A Computer-Augmented Procedure for Commercial Aircraft Configuration Development and Optimization

C. Haberland* and W. Fenske†
Technical University of Berlin, Berlin, Federal Republic of Germany
and
J. Thorbeck‡
Deutsche Lufthansa, Hamburg, Federal Republic of Germany

Based on an idealized computational model of the aircraft, the computer-augmented preliminary design procedure (CAPDA) for commercial aircraft design and optimization has been developed. Contrary to the sophisticated approach of existing complex CAD systems, which consider structural and aerodynamic aspects in more detail and even lead to a CAM interface, in the system presented here the configurational development is emphasized, with special focus on parametric studies and optimization. The iterative synthesis that is established on a corresponding analysis level and uses input data from an extensive statistical data bank results in a numerical representation of geometry and performance. For the development of an optimized baseline configuration, an optimization module based on a direct search strategy can be applied. The capabilities of the program system are demonstrated in several design examples.

Introduction

THE design of a transport aircraft combines many disciplines, which must be properly interfaced, leading to the "synthesis of aircraft design," as shown in Fig. 1. During the design phases (conceptual, preliminary, and detail design), the increasing interaction of the particular design elements (aerodynamics, structures, weight and balance, stability and control, avionics, propulsion, performance requirements, and economics) leads to a variational problem of a very high order, which does not have a closed solution.

The design process begins with specification of the flight mission and with the operational and airworthiness requirements. In this design phase, emphasis is placed on parametric variation of a large number of design variables rather than on detailed analysis, which would require a high degree of computational effort. Therefore, the mathematical model of the aircraft is relatively simple, although all important design elements are included. In the conceptual design phase an initial baseline configuration is developed by comparison of various design concepts with respect to a certain objective function, e.g., the direct operating costs. In the preliminary design phase, the design with the highest merit is further developed, and again all properties and characteristics are analyzed. As the mathematical model is continuously refined, the applied analysis methods have to be increasingly sophisticated. Because computational effort prohibits any analytical optimization, iterative methods have to be applied. In order to perform systematic variations in an acceptable time span, the computer is the only appropriate tool.

A survey of existing CAD systems indicates that the complexity of most of the investigated programs that claim to cover a wide range of design levels prohibits efficient fundamental investigations, e.g., parametric optimization and sensitivity studies at an early design level. An appropriate program structure should rather reflect a design philosophy that corresponds to the analytical approach of manually performed design. The resulting CAD system can be expected to be transparent to the user who retains full monitoring capabilities. This flexibility does not preclude a schematic proceeding but encourages user creativity. Experience shows that this claim of flexibility and transparency cannot be realized through a large integrated design program. On the contrary, a modular structure comparable to a bank of methods controlled through a highly flexible monitor system becomes necessary. This enables the designer to shape the design object according to his ideas and demands by means of a set of numerical tools. The basis of such a system is a data base of the complete, progressive numerical representation of the geometric and mathematical model of the aircraft, a data base that is continuously updated as the design process progresses. The model of the projected design system should be simple enough to allow multivariate optimizations. On the other hand, it should be expandable to permit more advanced design tasks, such as off-design analysis on the preliminary design level. The methods of the analysis and synthesis disciplines of the particular design levels have to be contained in a bank of methods and external data bases, e.g., aerodynamic and power plant, and statistical data have to be attached.

Concept of CAPDA

In 1982, a research project to develop the computer-augmented preliminary design system for aircraft (CAPDA) was initiated at the Aero/Space Institute of the Technical University of Berlin. This development is part of an interdisciplinary project established at the university that aims to develop new computer-oriented design models for general mechanical engineering applications. It is the intention of the Aircraft Design section to formulate guidelines for the structure of geometrical and physical models of commercial aircraft, as well as a problem-oriented design data base for conceptual and preliminary design and a flexible, dependable monitor system to the design process. The primary goal is to retain the flexibility and transparency of manual aircraft design by limiting the scope of the system, in constrast to the sophisticated design systems of the aerospace industry, which

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*Professor, Aero/Space Institute.
†Research Engineer, Aero/Space Institute.
‡Systems Engineer, Structures Division.

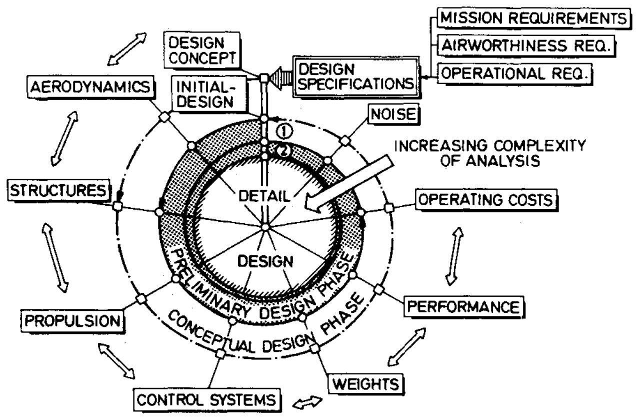

Fig. 1 Synthesis and phases of aircraft design.

