CONCEPTUAL DESIGN OF CIVIL TRANSPORT AIRCRAFT

by

A NUMERICAL OPTIMIZATION TECHNIQUE

MICHAUT C., CAVALLI D., HUYNH H. T.
O.N.E.R.A.
(Office National d'Etudes et de Recherches Aérospatiales)
BP 72 - 92322 Chatillon Cedex - FRANCE

Abstract

A numerical code has been developed in order to quantify the impact of new technologies on the whole aircraft from their preliminary design step.It is composed of two parts related to the aircraft and to an iterative optimization technique,based on a generalized gradient algorithm.This method allows to determine the best choice of the aircraft main parameters (wing planform,weights,flight profile) which minimizes a selected criterion,while satisfying all the mission requirements (take-off field length,approach,speed...).

Validation of this code has been achieved by comparison between results provided by the proposed method and real parameters related to a current transport aircraft.

Introduction

The civil transport system is encountering major changes related especially to the industrial and economical growth of the Pacific South Rim nations, the economical and political changes in Europe (Europe 1992) and the opening of the eastern Europe market.

In the seventies fuel savings were a major concern; now airlines and customers are focusing on economics. Moreover all new products entering on the market must meet not only technical challenge but they must fit exactly into a world where environment and regulations become more and more important.

In order to define further studies related to a future aircraft project, it becomes thus necessary to be able to quantify in an efficient way the influence of all these features; this could be achieved by analyzing their consequences on the whole aircraft from the conceptual design stage.

For this purpose was developed at ONERA a prospective numerical code in order to analyze at the aircraft preliminary design stage the impact of new technologies on aircraft economics (ie the aircraft Direct Operating Cost in this case) and the possible technical choices offered to the engineer.

Similar numerical codes have also been developed in other countries [1 to 6].

The code is first presented,then validated on subsonic transport aircraft.The impact of new technologies is evaluated on a short range subsonic aircraft.

Numerical code description

The aim of the numerical code was to determine the basic parameters defining an aircraft related to a specific mission (payload and range); this aircraft must also fulfil all the operational and regulatory constraints (take-off field length, approach speed,...) while minimizing a chosen criterion - the DOC for the civil application.

The prospective code has been developed by using a numerical optimization technique based on a generalized projected gradient algorithm.

The code itself may be divided in two different parts as described in the architecture (fig 1) :

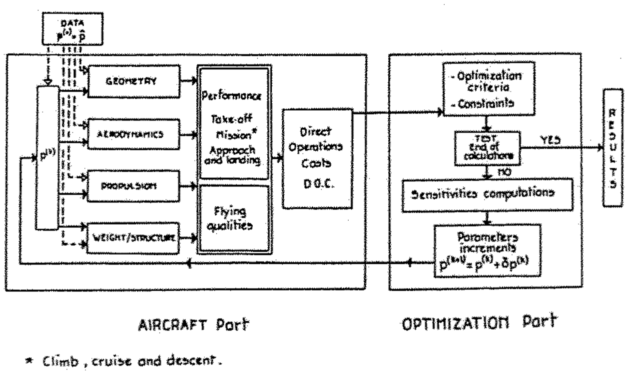

Fig. 1 – Preliminary design of a transport aircraft.

- the aircraft part composed of specific modules related to the aircraft geometry, its aerodynamics, the available propulsion system, the weight balance and the mission performance;
- the optimization part which integrates all the modules and leads to the best set of aircraft parameters answering to the mission objectives .

All the numerical code components are described below. The numerical code is initialized by a special unit called " data unit".

Data unit

Data introduced in the "data unit" may be classified in three categories :
- constant data related to a specific technology ; they are of the engineer resort and depend upon experience acquired or main principles well known in the aircraft design process; they remain constant during a typical exercise;
- initial set of data to be optimized concerning the aircraft general geometry such as the wing planform (area, aspect ratio, sweep,...) aircraft weight (take-off gross weight), mission fuel consumption, parameters related to the mission profile such as cruise altitude and Mach number, flying qualities,...;
- constants related to the optimization process itself ; the versatility of the code has been achieved by organizing this unit in such a way that the user can easily define ,through a judicious choice of these constants , the parameters to be taken into account and the constraints to be considered.

