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A new numerical design tool for concept evaluation of propeller aircraft

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Abstract

Besides the conceptual configuration development of an aircraft, a modern design tool should cover the evaluation of competitor aircraft, allow the assessment of technological and operational scenarios, and thus should have the potential to 'right first time design'. For that purpose, the design system VisualCAPDA was developed on the basis of the former CAPDA system by evolutionarily introducing modern software standards under the premise of maximum reusability of existing FORTRAN coded methods. The new system plays the role of a workbench, which has to provide the analysis methods and necessary data. Through a graphical user interface the application of the system comes along as comfortable for the user as possible. In order to cover also turboprop aircraft, new modules with respect to cabin layout, propeller aerodynamic and acoustic analysis, propeller slip stream, engine modeling, geometry modeling are integrated into the design tool. The flexibility of the new system is demonstrated by applying it to the configurational development of propeller aircraft, investigating actual problems such as 'Twin or Quad', 'Turboprop or Turbofan', and finally, dealing with typical optimization problems. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The early inclusion of technological and operational scenarios into aircraft design as well as the ability to cover the analysis of competitor aircraft asks for a flexible software system. Hence, numerical conceptual design of aircraft is more and more regarded as a chance for 'right first time' design. That is due to the flexible variation of the relevant aircraft parameters in the early design

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phase and the assessment of their impact on aircraft performance and costs. This gives the chance to extensive comparative configuration investigations before handing over a promising layout to the next design phase. Particularly, besides competitor aircraft analysis, the discussed numerical system should cover the simulation of operational aspects such as flight routing taking into account emission characteristics as well as consideration of new technologies in propulsion, structure or aerodynamics.

However, traditional research activities have laid the emphasis more on the development of sophisticated analysis methods for all disciplines involved in the design process rather than on the introduction of modern software technologies in an aircraft design system. A modern design tool has to cope with complex data management and varying input schemes. It should flexibly allow the integration and interaction of the analysis methods, should manage input data, should provide a complex but consistent computer internal representation of aircraft geometry, performance and aerodynamics, allow project management, control the calculation loops and finally should generate an output on a high engineering level. The role the design tool has to play is that of a workbench, which for each analysis level supplies the analysis methods with their required information.

There are numerous design systems, e.g. CAPDA, which enable complex data management and varying input schemes, but they are conventional in the sense that they lack modern interfacing mechanisms like graphical user interfaces or extensive user-input validation. Due to their batch-oriented behavior they are not usage-flexible and their complex procedural architecture can only be extended with difficulty.

On the other hand, the system should allow to reuse procedurally coded analysis methods, which, mostly in FORTRAN, have been developed over the years, with reasonable modification. On the basis of these premises the CAPDA-System is chosen to evolutionary introduce modern software technology into a design system for conceptual aircraft design and analysis. The system called VisualCAPDA and developed by TU Berlin and PACE Aerospace and Information Technology Company will be applied to turboprop aircraft. The results show the ability of the system to quickly adapt to new problems such as consideration of propeller slip stream, integration of propeller charts, engine card decks and aerodynamic propeller analysis including acoustics.

2. The VisualCAPDA design system

2.1. Program architecture and interfaces

VisualCAPDA is a tool for the analysis and conceptual design of commercial aircraft, which is characterized by its modular concept, modern graphical user interface, extensible methods library as well as an open system architecture and a powerful post-processing facility.