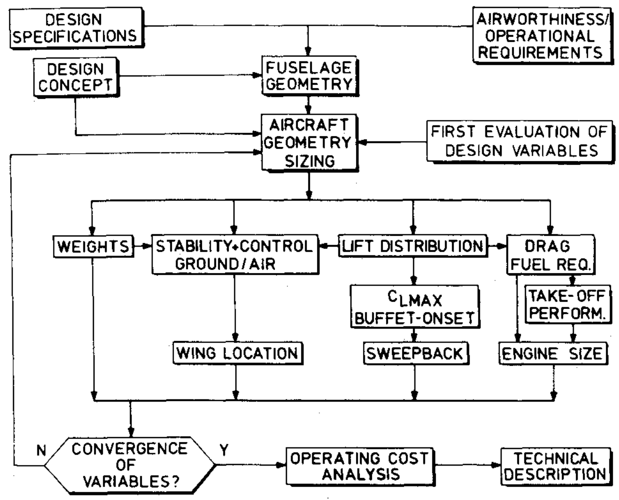

Fig. 2 Flowchart of the preliminary design synthesis.

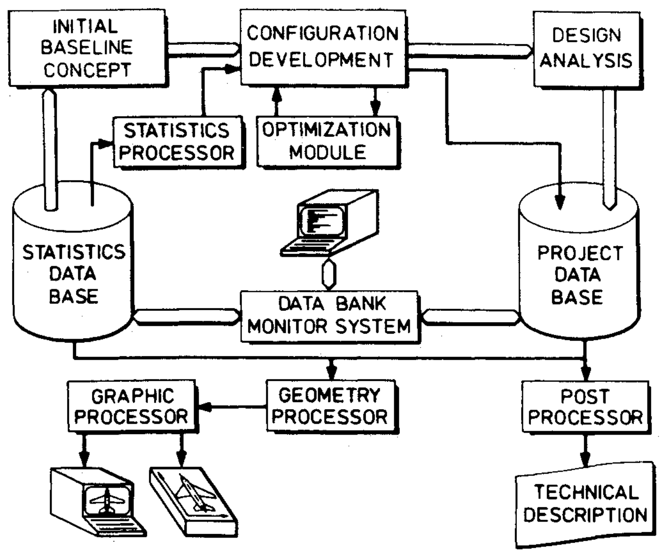

Fig. 3 Concept and structure of CAPDA.

attempt to cover the whole range of aircraft design. Emphasis is placed on a modular, transparent structure of the control program (monitor) and conveniently sized analysis modules rather than completeness and complexity of both.

As a first step, the automated design synthesis program FEPSY[1,2] was developed to investigate the mechanics and dynamics of preliminary design iteration. The structure of this program is outlined in Fig. 2.

After having specified the flight mission and the operational/airworthiness requirements, the concept parameters (e.g., high/low wing, number of engines, position of horizontal tail plane) are fixed. By choosing the general cabin layout (e.g., wide/narrow body, number of seats abreast, number of aisles, container size), the fuselage geometry is then automatically generated. This part of the aircraft will remain unchanged during the remainder of the conceptual design procedure.

First estimates for the design variables and an overall geometry are obtained by means of statistical formula. The four major aircraft sizing criteria are: 1) wing sweep-back, 2) wing location, 3) engine size, and 4) component weights. These constitute a set of inner iteration loops that are successively passed until final convergence of all design variables is reached. The analysis methods used herein are mainly of a statistical type corresponding to the accuracy level of conceptual design. Aerodynamic performance and high/low-speed lift limitations are calculated by means of USAF-DATCOM—type methods, such as Deiderich's method for wing lift distribution; parasite drag is calculated by wetted-area analogy, and trim drag is determined by simple equilibrium considerations. Weight formulas are based on statistics comparable to, and partially identical with, those described in Ref. 3. Engine performance maps are incorporated by means of interpolation of experimental data. A more detailed description of the program and the methods used therein is given in Ref. 2. Depending on the desired accuracy level of convergence, computation time varies from 2-10 s on a CD Cyber 170.

The experience gained with this synthesis program in regard to program flow control, program sequencing, analysis method selection, and pre- and postprocessing led to the definition and specification of the CAD system CAPDA, the preliminary structure of which is shown in Fig. 3. The clear separation of the following four subtasks is apparent: preprocessing; data handling; design iteration, optimization, and analysis; and postprocessing. Data handling is performed by the independent data base monitoring system (DBMS), which controls two data bases of identical structure consisting of statistical and project design data, respectively. The statistical data base will be used to obtain statistical formula for the configuration development module. Another application will be the derivation of first estimates for the design variables. Since this statistical data base consists of the pertinent design data of some 160 different commercial turbofan and turboprop aircraft, it is expected that the statistics processor can achieve very good results for both tasks.

The three modules—initial baseline concept, configuration development, and design analysis—are largely similar to the modules described in Ref. 2. The configuration development block, for instance, is a modified version of the above-described synthesis program FEPSY. Major improvements include replacement of the interpolation formula used for experimental data by corresponding approximation formula and a general streamlining of the program flow, especially the integration of the four inner interation loops into one, which cuts computation time by 80% and allows an efficient utilization of the optimization block.

The optimization module consists of several nonlinear numerical optimization routines for the minimization of implicitly and explicitly restricted multivariate functions. The routines include a Hooke-Jeeves/feasible direction method and several Lagrangian methods. A survey of the optimization block and several benchmark tests of the routines implemented here are given in Ref. 4.

In the design analysis module, several routines for a more detailed analysis of aerodynamics, takeoff and landing, and direct operating cost are provided. Since this module has not been used in preparing this paper, it will not be elaborated on. A detailed description of the methods used in the design analysis module and their range of application is given by Thorbeck.[2]

Various options for graphic and alphanumeric post-processing are implemented in CAPDA. Standard graphic routines are: simple three-view drawings, complex three-view drawings, wire frame models, hidden-line wire-frame models, and shading models, as well as routines for the visualization of the development of the design parameters during an iteration or optimization sequence.