This unit includes more than one hundred data, at most twenty of them may be optimized.

Optimization part

The optimization part integrates all the aircraft model units and computes, from an initial set of parameters (p), the best one (p*) which minimizes a criterion J(p), while fulfilling all the requirements and constraints. This can be formulated as a non linear parametric optimization problem with both equality and inequality constraints as follows :

$$(1) \quad p^* = \text{Arg Min } J(p) \qquad p \in R^n$$

subjected to:

$$(2) \quad g_i(p) = 0 \qquad i=1,2...I$$

$$(3) \quad h_j(p) \leq 0 \qquad j=1,2...J .$$

The optimization algorithm process uses an iterative numerical technique which has been developed in house for several purposes : the generalized projected gradient (GPG) method [7]. It is a first order iterative algorithm which provides, at each computation step, a new set of parameters by adding small increments to those derived from the previous step.

The iterative procedure, illustrated fig 2, can be briefly summarized as follows, for the problem (1) subjected to equality constraints (2).

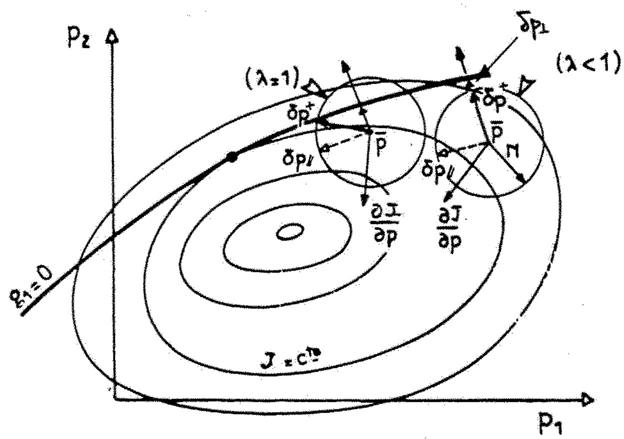

Fig.2 Generalized projected gradient method.
Simplified case of two parameters and one constraint.

Let us define $\bar{p}$ as the nominal set of parameters related to one current step of the algorithm. The equations (1) and (2) are firstly linearized about this nominal set of parameters :

$$(4) \quad \delta J = J(p) - J(\bar{p}) = \frac{\partial J}{\partial p}(\bar{p})^T * \delta p$$

$$(5) \quad \delta g = g(p) - g(\bar{p}) = [\, G^T \,] * \delta p$$

where:

$$\delta p = p - \bar{p} \;;\; g^T = [\, g_1 .....g_I] \;;\; G = \frac{\partial g}{\partial p} .$$

At the next iteration step, p^+ is the new set of parameters and the increment vector $\delta p^+ = p^+ - \bar{p}$ is then defined in the following form :

$$(6) \quad \delta p^+ = -k\, \delta p_{//} + \lambda\, \delta p_\perp$$

with

$$\delta p_{//} = [\, I - G(G^T G)^{-1} G^T] * \frac{\partial J}{\partial p}$$

$$\delta p_\perp = -G\, [\, G^T G]^{-1} * g(\bar{p}) .$$

The vector $\delta p_\perp$ is the theoretical increment which is normal to the subspace defined by the linearized constraints (5) to be performed in order to satisfy the constraints (2). The component $\delta p_{//}$ is the projection of the gradient vector $(\partial J/\partial p)$ in this subspace.

In order to prevent a too large step size of the algorithm beyond the validity domain of the linearized equations (4) and (5), a scalar scale factor λ was introduced on the component $\delta p_{\perp}$ (the ideal value of λ is of course equal to 1). The constant k defines the search direction along the projected gradient $\delta p_{//}$. The choice of the constants k and λ which define thus the algorithm step is computed in order to satisfy firstly the constraints (2) and secondly to reduce the criterion (1).

The inequality constraints (3) are ignored when satisfied and taken into account in the same way as the equality constraints otherwise.

