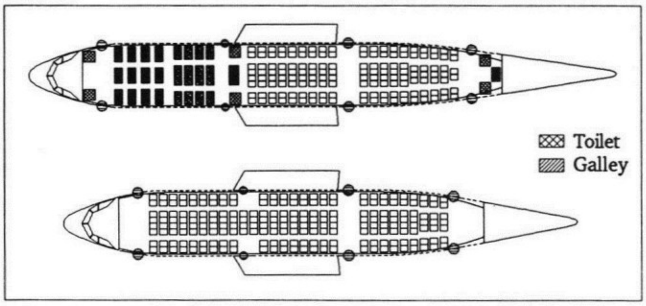

Fig. 3 Geometry Model. Cabin layout.

The initialization of aircraft to be configured for a given flight mission is based on data stored in the Statistics Data Base. For the generation of a first fuselage geometry the Initialization Module assumes an economy class arrangement for the entire cabin and selects the number of galleys, lavatories, doors and emergency exits on the basis of statistical data. All other aircraft components are also generated on the basis of statistics. The configuration proposed by the Initialization Module can then be modified as desired through graphical interaction. Figure 3 shows as example a cabin in standard and modified configuration. By means of the methods selected over the Methods Editor these configurations can be analyzed, reconfigured to meet the design specifications in the design synthesis, and finally optimized with respect to a selectable merit function. The resulting performance data and geometries can be visualised through graphical post-processing. As an example, figure 4 shows a shaded model of an optimized medium range twin-jet as highest level of geometry presentation.

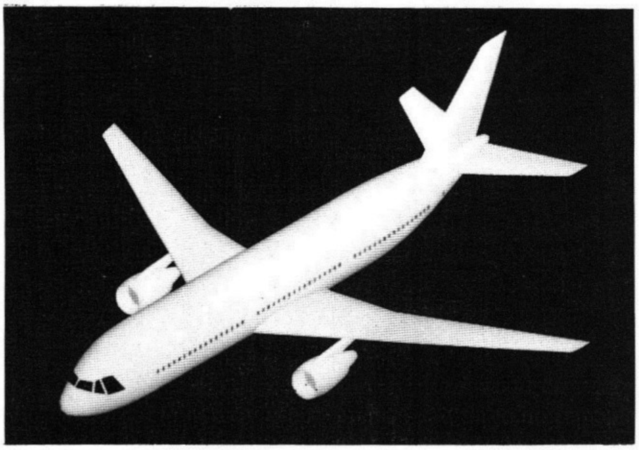

Fig. 4 Graphical post-processing. Shaded model.

3 Computer-Internal Modelling Concept

3.1 Geometry Model

In the conceptual phase main design parameters of configuration concepts are adjusted to the criteria of the design specification. During this phase it is sufficient to describe the aircraft geometry through a few global parameters. Consequently, the detailed information necessary for conventional - but memory-intense - representation of freeformed surfaces through B-Splines or Coon's Patches is not available. A solution for generating complete aircraft geometry with the information at hand and with far less computational effort was found through applying the principle of dynamic variant programming[12]. Apart from being particularly convenient for the modelling of aircraft geometry this method is increasingly finding application in established CAD-systems.

Dynamic variant modelling applies basic profile functions, e.g. a hyperellipsis to describe the cross-section of a fuselage, which is swept along a line of projection, e.g. the fuselage centre-line, to create the desired surface, figure 5. The functional development of the parameters along the projection line (Projection Function) depends on the surface contour which in turn is described through distinct analytical functions defined by a number of global configuration parameters. These are changed during the progressing design process to give increasingly concrete information of the aircraft geometry.

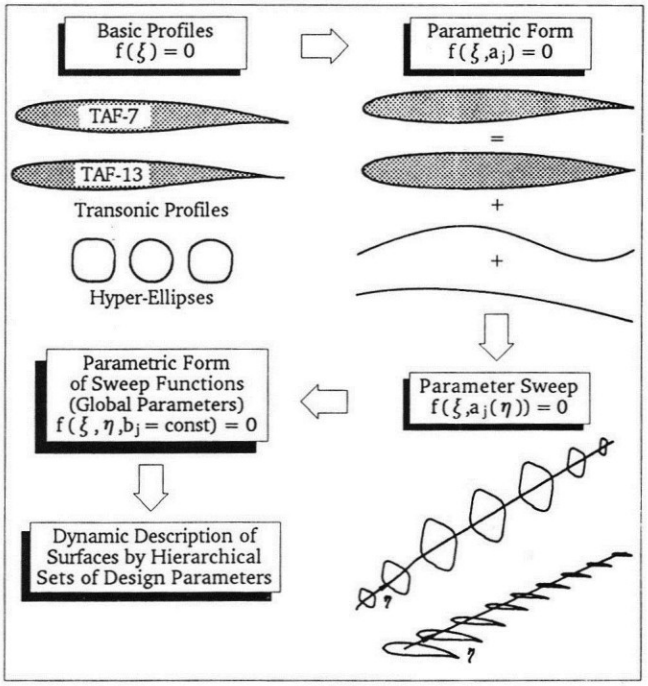

Fig. 5 Geometry Model. Principle of Dynamic Variant Programming.

