MULTIOBJECTIVE OPTIMIZATION PROCEDURE FOR THE WING DESIGN AT CRUISE AND LOW-SPEED CONDITIONS

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Abstract

The procedure for wing aerodynamic design based on the algorithm of simultaneous multiregime optimization of cruise and low-speed performance is considered. The method is based on the combination of fast direct methods for subsonic and transonic wing analysis, geometry variation module and the optimization procedure. The description of all the components and examples of practical application of the developed technique for design of the conventional medium-haul airplane wing and the "Flying Wing" configuration are presented.

1 Introduction

Cruise and high-lift characteristics are the most important but often conflicting requirements in the airplane aerodynamic design. Despite of a relatively small time share of takeoff and landing regimes, they often define constraints on wing surface area and influence the whole airplane configuration. Improving low-speed lift of the aircraft allows to increase payloads, shorten takeoff and landing distances and to reduce aircraft noise, while the lack of high-lift efficiency results in wing surface area greater then required for economic cruise flight with corresponding drag and weight penalties.

For the definition of cruise and high-lift wing configurations the well-developed design methods exist, such as inverse and optimization methods [1-12]. However, according to the author's knowledge the question of simultaneous optimization of cruise and low-speed characteristics has not been considered thoroughly in the literature. In general, the improvement of low-speed performance leads to the loss in cruise aerodynamics at transonic speed and vice-versa. Usual recommendations on this issue generally add up to the wing profiles leading edge droop or increase of the leading edge radius for low-speed Cl_{max} increase with some losses at cruise [13, 14].

In this article the possibility is shown of the simultaneous wing cruise and low-speed characteristics optimization. The objective function is presented by the linear combination of wing performance at several cruise regimes and its characteristics at low speed. Fast transonic and subsonic analysis methods permit numerous flow evaluations in optimization loops without excessive time consumption. A brief description of the optimization procedure and examples of application of the developed technique are given below.

2 Design procedure

The optimization procedure consists of four principal parts: a direct method for transonic attached flows, a method for flow analysis over the wing at low speeds taking into account separation regions, a geometry variations generator and an optimization routine.

2.1 Direct transonic solver

When considering cruise flight regimes characterized by the absence of strong shocks and extensive separation zones, it is possible to apply with confidence full potential methods in a combination with coupled boundary layer and wake calculations. The very fast full-potential code BLWF-56 developed at TsAGI [3] is used to analyze cruise aircraft configurations. This code is based on the iterative quasi-simultaneous viscous-inviscid coupling procedure. The calculation of an external flow is carried out by numerical integration of the conservative form of the full potential equation with the approximate non-isentropic correction on shocks. The solution of resulting equation system is obtained by using an effective approximate factorization algorithm. Three-dimensional computational grid of C-O type over a wing-fuselage configuration is generated using simple algebraic technique, Fig. 1. An inclusion of nacelles, pylons, empennage and winglets is possible on the basis of "chimera" approach, Fig. 2.