Design Synthesis and Configuration Development

Mathematical and Geometrical Model

Prerequisites for an efficient CAD system are the conversion of the described aircraft design philosophy into an algorithmic computational model, the creation of a geometrical and mathematical model, and the compilation of an extensive statistical design data base. The interaction between these two models and the analysis methods is apparent: The model has to provide input data for the analysis and has to react to configuration change demands created by analysis results.

The development of the aircraft configuration during a conceptual or preliminary design iteration consists primarily of four different sizing effects that correspond to the four inner iteration loops shown in Fig. 2:

1) Sweepback of the one-quarter-chord line of the wing due to lift limitation by buffet onset.

2) Longitudinal wing location to meet minimum control and stability requirements in cruising and taxiing condition.

3) Engine size and thrust to meet takeoff, climb, and cruise requirements.

4) Component weight due to changing design takeoff weight and, therefore, overall size of the aircraft.

Since it is not always possible to meet all design requirements by changing the aircraft configuration parameters, several restrictions may remain violated after final convergence of the iteration sequence. These have to be met by adjusting the design or concept variables. Typical restrictions are: 1) horizontal tail plane area too small for control, 2) wing fuel tank capacity insufficient for this flight mission, 3) maximum angle of rotation for takeoff or landing too small, and 4) wheelbase or wingspan too large for the intended airport category.

These restrictions depend on which design data are considered constant during an iteration and which are synthesis variables. For example, it is obvious that the effect of the stability and control requirements is influenced by whether the horizontal tail plane area or its ratio to the wing area is held constant. Therefore, the term "design restriction" has to be used very carefully here.

In order to be included as implicit restrictions for the optimization routines, physical design restrictions have to be measured in some numerical quantity. Here, the difference between the amount provided (e.g., wing fuel capacity) and the amount required (e.g., fuel capacity for the specified range) is used. An example of the effect of some restrictions on the permissible range of two important design variables is shown in Fig. 4 for a medium-haul executive aircraft.

It is essential for the success of any computer-aided design system to properly coordinate the underlying mathematical and geometrical models. In the configuration development phase of aircraft design, it is the generation of a too sophisticated rather than an oversimplified model that one has to worry about. The former would necessitate a significant computational effort in determining even simple geometrical properties and thus reduce the effectiveness of simple analysis in the first design stage. On the other hand, the model should permit calculation of surface areas, volumes, c.g. positions, and cross-section area distributions of individual components. Furthermore, it must be possible to generate surface coordinates for graphical output as well as input for more sophisticated analysis modules, e.g., panel methods. As the

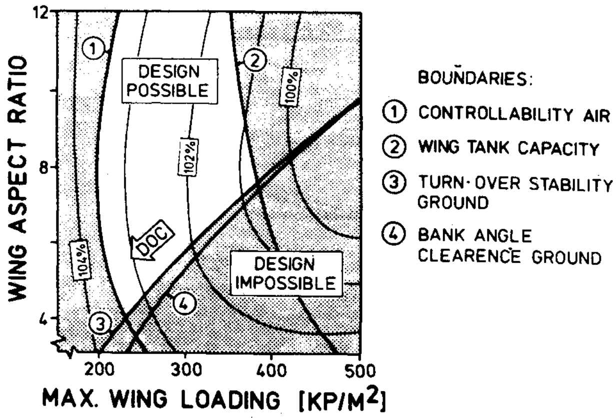

Fig. 4 Executive aircraft: implicit restrictions on wing loading and aspect ratio.

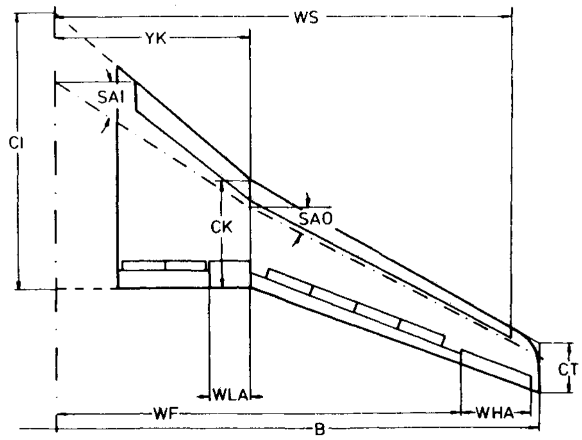

Fig. 5 Wing geometry: definition of planform parameters.

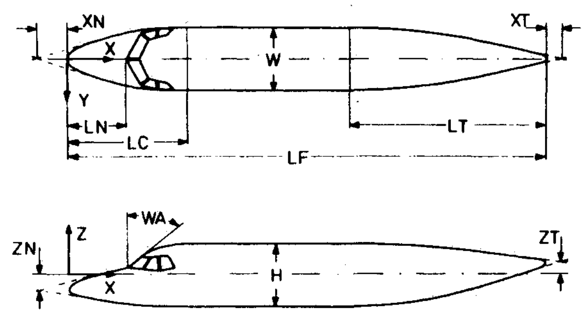

Fig. 6 Fuselage geometry: definition of shape parameters.

best compromise between these two requirements, the following model was chosen. In accordance with the principle of variant programming, the surface is described by parametric, piecemeal analytical functions. The parameters of these variants are mainly geometrical dimensions, e.g., fuselage length, wing position, kink position, sweep angle, which can also be used as input data for more simple synthesis and analysis methods. The most important drawback of sophisticated geometrical models, as described above, is thereby eliminated. Furthermore, this approach allows convenient cataloging of the geometry of existing aircraft in the statistical data base by simply determining the necessary parameters rather than digitizing the whole geometry.