Through this approach the choice of appropriate basic profile and projection functions predefines a shape variant which contains principal geometry information and requires only few parameters to be adjusted to fit relatively complex bodies. Herewith the design engineer is provided with the possibility of creating a variety of aircraft geometries through variation of the global configuration parameters under automatic retention of surface continuity, smoothness and consistency. Furthermore, this approach allows convenient cataloguing of the geometry of existing aircraft in the Statistical Data Base by simply determining the parameters rather than digitizing the entire geometry. Figures 4, 6 and 7 demonstrate the potential of dynamic variant modelling.

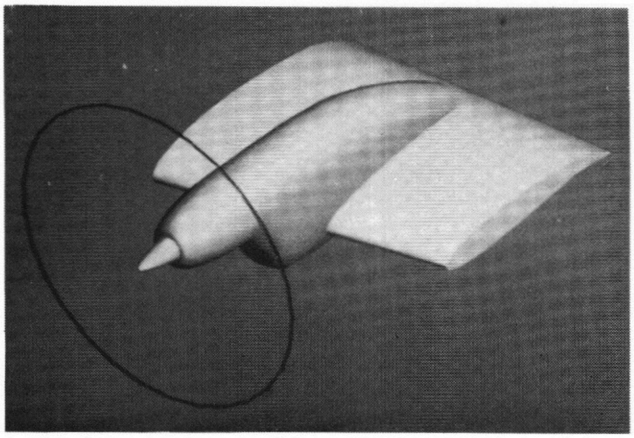

Fig. 6 Graphical post-processing. Shaded model of turboprop engine.

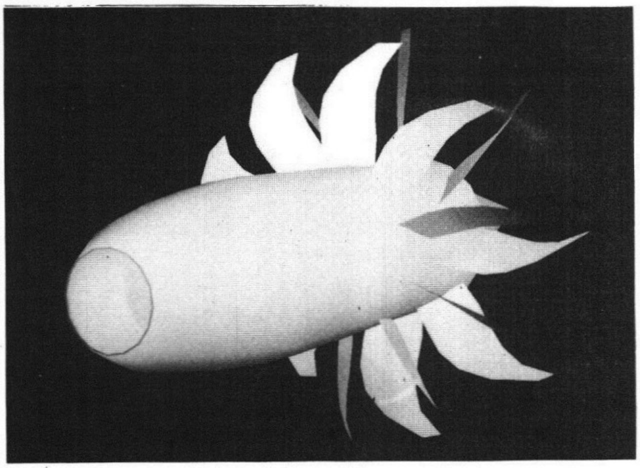

Fig. 7 Graphical post-processing. Shaded model of UDF-engine.

3.2 Performance Model

The Performance Model[11] comprises the consistent functional description of the aircraft aerodynamics and engine characteristics. Independent of the degree of analysis of the applied methods, the specific data can be accessed over central interfaces. The model consists of the Flight Performance Interface and the Simulation Module which both get the required engine and airfoil data out of the Empirical Data Base. This contains functional descriptions of the geometry and aerodynamic properties of actual subsonic and transsonic airfoils.

For the representation of characteristic turbofan and turboprop data it also contains generalised thrust/power and consumption approximations which base on performance data determined analytically or through experiments. Figure 8 shows as example diagrams generated for a turboprop.

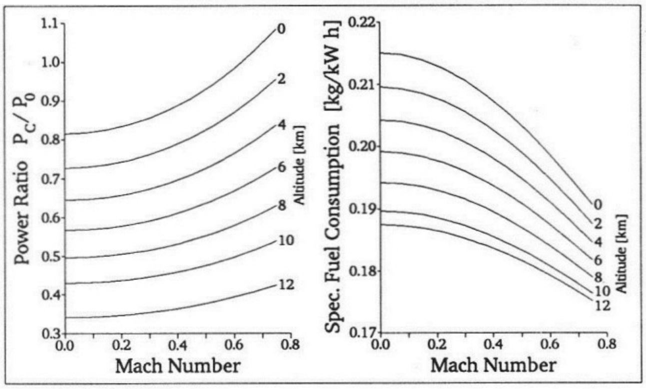

Fig. 8 Empirical Data Base. Generalized turboprop charts.