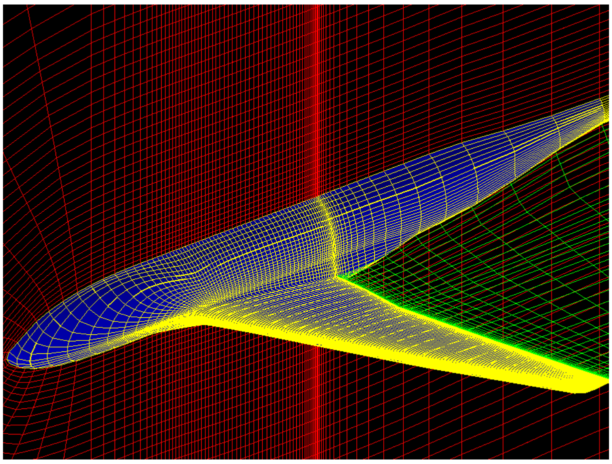


Fig. 1. Wing-fuselage grid

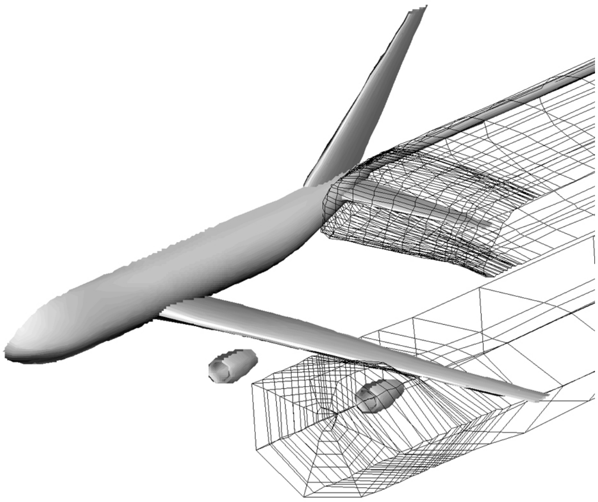


Fig. 2. "Chimera" grids for nacelle and empennage

The calculation of a compressible laminar and turbulent boundary layer on a surface of a wing and empennage is carried out by finite-difference technique. Robust quasi-simultaneous technique provides fast convergence of viscous-inviscid iterations, both for attached flow and moderate separation regimes. As a rule, five viscous-inviscid iterations for the achievement of full convergence are sufficient. Small CPU time (the time of one run is about 20 sec on PC Pentium-IV 3000 on the finest grid) and automatic grid generation provide a good basis for its application in optimization design procedures. As an example Fig. 3 shows BLWF-56 results for advanced passenger aircraft configuration at cruise regime.

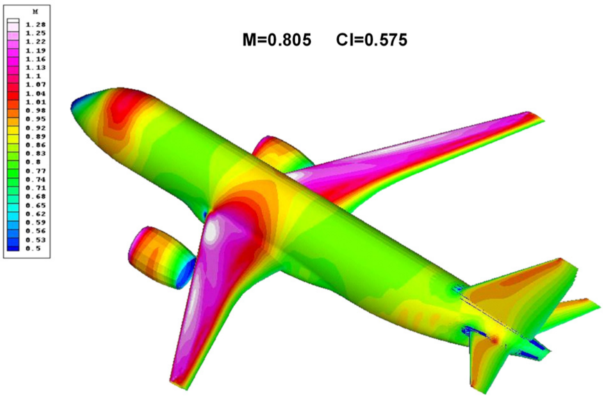


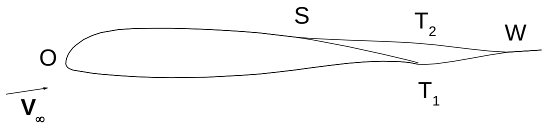
Fig. 3. BLWF-56 results for medium-haul aircraft layout

2.2 Direct subsonic solver

As concerns for the subsonic high-lift analysis it is obvious that significant simplification of the flow simulation is needed. In fact, the flow over real wing with high-lift devices deployed is very complicated not only by the complex multi-element geometry itself, but also by the nature of flow physics including regions of separated flow, confluent boundary layers and wakes, regions of supercritical flow, strong trailing vortices emanating from the edges of deflected flaps to be mentioned among others. Besides all these flow effects as well as transition phenomena are strongly and non-linearly dependent on the Reynolds number. Due to extremely complex nature of the real high-lift flow it is impossible currently to predict reliably the value of 3-dimensional Cl_{max} even with the most advanced Navier-Stokes methods [9,15]. Instead the quasi-3D procedure (coupling of a 2D section characteristics with a lifting line/surface method) is often used for assessment of the complete wing performance and design purposes [8,13,16].

For simplicity the lift of a wing without high-lift devices is considered in this paper with the assumption that additional ΔCl_{max} on isolated wing will lead to the similar increase of Cl_{max} of the wing with high-lift devices. This assumption is based on routine practice and seems to be more or less valid. Let's notice that term Cl_{max} here and later on means maximum lift capability of the wing (profiles) rather then the maximum lift of a realistic wing which may be considerably lower due to unfavorable local disturbances.

For evaluation of low-speed high-lift three-dimensional wing characteristics WSEP code is used [17]. In this method the simple engineering model of the wing separated flow is accepted, namely, modified Morino panel method plus boundary layer theory plus semi-empirical "dead-water" model of the separation zone with a condition of the pressure constancy from the separation point to the trailing edge (Fig. 4).