Let us notice that the retained GPG algorithm offers a great versatility thanks to its large convergence domain and its ability to be initialized with off-designed aircraft parameters (the related aircraft configuration does not satisfy necessarily equality (2) and inequality (3) constraints).

Aircraft modelization

To increase the numerical code potential the aircraft modelization is composed of several specific units as described in Fig.1; these units may be validated separately and offered also a large versatility to the engineer. The details of the main units and their application on a chosen case are given below.

Geometry

Under this term are calculated several parameters used in other modules. From the specified mission data (ie payload , range ,...) this unit gives :

- the fuselage dimensions, length and diameter ; they are calculated when feeding the unit with the type of accommodation chosen to perform the mission, the number of classes (first and tourist ,...) , the number of seats in each class, the number and width of rows, the standard space between seats;

- the number of cabin crew members which is a function of the number of passengers and type of mission (short , medium or long range) ;

- other geometrical parameters , in particular those which are used further in the aerodynamic model (ie span , fin and tailplane surfaces).

Aerodynamics

From the data related to aircraft geometry and involved technology, this unit defines the main aerodynamic characteristics, that means the polar for clean and low-speed configurations; in this last case, the polar curve takes into account the profile modifications or airfoil camber increase due to flaps and leading edge devices deflections.

The method relies upon analytical results and experimental data obtained from wind-tunnel or from current aircraft [8,9,10].

In the case of a short range aircraft two different types of profile are considered :

- classical with devices like slats and flaps; a first global exercise made on a supposed laminar wing without leading edge devices has shown that the take-off constraint implied a wing surface increase and a penalty on the optimization criterion , the DOC;

- laminar ; in this case the profile has been defined such as the a natural laminarity may be maintained on the surface of the wing; the use of normal slats was prohibited because of the transition that may occur at the wing leading edge; so the aerodynamics unit was modified in order to take into account the use of Krüger to allow better low speed aircraft performance.

Propulsion

This unit offers two possibilities:

- the use of an engine model which provides the engine thrust and specific fuel consumption in function of primary engine parameters such as turbine entry temperature (TET) and bypass ratio (BPR).

- the use of an existing well defined engine; in this case, tables provide thrust, fuel consumption in function of the flight conditions.

Up to now only the second approach has been used in calculations.

Weights / Structures

This unit provides the aircraft empty weight and the take-off gross weight; the aircraft empty weight is divided into twelve different components which are computed by using a statistical methodology. Each component's weight (i) may be written in the following form :

$$M_i = k\ A^{\alpha}\ B^{\beta}\ C^{\gamma}\ D^{\delta}\ E^{\varepsilon}$$

The design parameters A, B, C, D, E are chosen for having a good correlation with the weight of the considered component ; the constant k and the design parameters exponents α, β, γ, δ, ε are determined by a logarithmic regression technique from a fair sample of similar existing aircraft.

Performance

This unit computes the aircraft performance for the specified design range : take-off field length, fuel consumption and flight time for each phase, approach speed.

The flight profile used in the "mission" part is a simplified one (Fig.3). The different phases are calculated according to the following assumptions :

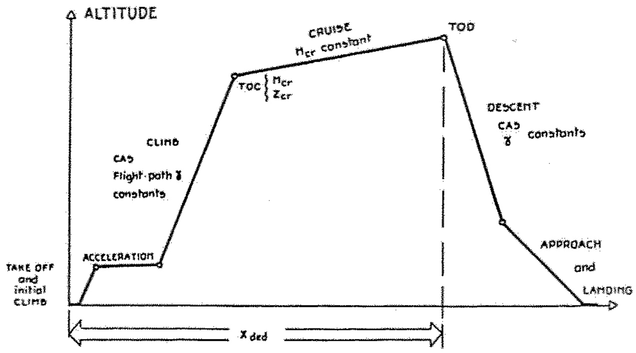

Fig. 3 – Mission flight profile.