The description of the wing geometry (Fig. 5) is derived from the methodology for conventional wing design. The surface of the wing, and of the vertical and horizontal tail, is generated by projection of a given profile along the leading and trailing edges and the line of maximum thickness. By this approach, the surface is completely described when the basic geometry parameters of Fig. 5 and the spanwise distribution of relative thickness and twist are given. Analog parameters are defined for the tail surfaces.

The fuselage cross section is approximated by hyperelliptic functions of fuselage width, height, and centerline position. Common elliptical and circular cross sections, as well as the more hyperelliptical cross sections of small aircraft such as the Dornier Do 228, can thereby be generated. The longitudinal distribution of the fuselage width, height, and vertical centerline are generated piecemeal by means of regularly transformed hyperellipses. Remaining free parameters are either user-controlled—i.e, they are design parameters such as length and diameter (Fig. 6)—or determined by design requirements, especially provision for an adequate cockpit.

An appropriate choice of these parameters, as well as the position of the vertices of the respective enveloping cones of the radome nose and the tail section, yields an acceptable approximation of the fuselages of all existing aircraft included in the statistical data base. In the case of two-deck aircraft, such as the 747, additional parameters describing the upper deck become necessary. The above-mentioned hyperellipses are then adequately deformed. The resulting surface has continuous second derivatives everywhere except within the cockpit window section.

Closely related to the fuselage geometry model is the turboprop geometry module. By consequently applying the principle of variant programming described above, the modeling of arbitrary turboprop configurations with one or two propeller planes becomes possible. The automatic adjustion of the engine fairing to allow for wing-mounted landing gears is provided. Design parameters, such as shaft horse power, position relative to the wing, and undercarriage geometry, govern the determination of the engine shape. Taking into account the incorporation of the landing gear into the nacelle and the resulting deformation of the cross-sectional hyperellipses, a very wide variety of turboprop engine configurations can be modeled. Figure 7 gives an example of a hidden-line visualization of the engine geometry of a typical turboprop engine.

Statistical and Experimental Data Utilization

Desirably short execution time for one design cycle requires synthesis and analysis methods that obtain consistent and satisfactorily accurate results with a minimum of computational effort. Appropriately simplified analytical methods usually yield poor-quality results. Statistical methods based on existing aircraft offer an attractive alternative. A typical example is the component weight determination carried out by statistical means only. Furthermore, the rate of convergence of the design iteration is influenced to a very high degree by the initial baseline configuration. Therefore, a statistical data bank has to be used to obtain a set of initial design variables which reflect the technological standard. The user should be able to extract design data of aircraft comparable to his design project from such a data bank and analyze them by statistical methods. This data bank has to contain the following data of all important civil turbojet and turboprop aircraft:

1) Geometric data (schematic components dimensions).
2) Engine data (thrust, bypass ratio).
3) Weight data (component weight, fuel weight, payload).
4) Performance data (range, fuel consumption, characteristic speeds, noise).

In the CAPDA project, care had to be taken that data selected to be stored were free of implicit or explicit redundancies. Use of relative data had to be waived due to the consequences of a change of reference length. For convenience, all geometry parameters should be measurable directly from three-view drawings. A list of 140 relevant data was selected after intensive studies of their reliability and availability. The list was subdivided into eight sections, which contain fuselage-, cabin-, wing-, empennage-, and undercarriage geometry data and engine performance and weight data. The data bank will, when completed, consist of 38000 – 42000 data points of 250 – 300 aircraft, even though it is restricted to civil passenger and transport aircraft with a minimum payload of one ton or ten passengers. Figure 8 shows two examples taken out of the statistical data base, using the two different graphical modules for three-side view and hidden-line visualization, respectively.

The statistics processor enables the engineer to define linear as well as nonlinear approximations of single design variables, determine the significance of the independent variables used by means of variance and correlation analysis, and then calculate the coefficients of the selected formulation. Usable methods are regression analysis, multiple linear approximation, multiple exponential approximation, and one-dimensional polynomial approximation. Selection of the particular method depends on the formulation of the respective problem and the amount of statistical data available.

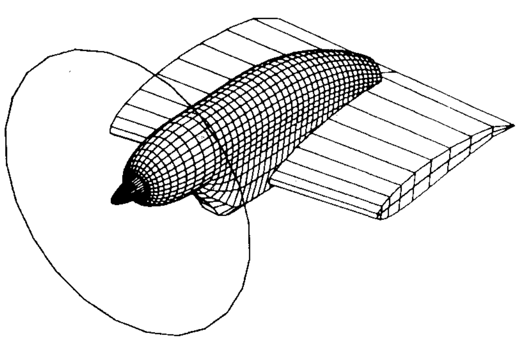

Fig. 7 Turboprop engine: hidden-line visualization.