Part of contour	Condition
WT_1OST_2W	$(V \bullet n)=0$
ST_2	$(V \bullet \tau)=const$
T_2W, T_1W	$(V \bullet \tau)_U = (V \bullet \tau)_L$

Fig. 4. Separated flow model boundary conditions

A number of similar two-dimensional engineering methods have been developed in 80-ies [18-19], but only some few attempts were undertaken in three dimensions [20-21]. WSEP has both two-dimensional and three-dimensional versions. The former has been successfully utilized in the airfoil design code OPTFOIL [10] intended for development of advanced high-lift low- and high-speed subsonic airfoils. The methods of such type are typically about two or three orders faster than the interactive boundary-layer approaches [9,22] or Navier-Stokes methods, whereas accuracy and reliability of results are not too much deteriorated for simple wing geometries with low or moderate sweep angles.

In the Morino panel method a wing is represented by a set of flat quadrilateral panels with constant source and doublet distribution [23,24]. In the standard mode the source strength on each panel is prescribed beforehand, and the program solves for the unknown doublet strengths. The internal Dirichlet boundary condition is applied, providing zero perturbation potential inside the configuration. Mixed boundary-value problem shown in Fig.4 is solved iteratively by prescribing source values at fixed segments of a surface and by adjusting doublet values at segments with prescribed pressure distributions. For acceleration of calculations specified boundary conditions are satisfied on the original surface of a wing and on the reference plane in the wake. Thereby, influence coefficient matrices are determined only once, and the subsequent solutions of the linear algebraic system concerning unknown singularities can be obtained through simple back run of the Gauss decomposition with different right-hand sides.

The code is usually run on a series of increasing angles-of-attack, a converged solution at previous angle of attack being the initial approximation for the subsequent one. Thus whole spectrum of flow conditions is passed, starting from the low angles of attack, where there is no separation at all, and finishing at deep post-stall regimes, when the flow separates practically from the leading edge. The calculation of the entire $Cl(\alpha)$ curve in 50 points demands about 3 min on the PC Pentium-IV 3000. As an example in Fig. 5 shown are computed lift curve for the baseline wing of the advanced medium-haul airplane at flight conditions and corresponding evolution of the separation zone over the angle of attack.

Summarizing it may be argued that despite the simplicity and engineering nature of the approach accepted it provides a rational compromise between the efficiency and accuracy required in the design process especially taking into account that increments rather than absolute values are important for the optimization.

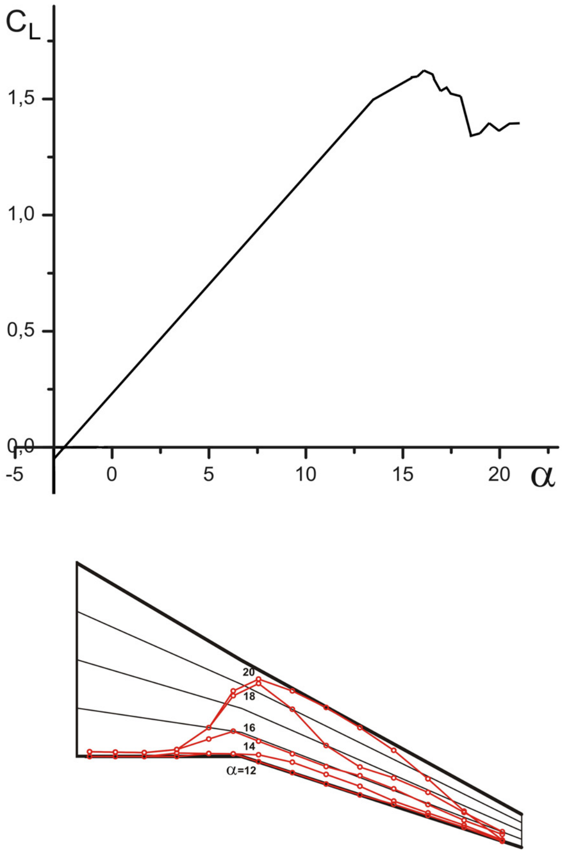


Fig. 5. WSEP results for medium-haul aircraft wing

2.3 Numerical optimization

Optimization methods play a key role in the process of aerodynamic design enabling one to obtain a really effective configuration with good trade-off multipoint behavior. Taking into consideration the complexity of the analysis codes, the necessity to examine a lot of different alternatives and the stringent overall design time constraints the requirements on the optimization methods utilized are extremely high. A lot of optimization methods exists each possessing its own virtues and shortcomings. Gradient method is chosen as an optimization method in this study, although the robust genetic algorithm can be used as well thanks to the speed of direct methods. Gradient information is computed via simple finite differences. The main weaknesses of the gradient method appear in case where target function has several local extremums and the problem exists to prevent the algorithm from sticking at one of them. To this end the method used includes several special features contributing to the global maximum search.