- Take-off : this phase is composed of three segments : acceleration at maximum thrust, rotation phase or lift - off and initial climb to an altitude of 100 meters. The take-off field length calculation is performed for two cases : without and with engine failure during take-off ;

- Climb: it is composed of an acceleration phase at constant altitude to reach the desired conventional climb speed and a climb phase performed at a constant conventional airspeed (CAS) and, either at constant engine rating, or at constant flight path ;

- Cruise: a climbing cruise, at constant Mach number Mcr and initial cruise altitude Zcr, has been adopted in the code;

- Descent : this phase is performed in the same way as the climb phase. The end of descent has been arbitrarily chosen at the altitude of 1000 m ;

- Approach and landing : during the final phase, the program computes the maximum allowable approach speed.

Flying qualities

This unit computes the parameters related to aircraft flying qualities (trim,static margin) ; this may lead to a further study about the impact of CCV.

Economics

One of the determinant factor in the aircraft operators' choice based on economics considerations is the direct operating cost (DOC). Since the ATA formula in 1967,different methods were derived or developed. The Airbus Industries DOC method has been adopted because it takes into account a large number of items and also because it provides a realistic evaluation of the impact of new technologies on aircraft costs (Fig.4).

ITEMS		ATA 67	AI 87
ACQUISITION COSTS	Depreciation	*	*
	Interests	*	*
	Insurance	*	*
FUEL	Fuel	*	*
CREW	Cockpit crew	*	*
	Cabin crew		*
MAINTENANCE	Airframe	*	*
	Engines	*	*
TAXES	Landing fees		*
	Navigation charges		*

Fig. 4 – D.O.C. method items.

The main items contributing to the aircraft economics are the acquisition cost (depreciation, interests, insurance), the fuel cost, the crew cost (cockpit and cabin crew), the maintenance cost composed of airframe and engines cost (both divided into material and labor costs) and taxes relative to the flight (airport landing fees and navigation charges).

Validation of the numerical code

Evaluation of a medium-range subsonic aircraft

The classical medium-range airplane requirements and constraints are listed in Fig.5. It has a range of 3700km (2000NM) with a payload of 21,5 tonnes. Cruise Mach number is fixed at 0.79 and initial cruise altitude at 10700m. The different DOC estimations are carried out using 1987 costs and the fuel price is equal to 0.72$ per gallon.

The aircraft parameters to be optimized are limited to the wing planform (aspect ratio AR, leading-edge sweep angle Λ and area A). Other conceptual parameters are definitely fixed.

The constraints are the balance take-off field length with engine failure (Take-Off Field Length < 2300 m) and the maximum approach speed (Vapp < 145 kt).

Numerical implementation of the GPG algorithm

The implementation of the GPG algorithm consists in defining the set of parameters and the equality and inequality constraints to be involved in the optimization process.

For this example, a total of six parameters have been taken into account : wing planform parameters (aspect ratio, sweep angle, area) , gross weight , fuel weight and distance up to the top of descent , Xded (Fig.3). This number increases to eight when the mission profile, defined by the cruise mach number Mcr and the initial cruise altitude Zcr, is also optimized.

Three equality constraints , the maximum take-off gross weight (MTOW) ,the fuel weight and the design range, have been introduced. The first two constraints, artificially incorporated, are necessary to obtain a good coherence in the optimization process. The range equality constraint provides a computed parameter Xded which satisfies the design range requirement for the aircraft to be defined.

* MISSION : . Payload = 21.5 tonnes
  . Design range = 3700 km (2 000 nm)
* FLIGHT PROFILE : . Cruise M_{cr} = 0.79
  Z_{cr} = 10 700 m
  . Climb/Descent CAS cst 130 m/s (250 kt)
  Flight path ± 3.2 deg.
* PROPULSION : Two engines 50 000 lb
* COSTS : . Year 1987
  . Fuel cost 0.72 \$/gallon
* CONSTRAINTS : . TOFL < 2300 m
  . Approach speed < 75 m/s (145 kt)

Fig. 5 – Evaluation of a medium-range subsonic transport.

Other constraints, such as those related to the take-off field length and the approach speed may be directly taken into account in the form given by (3).

In the numerical computation the above equality constraints are satisfied very quickly within few iterations (3 or 4). The algorithm is pursued further up to 30-40 iterations as long as no significant improvement of the optimization criterion is reached. In the case studies, only main aircraft and mission profile parameters, which are obtained at the end of the optimization process, are commented.