On the basis of this Empirical Data Base the aircraft performance during all conceivable flight phases and conditions during operation can be analyzed by means of a Flight Performance Interface. This interface allows the consistent calculation of all performance data necessary for examining

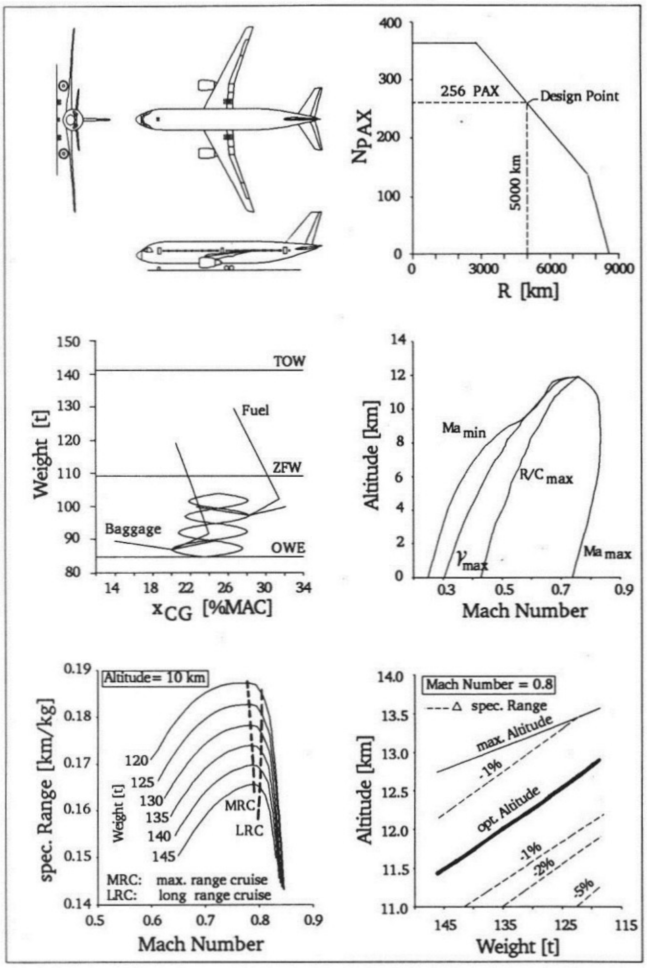

Fig. 9 Performance Model. Typical diagrams.

the influence of off-design flight missions on the configuration developement. Typical diagrams for evaluation of performance include payload-range, weight & balance, flight envelope, specific range as a function of altitude and weight, and altitude selection, figure 9.

Using this Flight Performance Interface as well as the Empirical Data Base the dynamic flight-mechanical behaviour of a design can be considered in the configuration development by the Simulation Module[13]. With this module, simulation tasks which are typical for the configuration development phase can be solved, e.g. engine failure, flight near ground. If the calculation of the flight properties proves that the design specifications are not met, the configuration has to be readjusted and a new design synthesis started, figure 10.

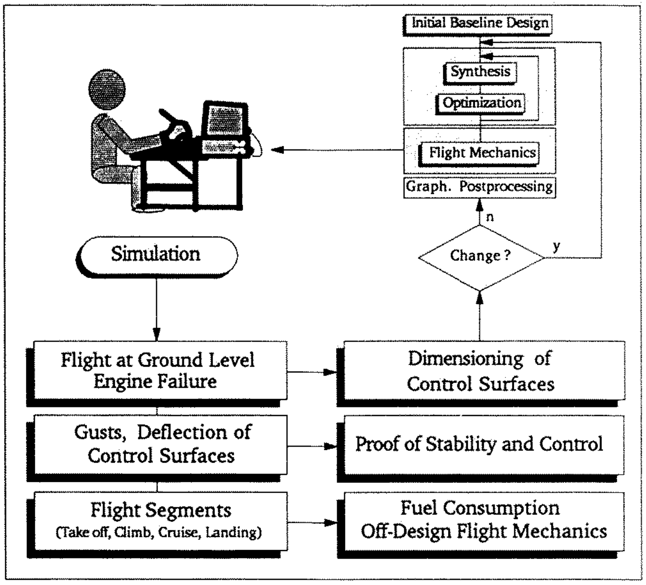

Fig. 10 Flight Simulation Model. Potential of applications.

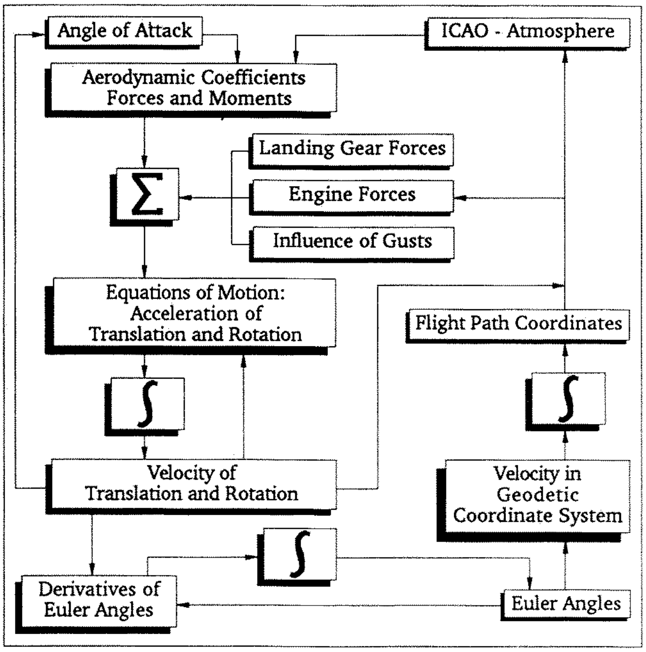

Fig. 11 Flight Simulation Module. Flowchart.