It is based on the former CAPDA architecture [1], Fig. 1. Like its ancestor, VisualCAPDA allows to perform the classical design synthesis loop which determines masses and performances, sizes wing and tail areas, and fixes engine thrust. A calculation loop which is wrapped around the design process enables to adapt the aircraft to specific constraints. The system allows multivariate and restricted optimization of geometric and non-geometric parameters for various merit functions. The optimization of cruising speed and altitudes [2], the consideration of range flexibility in

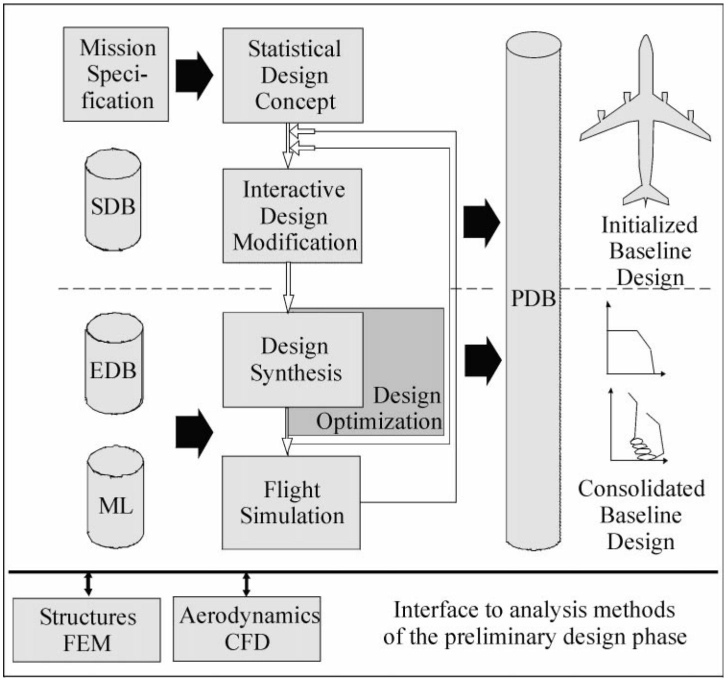

Fig. 1. CAPDA flow chart.

the design process [3], and ecology-oriented flight routing [4] have demonstrated the capability of the new tool.

The new design system shows the following features:

- In contrast to CAPDA, in the new design tool design and analysis control as well as database handling are performed by a newly developed graphical user interface (GUI), basing on X-Windows, instead of a FORTRAN code module. This allows to make use of the multi-window technique which allows the simultaneous initialization of aircraft geometry and design parameters as well as the performance of synthesis calculations or time-consuming optimization procedures, Fig. 2.
- The inherited open system architecture could be improved through a new library concept which is fully based on dynamically linked and loaded modules. Thus, a flexible extension of the method library becomes possible without need of access to the kernel program. The user can apply analysis methods from abroad or add his own know-how to the system without new compiling of the complete program system, Fig. 3.
- The system has a very large operative flexibility through a practice-oriented philosophy. For parameter optimization or trade-off studies an interactive selection of the merit function, optimization variables and constraints as well as corresponding control parameters is performed, Fig. 4.
- An on-line information system which helps the designer to directly manipulate the design parameters and the selection of the analysis method from the methods library.