Influence of the initialization on the numerical convergence

To eliminate the risk of a local optimum existence , the unicity of the "optimal" configuration solution is first verified by initializing the code with two different sets of aircraft parameters :

Parameters	AR	Λ ,deg	A ,m^2
First set	7	35	190
Second set	11	25	250

Three different criteria are also considered and the results are illustrated Fig.6 and 7. They show that ,in each case, starting from very different initial set of data, the algorithm leads nearly to the same optimal aircraft configuration. Variation between parameters are below 10% and the differences between corresponding values for each criterion are within 0.5%. For the purpose of the study these results are acceptable.

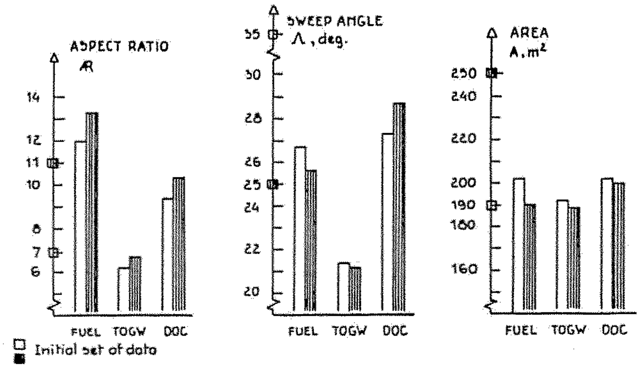

Fig. 6 – Effects of optimization criteria on wing planform parameters (case 1).

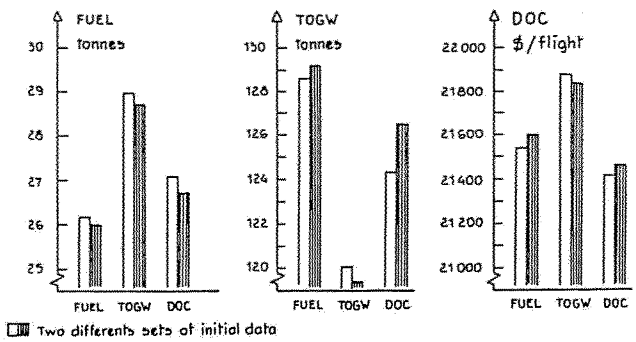

Fig. 7 – Effects of optimization criteria on a medium-range aircraft (case 1).

Influence of the design optimization criterion choice

Three different optimization criteria are considered : fuel weight, take-off gross weight (TOGW) and direct operating cost (DOC). In the optimization process only the take-off inequality constraint has been taken into account. Results are illustrated on Fig.6 for optimization parameters and on Fig.7 for the various calculated criteria. Three "optimal" configurations are determined :

The minimum fuel airplane wing planform is primarily characterized by a high aspect ratio (12-13). Such a large aspect ratio wing is aerodynamically efficient but has a high take-off weight ; and even if the fuel weight is minimized, the structural weight is important, the minimum fuel airplane has the highest take-off gross weight.

The minimum TOGW airplane has a low aspect ratio, a reduced sweep angle and the lowest wing area. Its structural weight is low because the fuel part of the TOGW is important; this configuration has the highest DOC

The minimum DOC airplane configuration remains between the two previous configurations because fuel burned and take-off weight are two main factors of the DOC. Optimal results show an aspect ratio in the order of 9-10, a sweep angle close to 28° and a wing area of 200 m^2.

In general it may be noticed that the wing area is the less sensitive parameter to the optimization criterion choice. Its values are realistic due to the fulfillment of the one engine inoperating take-off field length constraint. For each calculation the approach speed is exceeding the limit - value by about 7%.