The solution of the equations of aircraft motion, figure 11, enables the investigation of typical aspects not considered in the design synthesis, such as:

- the calculation of important geometry parameters of the configuration which in the Initialization Module are merely determined on a statistical basis, e.g. the vertical positioning of the horizontal tailplane or the sizing and positioning of the ailerons and vertical and horizontal control surfaces,

- the calculation of dynamic longitudinal stability at aft c.g. position and with a given stability margin as well as the logitudinal control at foremost c.g.,

- the analysis of static and dynamic stability and control with leading edge and trailing edge high lift devices deflected,

- the determination of static and dynamic lateral stability and control, in particular with engine failure.

To demonstrate the potential of this Simulation Module, figure 12 shows the dynamic stability behaviour of a conventional low wing aircraft as a function of c.g. position, influenced by a gust.

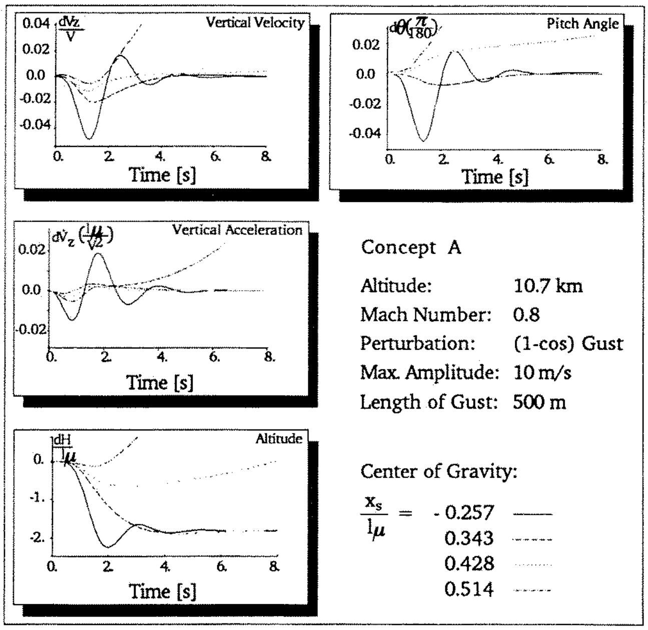

Fig. 12 Flight Simulation Model. Dynamic stability behaviour.

4 Potential of the modelling approach

4.1 Aerodynamic Analysis of Aircraft Configurations

In order to be able to predict the aerodynamic performance of a developed configuration it is necessary to apply a range of aerodynamic analysis methods of varying complexity and accuracy. Classical methods of aerodynamic performance of transport aircraft wings at subsonic speeds are based on the solution of the potential equation of three-dimensional incompressible flow by means of

- lifting line analysis,
- lifting surface analysis, and
- integral solutions.

The application of more sophisticated methods within the realm of CAPDA would be inconsistent with the capability of the herein applied analysis methods for aircraft weight and engine performance and, therefore, has to be subject of more advanced design phases.

During the development of the CAPDA system, a simple lifting-line algorithm for conceptual design synthesis and two different lifting surface methods (a standard vortex-lattice procedure and the spectral method for the solution of the transonic small perturbation equation by Purvis and Burkhalter[14]) for the optimization of the wing planform, camber, and twist have been implemented. For the analysis of more complex configurations, e.g. wing-tailplane or wing-fuselage combinations, a first order panel method and a spectral panel algorithm[15] have been applied. An example of the application of these five methods to the calculation of the wing lift distribution of a transport aircraft wing at a flight Mach number of 0.8 and a design wing lift coefficient of 0.5 is given in figure 13. It is apparent that for this simple planform configuration all calculated lift distributions are in reasonable agreement and that the lifting line and lifting surface methods applied here can be expected to yield reasonable results in the conceptual design phase.

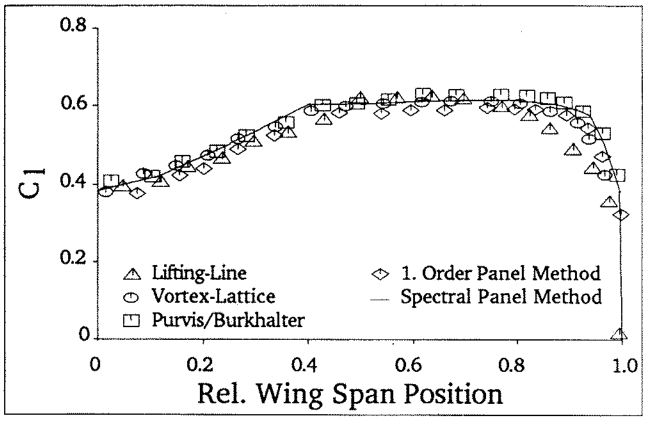

Fig. 13 Aerodynamic analysis. Comparison of methods for calculation of wing lift distribution.