2.4 Geometry variations

A set of geometry variations utilized in first studies was restricted to base section profiles variations with wing planform kept fixed. They could be local smooth variations, global variations of a contour, such as change of thickness or camber, position of the maximal ordinate along chord, vertical displacement, twist variations, nose or tail deflections, etc.; finally, they might be differences of coordinates of known airfoils. Especially useful shapes for the outer wing sections may be generated with the help of OPTFOIL code [10] – these specially developed “aerofunctions” naturally combine good transonic and high-lift subsonic performance. On an average about ten geometry variations are attributed to each wing base section.

Later on simple planform variations such as wing sweep and taper ratio have been introduced in addition to profiles variations.

During optimization not only aerodynamic features but also the requirements on the wing surface curvature may be taken into account to obtain smooth shape along chord and span with acceptable manufacturability.

3 Design examples

3.1 Model task

The developed method was checked firstly on the model task of the medium-haul aircraft wing optimization. The baseline wing of the aircraft was designed by means of multi-regime optimization procedure [25] similar to described in this paper but without direct account of low-speed behavior. The geometry of the wing is defined by five base sections. Four geometry variations – twist angle values of all but root sections – were chosen as design variables for model example. The objective function is presented by the linear combination of the averaged lift-to-drag ratio (L/D) defined at two cruise regimes (M=0.8 Cl=0.6 and M=0.81 Cl=0.5) and the maximum lift coefficient Cl_{max} at low speed:

$$Obj = w\cdot(L/D)_{mean} + (1-w)\cdot 10\cdot Cl_{max} \qquad (1)$$

where multiplier 10 is introduced for balancing both terms and weight factor 0<w<1 accounts for the relative importance of cruise and high-lift efficiency. The Pareto-front $(L/D)_{mean}$ vs Cl_{max} obtained on the basis of optimization runs (Fig. 6) shows that significant improvement of maximum lift may be obtained in comparison with pure transonic optimization with relatively small losses in cruise aerodynamics (see left edge of the Pareto-front). The results obtained display clear physical nature (Fig. 7) and confirm robustness and applicability of the proposed algorithm.

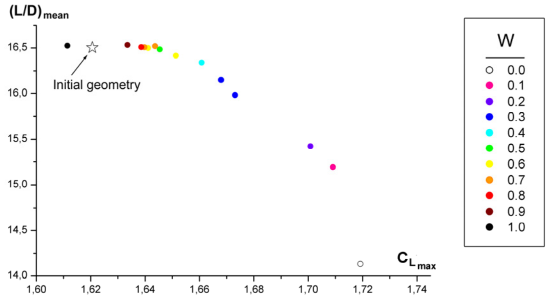
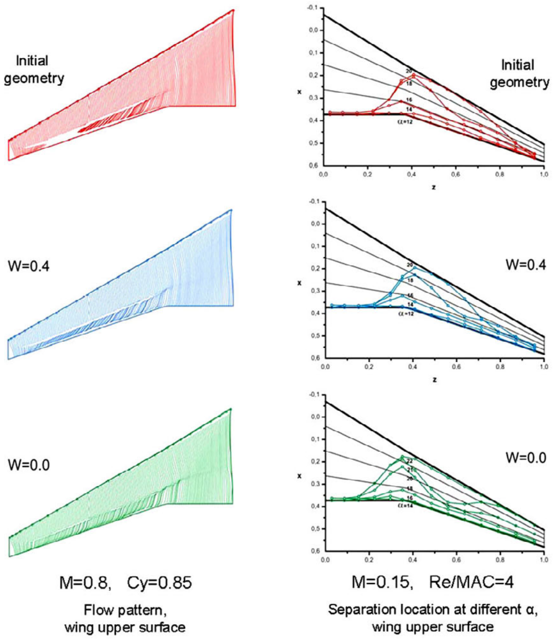


Fig. 6.
Pareto-front obtained in the model optimization task



M=0.8, Cy=0.85
Flow pattern,
wing upper surface

M=0.15, Re/MAC=4
Separation location at different α,
wing upper surface

Fig. 7. Optimization results
corresponding to different w values

3.2 Medium-haul aircraft wing optimization

After testing and first successful practical approbations [26] the described optimization procedure became a part of habitual cruise wing aerodynamic design process in our everyday practice.