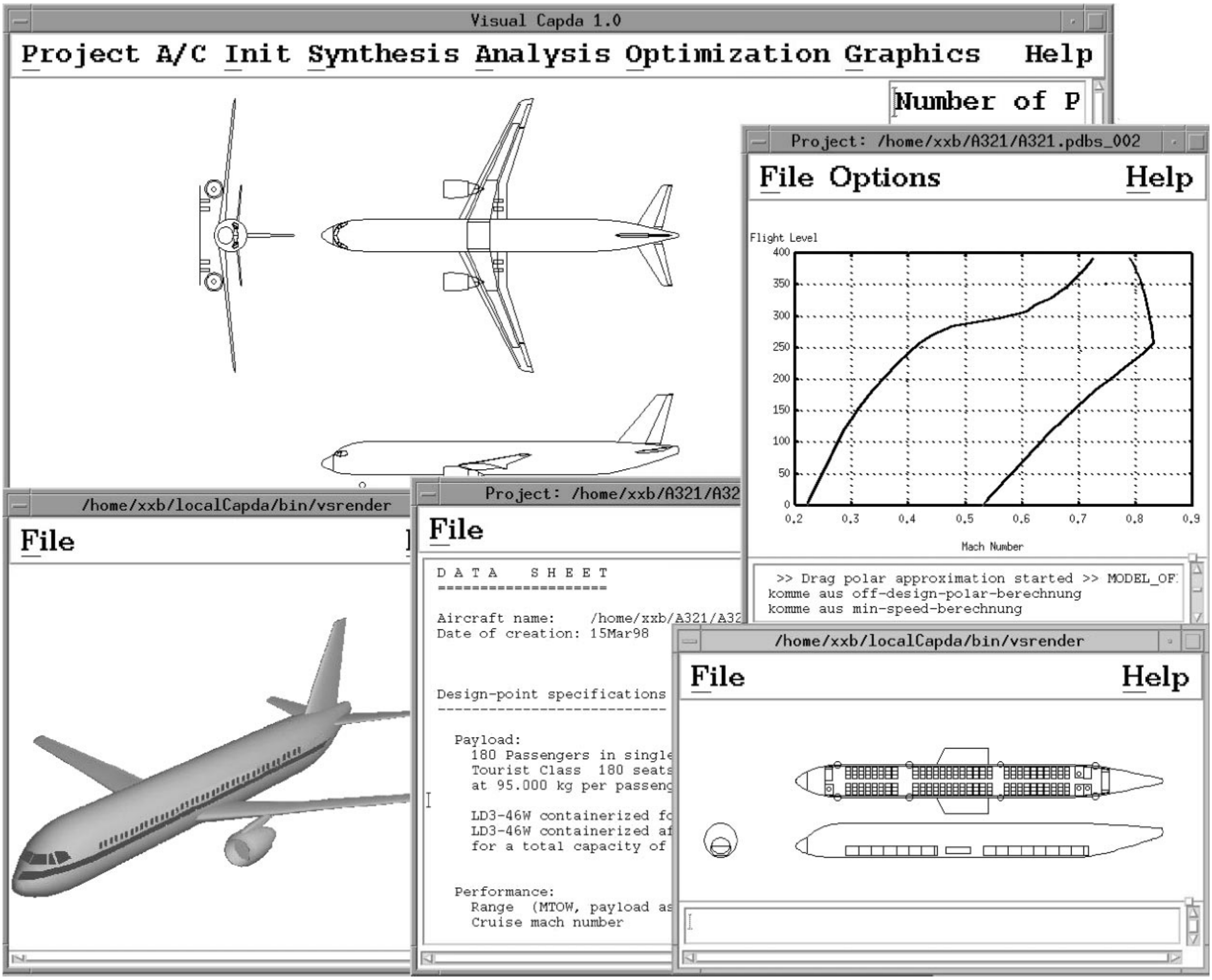

Fig. 2. Typical desktop of a design session with VisualCAPDA.

2.2. Program modules

For every major discipline, such as geometry, aerodynamics, masses, cabin layout and performance, standard program modules exist:

2.2.1. Cabin module

The GUI enables to comfortably calculate the distribution of required payload according to comfort and authority requirements. The cabin database contains a wide spectrum of standard seats, galleys, lavatories, or exits for the main deck compartment and currently used containers for the cargo compartment. If the required passenger number exceeds the available cabin space, the number of seats is decreased.