The geometric model presented here consists of a continuous functional representation of the individual aircraft components. Aerodynamic analysis methods for complex geometries which are based on the numerical solution of surface integrals, however, usually require a discrete representation of the aircraft component surface by means of triangular or quadrangular patches. This panel surface has to be derived from the representation in the geometric model by means of a fully automatic grid generator. The creation of a consistent and steady panel surface that enables the applied analysis methods to correctly predict the actual aerodynamic behaviour of the complete aircraft configuration, is an elaborous and time-consuming task and the utilization of fully automated surface grid generation techniques is elemental to the efficiency of the whole design process. Therefore, a blocked-grid algorithm for the generation of triangular surface panels on multiple intersecting surfaces, e.g. wing-fuselage, fuselage-tailplane, or wing-pylon-engine configurations, has been developed and applied[15]. Figure 14 demonstrates the automatic refinement of the panel size along surface lines orthogonal to the intersection of the components, here the wing-fuselage intersection of a medium-range twinjet. By this procedure, numerical stability and consistency of the aerodynamic panel and spectral methods is assured and the interference effects of neighbouring and intersecting surfaces can be expected to be correctly accounted for.

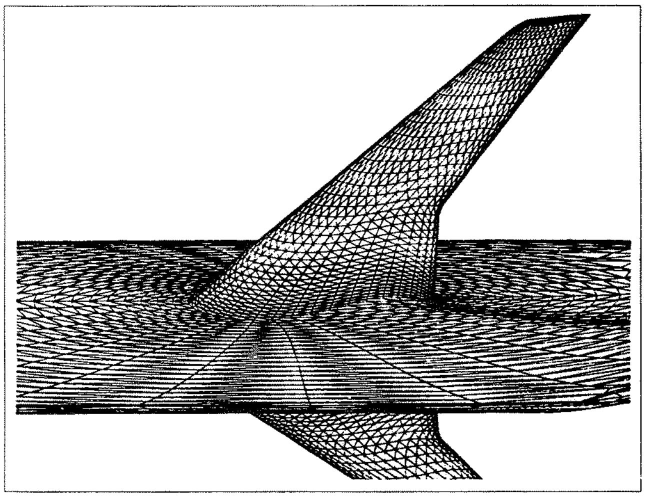

Fig. 14 Aerodynamic analysis. Grid generation.

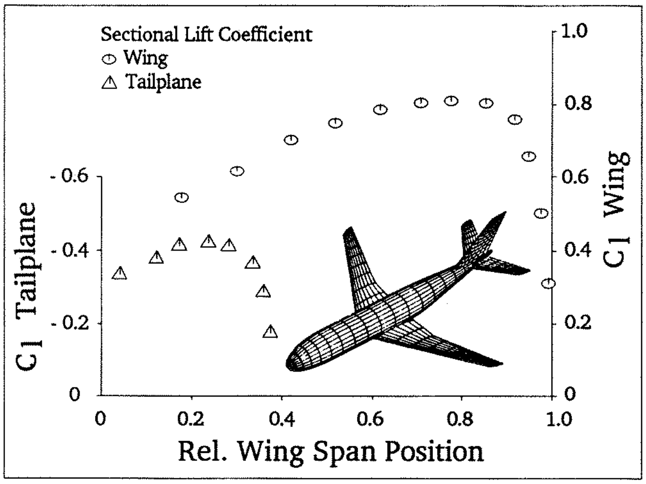

Fig. 15 Aerodynamic analysis. Application of panel methods. Lift coefficients related to respective surfaces.

As an example for the application of the described methods, figure 15 shows the sectional lift distribution generated by the wing and horizontal tailplane of the twinjet mentioned above. Wing planform and twist/camber distribution have here been developed to give minimum wing induced drag, wing pitching moment, and therefore overall trim drag. This demonstrates that a geometric model of the surfaces of commercial aircraft based on the principle of dynamic variant programming can flexibly handle the continuously changing and developing geometry over the conceptual and first preliminary design phases.

4.2 The Synthesis-Integrated Optimization

Optimization of main design parameters with CAPDA have in the past been executed with a modified Hooke & Jeeves strategy[16]. Although this method is characterized by a high reliability in finding the optimum it has the disadvantage of needing large computational effort due to the calculation of the merit function after complete consolidation of the design. Recent research regarding the convergence behaviour of the design synthesis has shown that only few iterations are sufficient to determine the trend of the merit function. Therefore it is obviously more efficient to change the optimization variables to minimize the merit function already during the design synthesis.

In order to realize this approach it was necessary to develop a new optimization strategy which could be integrated in the synthesis process. As a compromise between the multi-level optimization approach developed by Sobieszczanski-Sobieski[17,18] and the implemented Hooke and Jeeves algorithm this new more aircraft-specific strategy determines the gradients of the optimization variables as early as possible during the design synthesis. This results in a configuration which is simultaneously consolidated and optimized. This way the separated execution of design synthesis and optimization in two superposed loops could be given up in favour of a simultaneous proceeding[19], figure 16.