One of the recent examples is given here. The developed wing has been considered for the same cruise regime M_{cruise}=0.8 as the older one but with greater aspect ratio, Fig. 8. Notice, that older wing was designed without described procedure, just only leading edge radiuses were taken into account. So, it is natural to compare performances of the two wings to demonstrate the benefits from the new design methodology.

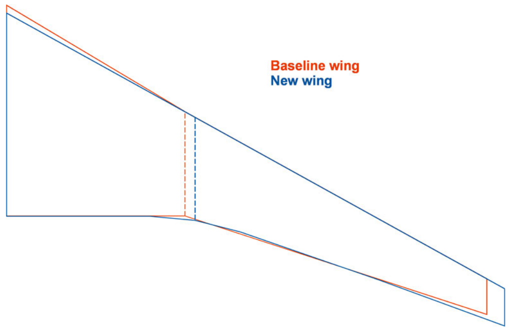


Fig. 8. Wings planform comparison

About ten transonic regimes with the prescribed priorities were taken into account and high-lift low-speed characteristics were estimated during each run. The whole number of design variables for wing section airfoils reached N≈70. Wing planform was kept fixed.

The trade-off curve (Pareto-front), corresponding to real-life design procedure is shown in Fig. 9. It is again evident that even with w≈0.925 weight coefficient (high cruise performance priority) appreciable gains in low-speed lift (ΔCl_{max}≈0.1) can be obtained.

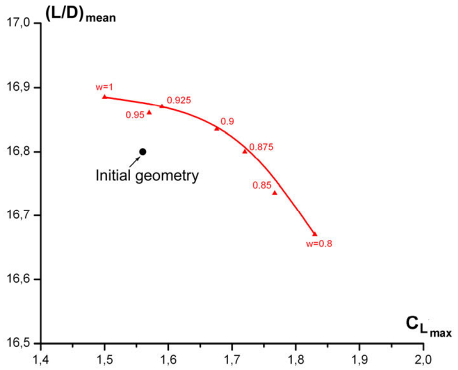


Fig. 9. Pareto-front obtained in the real optimization task

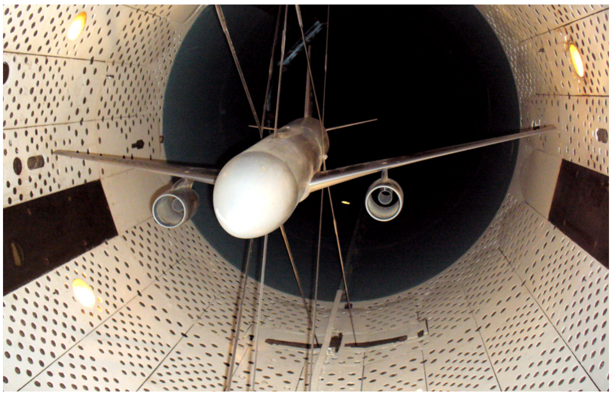


Fig. 10. The aerodynamic model of the medium-haul aircraft with designed wing in transonic wind tunnel

After computational design phase completion the proposals have been prepared for the new wing shape design and the aerodynamic model has been manufactured. The subsequent experimental tests of the model in TsAGI’s large transonic wind tunnel T-106M (Fig. 10) have confirmed the predicted improvements both in cruise aircraft aerodynamics: $\Delta M*(L/D)_{max}\approx 0.8$ (Fig. 11) and low-speed Cl_{max}: $\Delta Cl_{max}\approx 0.1$ (Fig. 12).