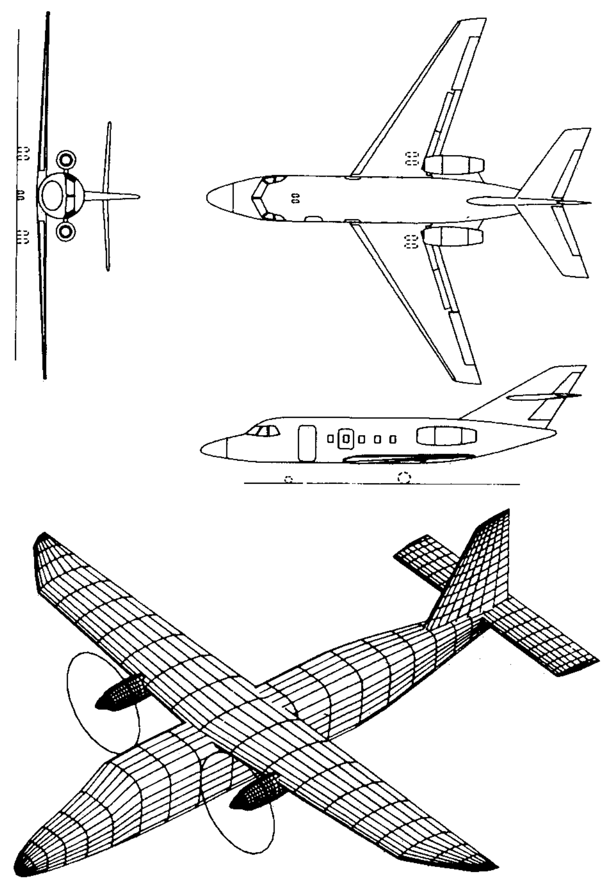

Fig. 8 Graphical post-processor: three-side view and hidden-line visualization.

Furthermore, it is possible to define arbitrary multivariate approximation functions and to evaluate their coefficients by means of different optimization software. Work on this part of the statistics processor is at an early stage. In particular, the kind and extent of statistical software yet to be implemented, as well as the necessity of further graphical presentations, are still to be studied; few results are available at this time. As an example, the length of the fuselage was approximated as a function of the number of passengers (NPAX) and the number of seats abreast (NSEAT), as shown in Fig. 9. The agreement between approximated and true fuselage length is satisfactory considering the simplicity of this approximation function.

A further application of the statistics processor is the approximation of experimental data, e.g., engine or propeller performance maps and airfoil polar diagrams. For that purpose, a multidimensional approximation program has been implemented that can approximate large amounts of data on the basis of a Taylor or Laurent series development. The successive removal of the smallest coefficient of the series followed by a new calculation reduces the number of coefficients until a certain error margin is reached. Following this procedure, the quantity of coefficients can usually be reduced to 20-30% of the initial amount without any intolerable increase in the relative error.

This program yields a smooth continuous approximation of irregularly distributed discrete data points of multivariate experimental and numerical investigations. Figure 10 shows the excellent agreement between measured and approximated data for a modern high-bypass turbofan. The input data for this approximation were taken from Ref. 5. The statistics processor also allows the designer to incorporate advanced technologies, such as prop-fan[6] into the design process (Fig. 10).

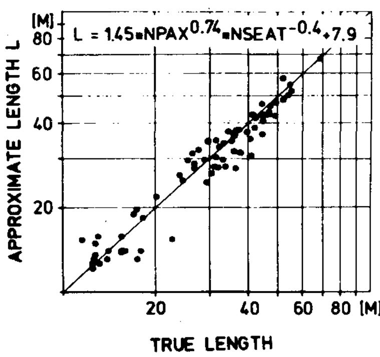

Fig. 9 Statistics processor: approximated length of fuselage compared to actual length.

Solution of the Synthesis Problem

For the solution of sets of nonlinear equations there are several numerical methods of different degrees of accuracy and computational effort. A single-step iteration procedure was chosen because of its resemblance to the approach of manually performed design and its relatively simple structure: The system of equations derived from the particular synthesis and analysis disciplines is successively solved for one design variable, respectively, which will be immediately used in the following computations. The vector of the dependent design variables is thereby successively approximated step by step with increasing accuracy, until changes in the variables remain below a certain error bound and, therefore, convergence is achieved. Figure 11 shows the development of some important derived design variables during one iteration sequence. It can be seen that, for this particular design problem, a satisfactory result is reached after 5-6 iteration steps.

Figure 12 demonstrates the improvement of the configuration during the iteration sequence. It had to meet requirements similar to the ones of the A310. The starting point was an intentionally poor estimate of the design parameters in order to underline the good rate of convergence of this method. Figure 12a shows the initial configuration, which obviously does not satisfy the design requirements due to poor wing and tailplane geometry and position. Successively, the wing, landing gear, engine, and tailplane design parameters are automatically adjusted to meet the design constraints, until a feasible configuration is found after the twelfth step (Fig. 12c). Comparison between the first step and the final result demonstrates the good rate of convergence. A detailed investigation of the convergence characteristics of this program and the effect of the iteration termination criteria on aircraft geometry, performance, and design restrictions is given by Fenske.[7]

Configuration Optimization

The aircraft design process primarily demands the search for a solution that is compatible with the design specifications. On the other hand, it is desirable to find configurations that are optimal in regard to a certain objective function. Potential merit functions, such as the direct operating costs or the payload fraction, are highly nonlinear, multivariate with respect to the design parameters, and usually not differentiable analytically. Therefore, nonlinear numerical optimization methods have to be applied here.