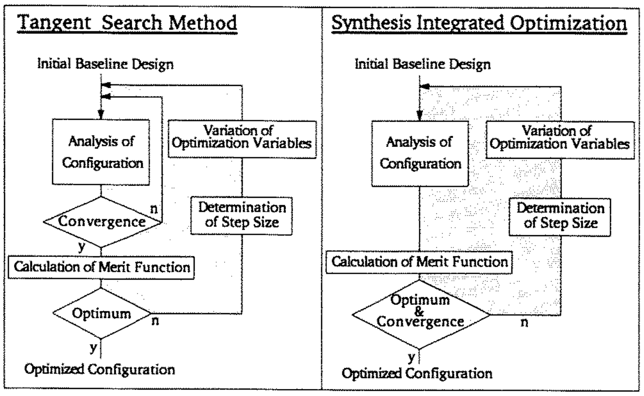

Fig. 16 Optimization. Comparison of the different strategies.

The following requirements have to be considered when developing a concept for this strategy:

- The convergence of the design synthesis must still be guaranteed.
- For all optimization variables the gradients with respect to the merit function must be determined for the same level of consolidation.
- The step size control must be independent of the value of the gradients of the merit function.
- The method must consider the design restrictions when searching for the optimum.

Applying the developed optimization strategy the search for the optimum starts with the definition of a variable vector and an initial step size for each variable. After a selectable number of synthesis-iterations the value of the merit function and of the design restrictions which are considered via external penalty functions are calculated. As soon as the location of the optimum with respect to all design variables can be predicted, an improved variable vector is determined by collectively reducing all step sizes. Consolidation and optimization of the configuration are finished when the criteria of termination of the synthesis are met, and the minimal step size is reached for all optimization variables[20].

The synthesis-integrated optimization was verified by comparative calculations with the modified Hooke & Jeeves algorithm implemented in the Methods Library of CAPDA. Based on exemplary optimizations of a commercial transport aircraft, figure 17 compares the efficiency and convergence behaviour of both optimization strategies for a univariate optimization of the aspect ratio and for a simultaneous optimization of aspect ratio and bypass ratio. In this figure the relative change of the optimized variables and the amount of needed synthesis iterations is plotted. The directness with which the curves strive towards the optimum allows an evaluation of the strategies and demonstrates the superiority of the newly developed synthesis-integrated optimization. In the displayed example the advantage in saved computer time increases with the number of optimization variables.

A further reduction in computational effort can be achieved by replacing the step size control described above through the Golden Section Method which determines the part of the examined interval in which the optimum lies and eliminates the rest. In contrast to the optimization through examination of the local environment the computational effort in this case is independent of the start vector. In addition, the number of iterations necessary to find the optimum can be determined in advance as a function of the

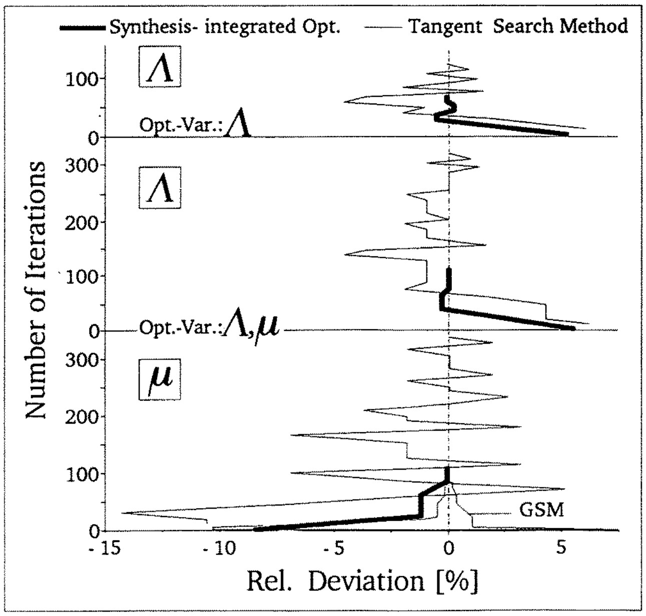

Fig. 17 Optimization. Comparison of efficiency of the different strategies.

demanded accuracy. Unfortunately, due to the fact that the topology of the merit function changes with advancing consolidation the application of the Golden Section Method could lead to the elimination of the wrong part of the interval if the final location of the optimum is not apparent at early stages of the synthesis. This effect can be recognized by the obvious convergence of the optimization variables towards an interval boundary and can generally be avoided by restarting the optimization with new interval boundaries.

5 Comparative Concept Evaluation

The objective of the conceptual phase of aircraft design is the comparative evaluation of competing configurations with the aim of selecting the best concepts for more detailed analysis in the following design phases. The CAPDA-system is particularly suited to effectively support this decision-making process by means of its computer-internal modelling concept with the consistent representation of aircraft geometry and performance. Furthermore the possibility of problem-specific selection of analysis methods from the Methods Library according to the physical properties of the examined concept, and the open system architecture allowing the implementation of company-internal methods, contribute to this suitability of CAPDA[2]. Another tool in the comparative concept evaluation is the Synthesis Integrated Optimization strategy described under 4.2.