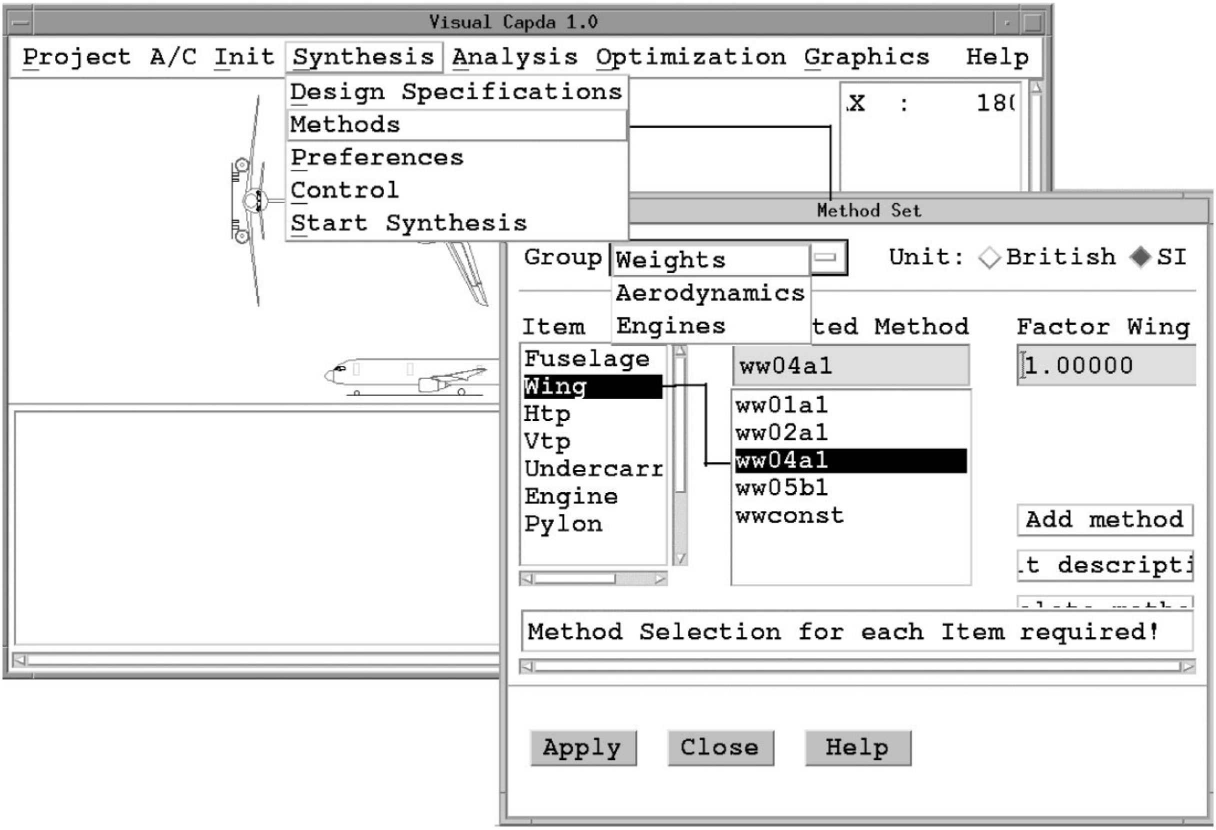

Fig. 3. Analysis methods interface.

2.2.2. Engine module

In order to easily change the powerplant of the project under investigation within the graphical user interface or to simultaneously adapt the engine within the design synthesis to a changed (e.g. ecologically based) flight routing, the need for a thermodynamic model becomes evident. This model should give reasonably precise data in the addressed early project phase in which real engine data are mostly not available. Thus, besides a 'rubber engine' modeling, in VisualCAPDA a thermodynamic model is implemented which allows to compute card decks which could then easily be integrated through the GUI.

2.2.3. Geometry module

The internal geometric representation must provide simple geometrical properties as well as detailed information on surface areas, volumes, center-of-gravity positions and cross-section area distribution of individual components. Therefore, a reasonable compromise between the degree of detailization and computational effort has to be striven for. This is done by description of the components' surfaces by parametric, sectionwise defined analytical functions while the definition of more complex shapes like fuselage tail and nose require more specific parameters. Fig. 5 clearly