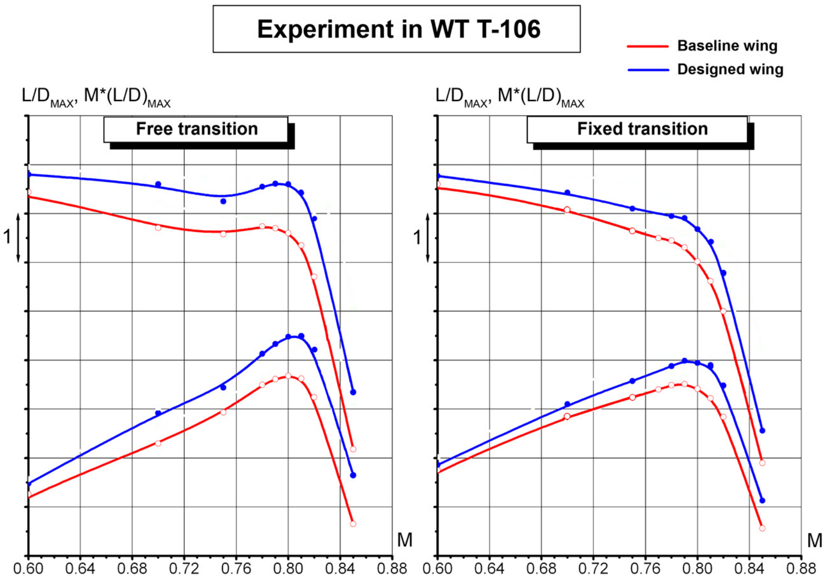


Fig. 11. Cruise experimental data

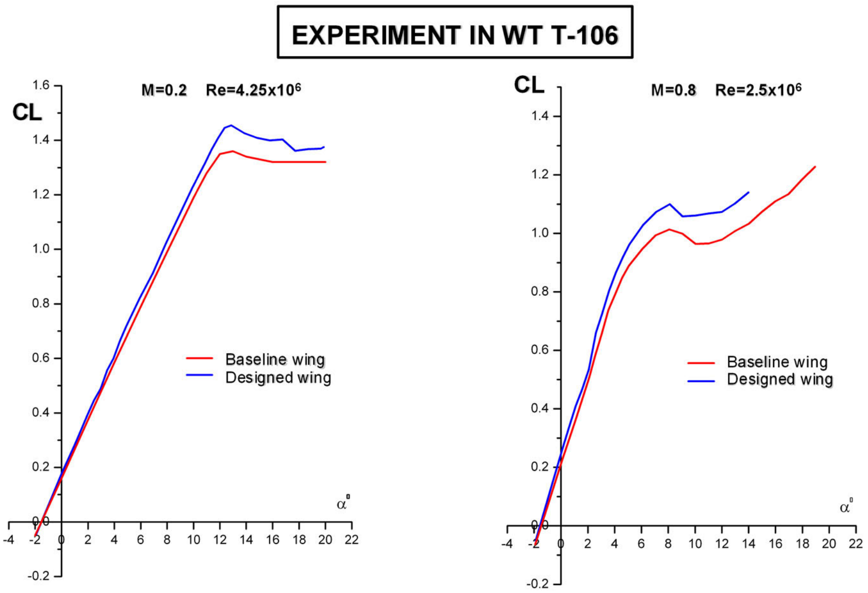


Fig. 12. High-lift experimental data

3.3 Flying Wing design

Despite of a number of weaknesses, it is common opinion now that the «Flying Wing» layout is one of the promising ways to increase efficiency of passenger transport of the future, Fig. 13. Its relative wetted area (S_{wet}/N_{pass}) is considerably smaller that this parameter for contemporary conventional, thus providing higher lift-to-drag ratio $(L/D)_{max}$~23-25 [27-28].

Fig. 13

The research aerodynamic model of the flying-wing type long-range aircraft with moderate passenger capacity is planned to manufacture and test in large transonic wind tunnel (Fig. 14).