Direct search and gradient methods are well suited to this purpose, using numerical differentiation of the merit function that have been extended to include arbitrary implicit and explicit restrictions on the design variables. Since the solutions of typical design optimization problems are usually

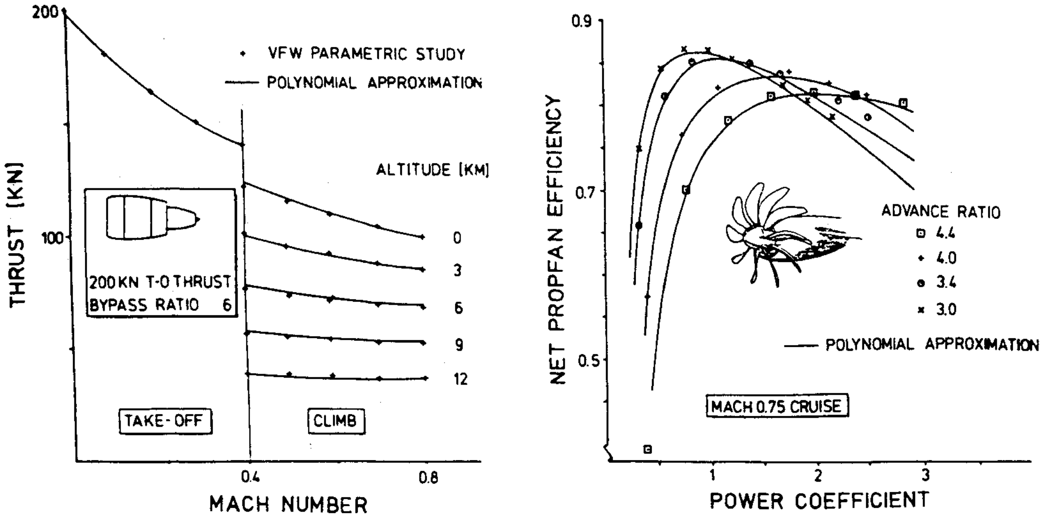

Fig. 10 Approximation of engine performance maps (left) and prop-fan performance charts (right).

located near an intersection between two restriction surfaces, an important criterion for the selection of a strategy is its reaction when the optimization path approaches or intersects a restriction surface. After a benchmark test of several candidate optimization strategies, a modified Hooke-Jeeves/feasible direction method was selected because of its reliability and relatively high efficiency.

An appropriate merit function for commercial aircraft optimization is the direct operating costs (DOC). The DOC reflect all significant aspects of aerodynamics, structural design, engine technology and operation, as well as maintenance. Optimization variables are those configuration and design parameters that have a significant influence on the result of the implemented analysis methods and that allow continuous variation. Discrete parameters, such as number of seats abreast and number of engines, can generally be optimized more economically by a parameter study, since there are only few feasible solutions.

Explicit restrictions can be imposed on all optimization variables either because of geometrical compatibility constraints or limited range of validity of the weight approximation formulas used in calculating the DOC. The implicit restrictions that have to be met were described above. Examples for two-parametric optimization are presented in Fig. 13, where the influence of wing aspect ratio and maximum wing loading on DOC, as well as some operational and numerical restrictions are shown. For both cases of optimization of a restricted and unrestricted merit function, the optimization module was successful after 5-8 optimization steps, respectively, using two different starting points.

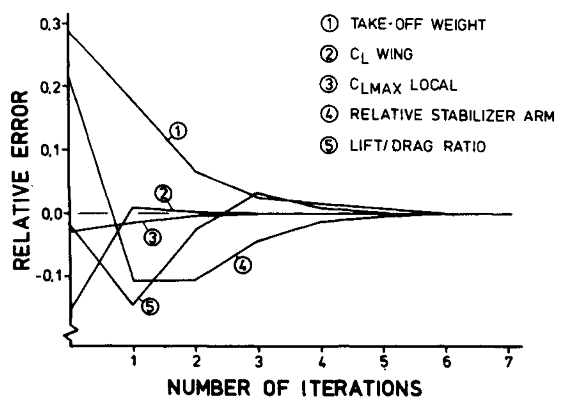

Fig. 11 Development of some design variables during the synthesis iteration.

An example for a more elaborated aircraft configuration optimization is presented in Fig. 14. The flight mission is

Range: 5300 km, Standard Reserves
Ma-number: 0.8
PAX: 237/8 abreast/twin-aisle fuselage
FAR-field length: 1900 m/ISA, s.l.
Fuel price: 0.60 $/kg

Design variables to be optimized are wing loading, aspect and taper ratio, kink position and chord length, and engine bypass ratio. The merit function used here is the DOC calculated by the Lufthansa method. A comparison of preliminary design optimizations using various different merit functions has been published in Ref. 7.

The starting point of the computation was a design of extremely poor efficiency, the design parameters so chosen as to demonstrate the convergence qualities of the method. As an output of the configuration development module, it does, however, meet all design specifications. Figure 14 indicates the reduction of wing area and takeoff weight due to decreasing taper ratio, development of a kink and increasing bypass ratio, and aspect ratio up to the 27th step. The static thrust initially decreases because of reduced drag/lift ratio; then, beginning at the 27th step, it is increased again due to the balanced FAR-field length requirement. At the last step, an obvious reduction in the aspect ratio leads to a balanced design with respet to cruise and takeoff requirement and, consequently, to reduced operating costs in spite of poorer aerodynamic qualities. This sequence was calculated on a Cyber 175 in batch mode. The optimization of seven design variables required 1400 CPU s, using 34K central memory. Calculating the merit function DOC, as well as its derivatives, required 290 configuration development iterations.