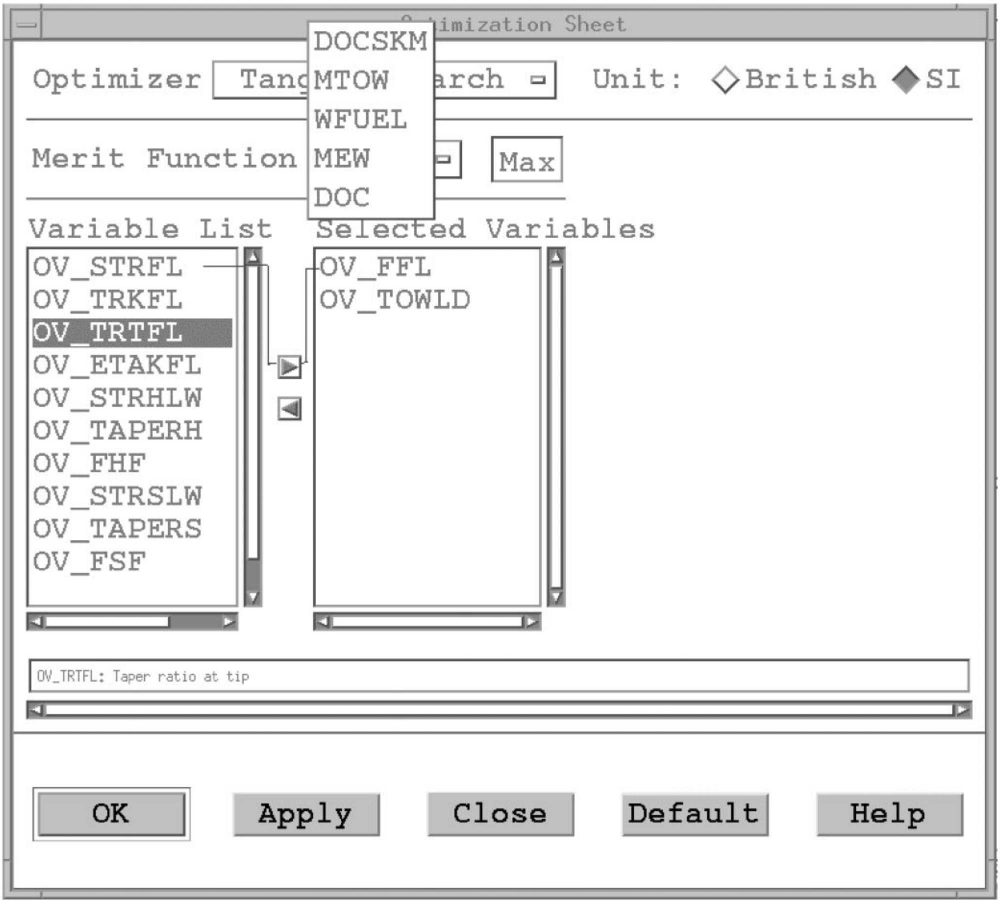

Fig. 4. Optimization interface.

shows the functional representation of aircraft geometry on the basis of main design parameters. The shaded-model visualization also demonstrates the flexibility of the module to react to more sophisticated configurations.

2.2.4. Aerodynamics module

This module provides calling subroutines with aerodynamic coefficients for each aircraft component. For the aerodynamic design it is very important to exchange drag determination methods, lift slope calculation procedures and routines for wing lift distribution calculation. Thus, the main feature of this module is its method-independent interface. That also enables the user to apply, for example, data files which can be handled like given card-deck data.

2.2.5. Performance module

The performance module handles the supply of speeds (flight envelope), rates of climb, specific ranges, glide angles or maximum, respectively, optimum altitudes for design as well as off-design conditions.