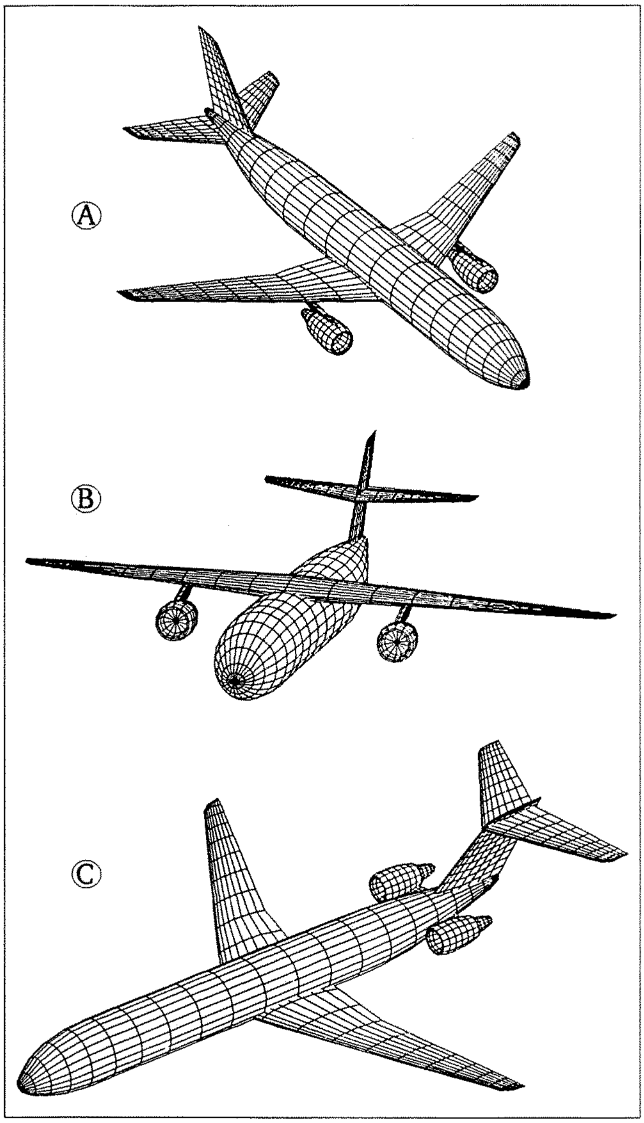

Fig. 18 Comparative concept evaluation. Concept suggestions for a medium-haul twin jet.

Figure 18 shows three concept suggestions for a medium haul flight mission. One example of how the CAPDA-system can support the design engineer in evaluating these configurations is the calculation and comparative display of the respective weight breakdown and DOC shown in figure 19.

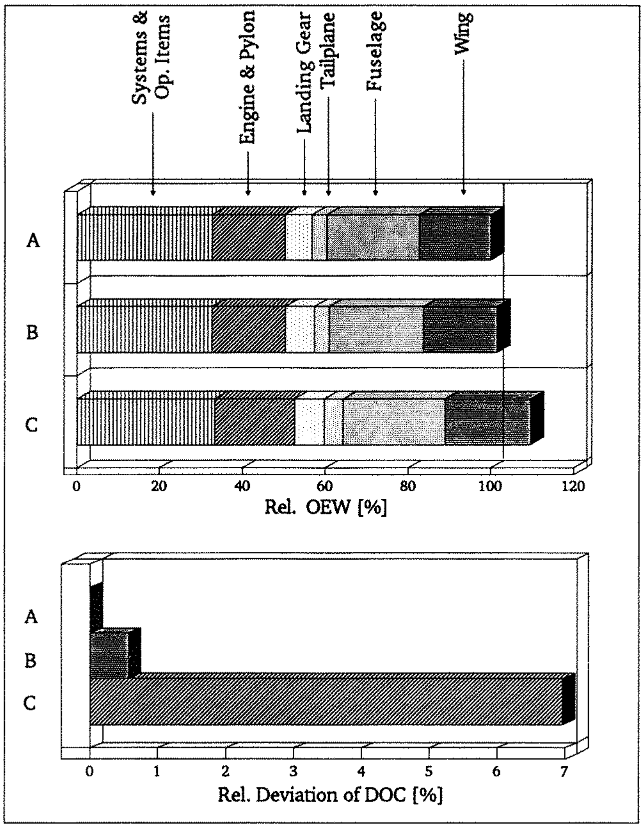

Fig. 19 Comparative concept evaluation. Weight breakdown and DOC.

An important assistance in finding the best concept is the examination of the influence different parameters have on the development of the configuration. As an example, figure 20 shows the influence of different fuel prices on the optimal aspect ratio and bypass ratio. Figure 21 deals with the weight reduction for instance resulting from the implementation of new materials. If a certain primary weight reduction is achieved the readjustment of main design parameters such as thrust, geometry and position of the wing and tailplane to the design requirements leads to secondary savings in weight. For instance a primary weight reduction of 10% for the Initial Baseline Design is increased in the following synthesis by the factor listed on the ordinate, resulting in a total weight reduction of 15% for the Consolidated Baseline Design.