A comparative configuration optimization of a three- and four-engined version of a long-range transport aircraft and a shaded-model representation of the results are given in Ref. 7.

Future Developments

This paper concentrates on the configuration development, the first part of the preliminary design phase, although a lot of work has been done for the following design analysis

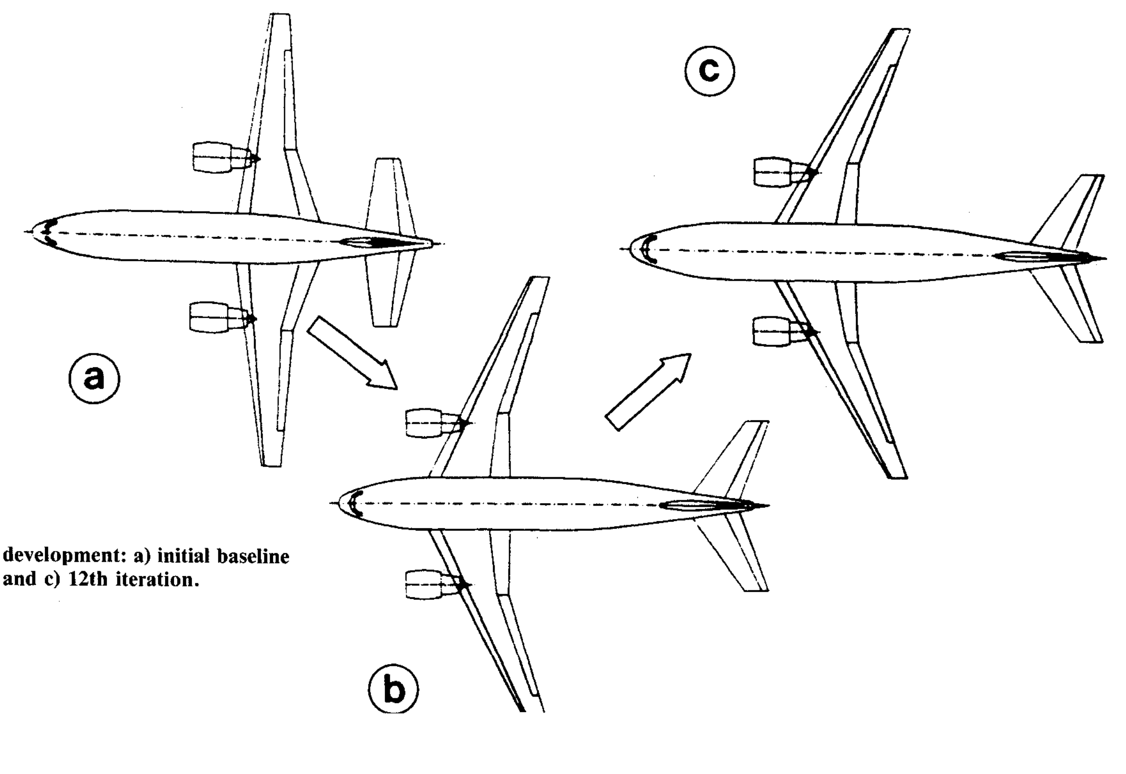

Fig. 12 Configuration development: a) initial baseline design, b) 1st iteration, and c) 12th iteration.

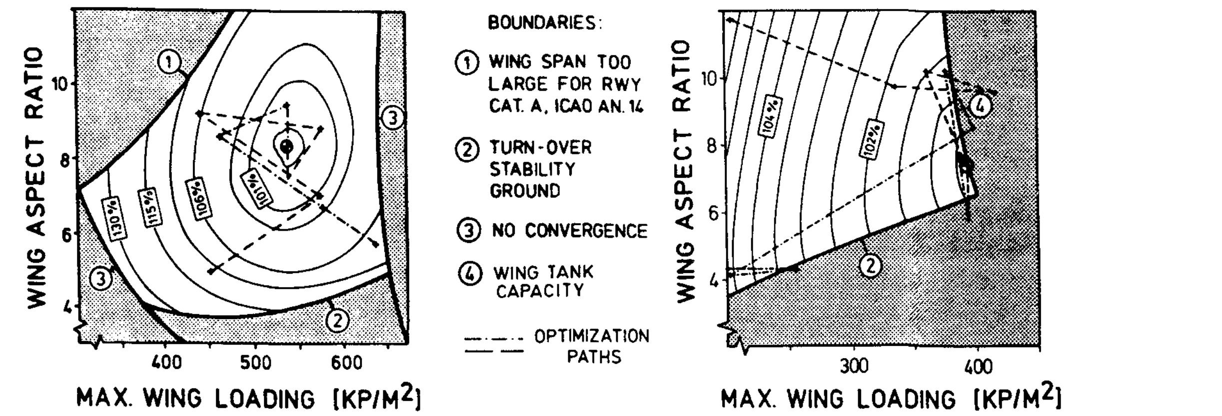

Fig. 13 Optimization of wing loading and aspect ratio. Medium-haul twin jet (left) and business jet (right).