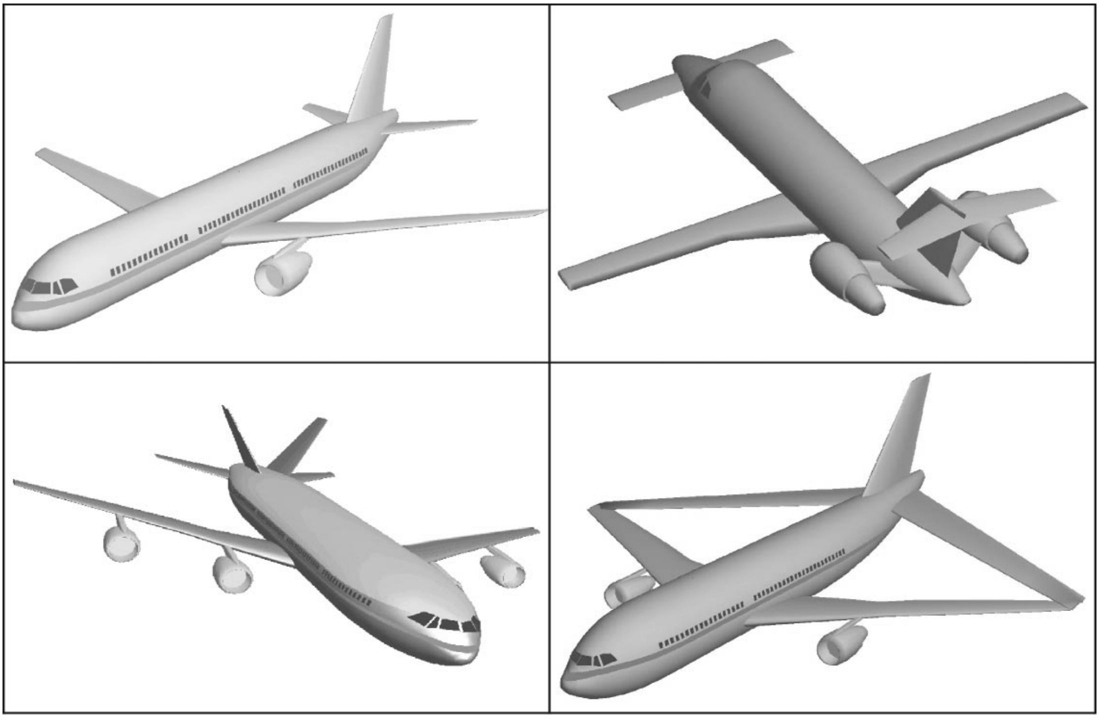

Fig. 5. Exemplary geometric modeling.

3. Adaptation to propeller aircraft

Since VisualCAPDA was originally developed for turbofan transport aircraft design, its application to turboprop powered commuter aircraft asks to integrate modified modules for engine modeling, geometry representation, aerodynamics, and cabin layout into the system.

3.1. Turboprop engine modeling

The main premise for the modification of this module is the applicability within the conceptual design phase and thus, the simplicity of its handling. Basis of the method is a simple but very meaningful approximation [5,6] in which the turbine characteristics are simplified in such a way that the reduced mass flow ratio only depends on the turbine pressure ratio. Since in cruising flight most of the turboprop engines apply the constant-rpm control principle, the effect of the turbine rpm-variation can be neglected without resulting in unacceptable inaccuracy of the card decks. In order to improve the modeling precision and extend the area of application of the model, a couple of modifications have been carried out by introducing new characteristics for the nozzle, combustion chamber, and high-pressure turbine. Furthermore, the accuracy of the model could be improved by taking into account the variation of masses in the particular engine planes.

3.2. Propeller aerodynamics analysis

A kind of Vortex-Lattice method (extended three-quarter point method [7,6]) was employed to calculate the aerodynamic propeller performance (thrust, efficiency as well as lift distribution along the blade). The paths of trailing vortices are assumed as spirals determined by the local resulting stream velocities (forward speed and tangential speed of the propeller) which have to be corrected with the axial induced velocities. Since for the determination of this velocity the circulation along the blades becomes necessary, which depends on the path of the trailing vortex, an iterative procedure has to be applied to calculate the propeller performance. The results have to be corrected with respect to viscosity, flow separation and compressibility through generalized profile polars. The verification of the method [6] for a 4-blade propeller for commuter aircraft (30–40 seats) and a 8-blade propeller (Hamilton Standard) for large aircraft (e.g. FLA) shows a good agreement, Fig. 6 and Table 1.