By means of the optimization strategies implemented in CAPDA it is also possible to examine the influence of different merit functions on the development of the configuration, for instance via a weight breakdown as shown in figure 22.

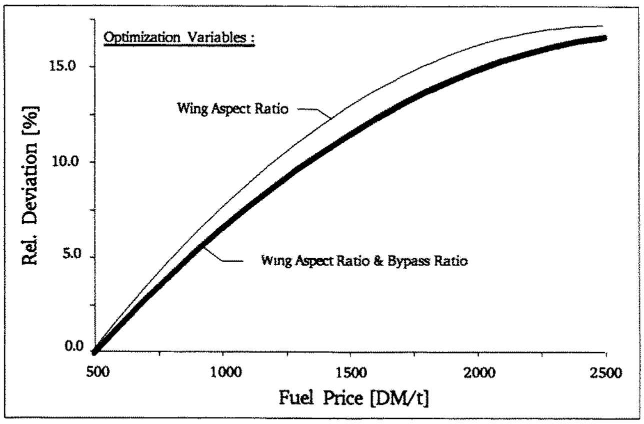

Fig. 20 Comparative concept evaluation. Influence of fuel price on bypass and aspect ratio.

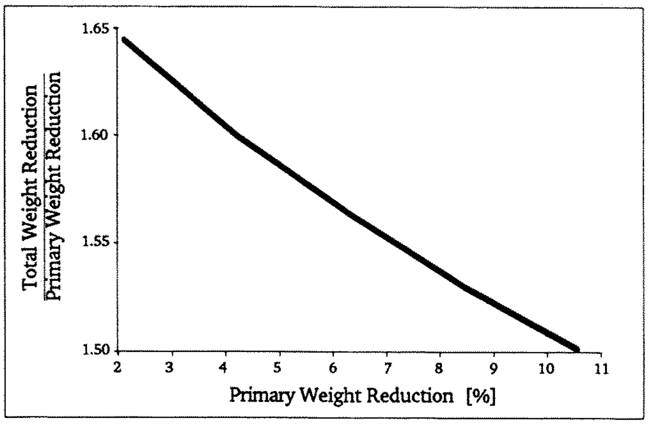

Fig. 21 Comparative concept evaluation. Snowball effect.

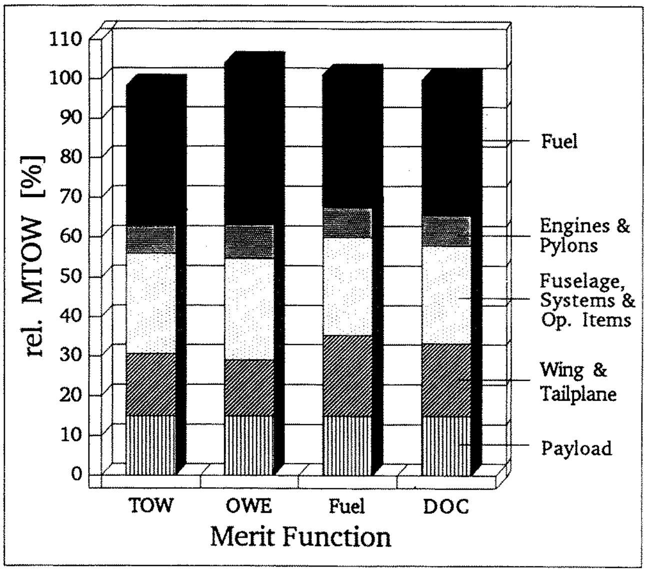

Fig. 22 Comparative concept evaluation. Influence of merit funtion.

6 Concluding remarks

The modular program system CAPDA for computer-aided aircraft configuration development with the main components Design Management System including Methods Library, independent algorithmic computer-internal modelling, Initialization Module, Data Base Management System and Graphic Module allows a problem-adapted solution of various tasks of conceptual aircraft design. In particular, with the flexible computer-internal modelling of geometry and performance the basis was established for implementing more versatile analysis modules of higher level which reach into the first preliminary design phase as well as for realizing a synthesis-integrated optimization strategy.

Since the representation of geometry and performance is based on a few parameters only the small amount of storage necessary enabled the compilation of a Statistical Data Base which, containing practically all existing transport aircraft, serves as the basis for approximations of initial statistical configurations for the design synthesis. This approach is not very useful when unconventional configurations and new technologies are involved. Therefore efforts are in progress to extend the Methods Library for all design disciplines, e.g. weight determination on a physical basis, engine/wing/fuselage/tail aerodynamics, consideration of fuel consumption dependent on a free definable flight profile, complete simulation of dynamic flight, implementation of propfan characteristics, and influence of commonality on the merit function.

Acknowledgement

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