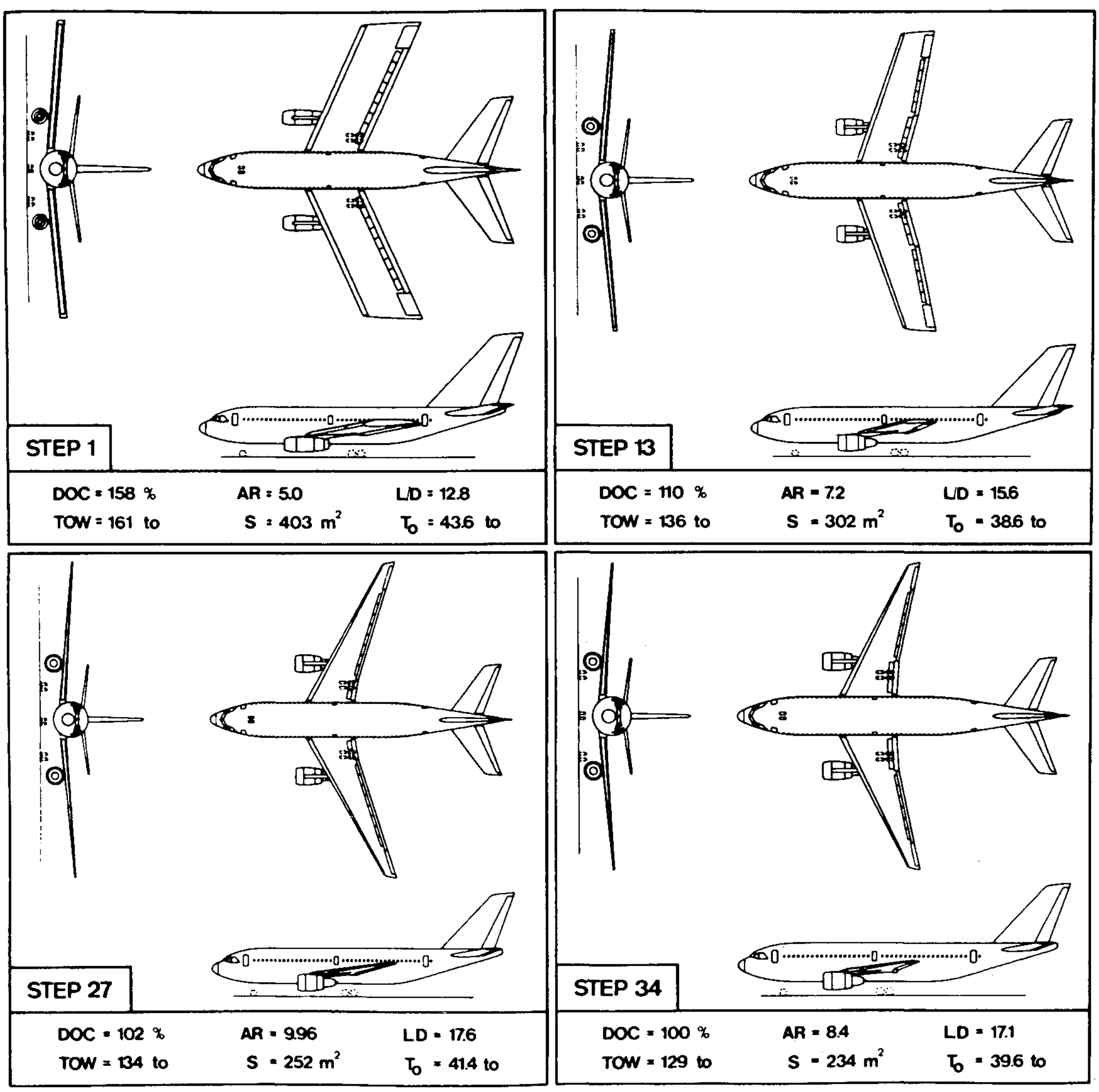

Fig. 14 Medium-haul twin jet: Optimization of wing-loading, aspect ratio, taper ratio, kink position and chord, twist, engine bypass ratio; and optimization steps.

phase. It is felt, however, that it would be desirable to extend the program system to a more general, accurate application in the whole preliminary phase. Therefore, future efforts for the following subjects will be necessary.

The effectiveness of the CAD system depends significantly on the performance of the monitoring system, which should control the design process as transparently as possible for the designer. The most important, but as yet unmentioned, capabilities which the monitoring system should be expected to have, and that will be implemented in the near future, are:

1) The input of the baseline configuration should be generated either manually, using the experience and judgment of the designer, or automatically by means of the statistical data base.

2) It must be possible to sequence the process according to the manual design procedure and employ the same logics.

This includes the option of manually controlled parameter variation in order to use the experience and intuition of the designer to achieve a faster convergence of the synthesis procedure.

3) The particular design sections should be sequenceable into an arbitrary number of single tasks. It must be possible to jump between different design levels as well as to interrupt at any operation sequence.

4) An integration of arbitrary analysis programs, e.g., panel methods, into the system should be possible without extensive modifications.

5) The statistics processor, up to now independent, which analyzes the data base, must be integrated into the program system. Furthermore, the data base monitoring system must be extended accordingly.

6) In order to prepare the graphical-interactive monitoring of the design process that enables the user to generate a three-view plot on the screen or to modify the result of the synthesis program, the development of a module for the interactive configuration input becomes necessary.

7) In order to present the computer-internal aircraft representation, a module for the presentation of design-related performance and operation graphs should be provided.

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