3.3. Propeller acoustics analysis

The propeller characteristics thus determined are also prerequisite for any noise calculation and thus the acoustic evaluation of competitive propeller aircraft. For the determination of the emitted propeller sound the analogy between sound and flow propagation is used: a good compromise between accuracy and computational effort yields the source line method [8] as solution of the FW-H equation [9] which has to be corrected with an empirical approach in order to take also into account atmospheric effects on the sound propagation.

The comparison of the calculated time history of the pressure signal (propeller I [8], Table 2) and the sound spectrum (propeller II [10]) with measurements in Fig. 7 shows good agreement.

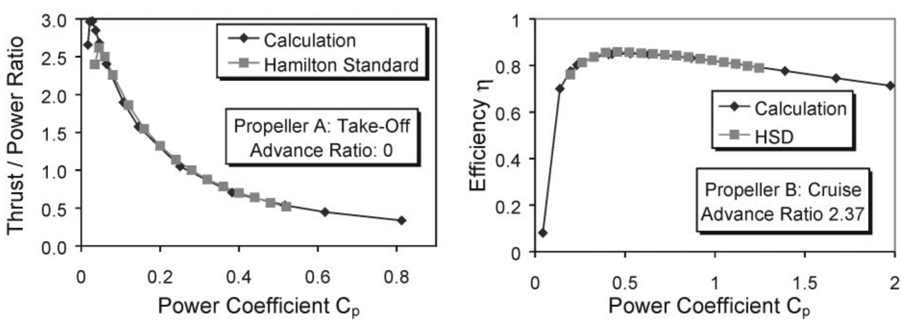

Fig. 6. Thrust/power ratio and efficiency.

Table 1
Main propeller parameters

	Blade number	Activity factor	Integrated design lift coefficient
Propeller A	4	160	0.5
Propeller B	8	140	0.5

Table 2
Propeller parameters

	D (m)	v (m/s)	N (rpm)	Blade number	Thrust (lbs)	L (m)	Φ (°)
Propeller I	0.673	36.6	7.890	3	40	0.528	30
Propeller II	0.476	29	10.000	2		0.49	40

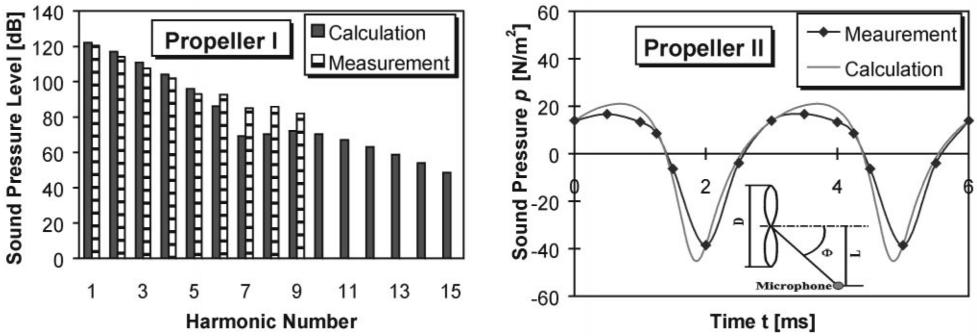

Fig. 7. Verification of acoustics analysis: propeller pressure signal and sound spectrum.

3.4. Propeller slipstream

The propeller slipstream yields significant influence on wing aerodynamics due to the completely submerged wing and the changed local onset flow angle at the wing caused by the propeller spin. Therefore, the lift distribution is very sensitive to the engine position.

To consider these effects an extended lifting-line method on the basis of [11] was implemented. Fig. 8 clearly shows for an aircraft configuration similar to a SAAB-340B the significant slip stream effect on lift distribution and a polar diagram which also outlines the additional friction drag due to the increased dynamic pressure.

3.5. Cabin module adaptation

Generally, commuter aircraft do have small passenger numbers, and thus, due to the required tail volume, small fuselage diameters. This makes under-floor cargo compartments impossible, and therefore, in practice on-deck compartments are provided. To take this situation into account, the cabin module had to be extended.