Influence of take-off and landing constraints

The third example is the analysis of the effects of take-off and landing constraints on design parameters (Fig.8). In this case the optimization criterion is the DOC.The flight profile (cruise Mach number and altitude) are also optimized. The first results are obtained with only take-off without engine failure constraint; this leads to a particular configuration layout with a rather small wing area (175m^2), an aspect ratio of 10 and a large sweep angle of 38°, a high cruise Mach number (M0.84). With the same take-off constraint, but with engine failure, a more realistic configuration appears with a 8.8 aspect ratio , a 32° sweep angle and a 218 m^2 wing area ; the cruise Mach number diminishes to 0.815 ; but the approach speed 78m/s is not within the limit fixed by the specifications. The addition of the landing constraint (Vapp < 75 m/s) introduces an increase of 5,5% on the wing area. Concerning this new configuration, a DOC reduction is due to the decreased cruise Mach number and fuel consumption. The cruise altitude stands between 10700 and 10800 m.

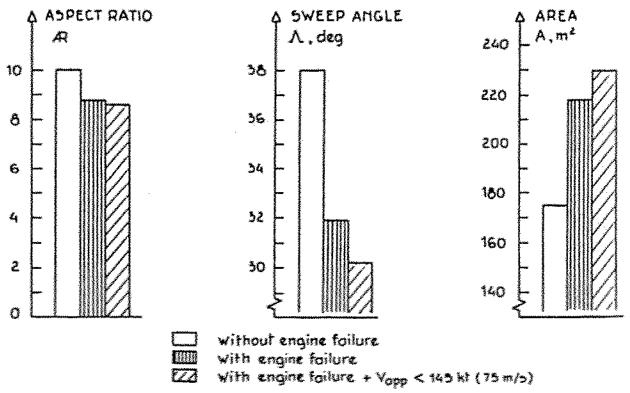

Fig. 8 – Effects of take-off and landing constraints on aircraft parameters (case 1).

Remarks

This validation test based on the evaluation of a medium-range transport aircraft shows reliable results with an accuracy sufficient for the objectives to be performed by the numerical code.

A second example based on a future short-range aircraft has led to the first evaluation of the influence of new technologies such as new materials and advanced propulsion [5] .This exercise is still pursued and the natural laminarity is evaluated.

Conclusions

A preliminary aircraft design code developed at ONERA is based on a generalized projected gradient method; it allows the evaluation of the impact of new technologies on future aircraft. The optimization code offers the possibility to find the best set of parameters (wing planform, aircraft weight and mission flight profile) leading to a configuration which minimizes a criterion while fulfilling the mission requirements.

A validation of the code has been achieved by the estimation of a current medium-range transport aircraft. Moreover, an evaluation of optimal configurations for a short-range aircraft integrating new technologies (new materials, advanced propulsion and wing natural laminarity) may show the real application of such an optimization code.

In the future, this code may be used for the evaluation of a supersonic transport aircraft .This would necessitate only main changes about the aircraft part .

REFERENCES

1 -Victor, Ken; Weir, Tom : Application of computers to aircraft design process. AIAA Paper 85-3044, 1985.

2 - Haberland, C. ; Thorbeck, J. ; Fenske, W. : A computer augmented procedure for commercial aircraft preliminary design and optimization. ICAS - 84 -4-8-1, 1984.

3 - Sliwa, Steven M. : use of constrained optimization in the conceptual design of a medium range subsonic transport. NASA TP 1762, 1980.

4 - Roskam, J. : Rapid sizing method for airplanes. Journal of aircraft, vol.23 , no.7, 1986.

5 - Fetterman Jr., David E. : Preliminary sizing and performance of aircraft. NASA TM 86357, 1985.

6 - Johnson, Vicki S. : Minimizing Life Cycle Cost for subsonic commercial aircraft. AIAA Paper 88-4402, 1988.

7 - Aumasson, C. : The parametric Generalized Projected Gradient method. Unpublished report, 1988.

8 - General Dynamics : Aerospace handbook. FZA-381II-Rev.A, 1973.

9 - Torenbeck, E. : Synthesis of subsonic airplane design. Delft University Press, Martinies Nijhoff Publishers, 1986.

10 - Nicolai, Leland M. : Fundamental of aircraft design. University of Dayton, 1975

11 - Michaut , C.- Cavalli, D.- Huynh, H.T. and Lethuy,H. Preliminary design of civil transport aircraft (AIAA paper 89-2152 (AIAA/AHS/ASEE Aircraft Design and Operation Meeting,Seattle,Wash.,31stJuly-2ndAug.1989)