An example for the cabin layout with forward and rear cargo compartment and the resulting loading diagram is given in Fig. 9.

3.6. Geometry model

The modification of the geometry module with respect to its application for propeller aircraft is demonstrated in Fig. 10 by a shaded-model and hidden-line visualisation of a turboprop engine. This is an example of x-wise aligned cross-sections which are based on hyperelliptical functions.

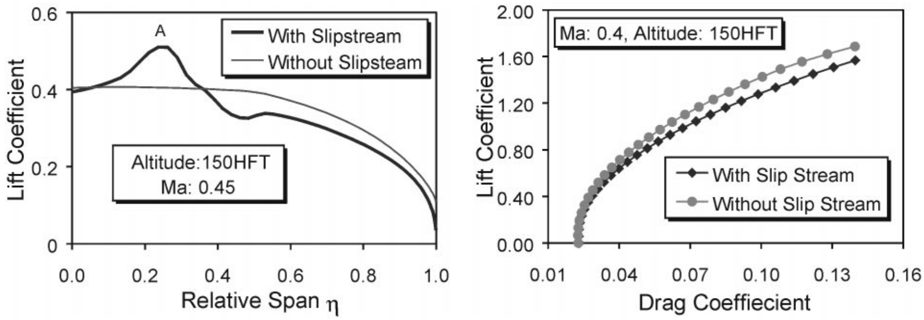

Fig. 8. Lift distribution and polar diagram.

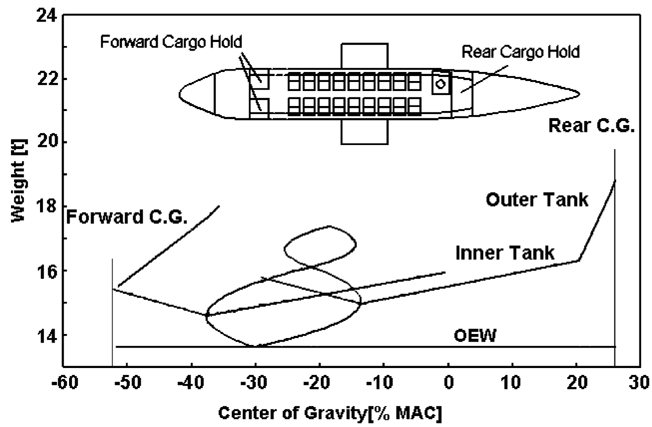

Fig. 9. Typical cabin layout and loading diagram.

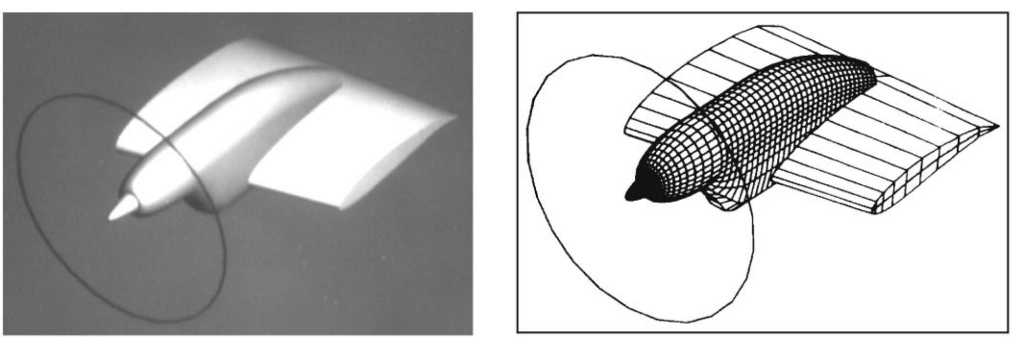

Fig. 10. Shaded- and hidden-line model.

3.7. Module validation

The potential of the new VisualCAPDA-modules is verified [6,12] by exemplarily re-designing some well-known commuter aircraft: after having automatically generated the cabin cross-sections as an input to the cabin-module on the basis of chosen seat types and cargo compartment layout,