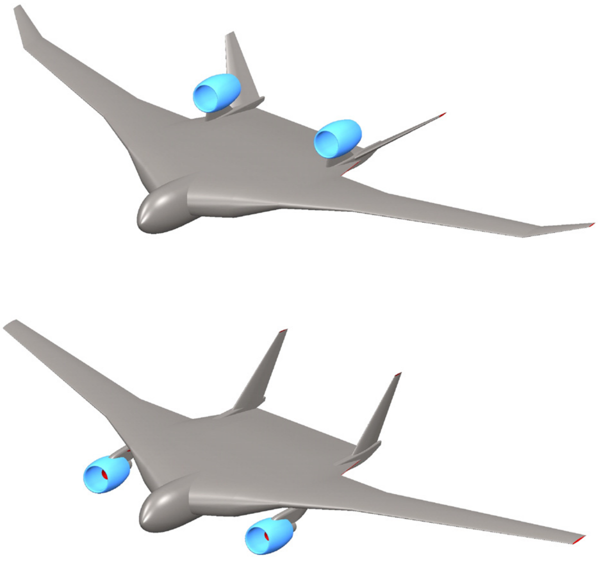


Fig. 14. Flying-wing type long-range aircraft mathematical model

One of the crucial problems in developing “Flying Wing” layouts is connected with large positive pitch-up at high angles of attack. Previous experimental studies of this phenomenon carried out at TsAGI showed significant influence of the wing planform (see Fig. 15).

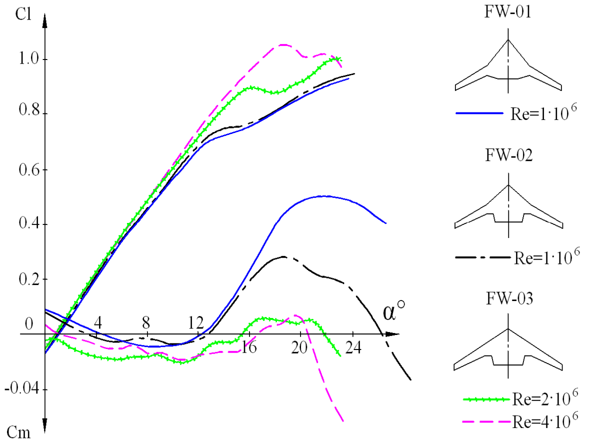


Fig. 15. Low-speed experimental data for Flying Wing model

In present work it was decided to investigate this problem numerically and to reduce its severity. Thus, the attempt was made to apply multiregime optimization procedure for increasing Cl_{max} as well as minimizing positive pitch-up at low-speed regimes and to ensure cruise aircraft performance at M_{cruise}=0.85.

To this end the preliminary analysis of influencing factors has been carried out. The planform and the profiles of the center-wing section were frozen because its geometry is mainly dictated by passenger cabin dimensions. As a rule there are no critical flow phenomena (shocks or separations) at this region due to small local lift coefficient (Fig. 16). Therefore the only variation prescribed here was the simultaneous center-wing sections tails deflection simulating stabilizer inclination – it will play significant role for self-balancing of the configuration at cruise.

On the contrary the outer wing works in more severe conditions exhibiting separation at increased angles of attack, which defines maximum lift and maximum positive pitch-up. Additionally, shock waves appearing at outer wing sections at high Mach numbers restrict speed capability of the airplane.

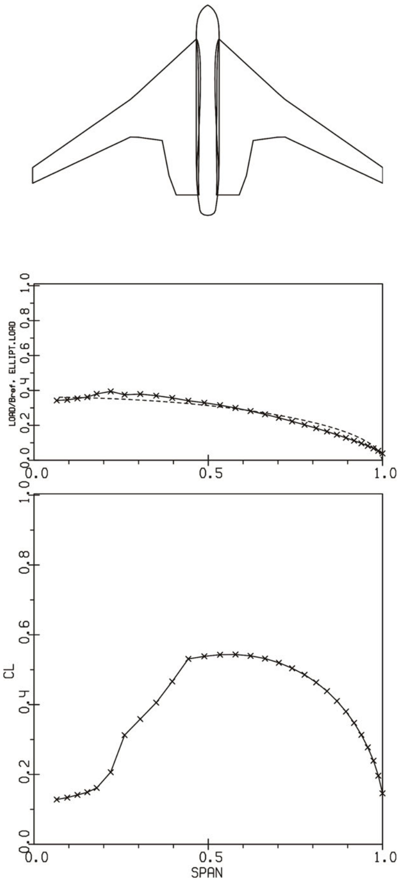


Fig. 16. Span load and local Cl distribution (BLWF-56 results)

That is why we concentrated our attention on the outer wing region. The 31 airfoils variations were stated for outer wing sections. However, preliminary computations showed that pitch moment characteristics are hardly changed without planform variations, so two additional variables were added to the set of variations: outer wing sweep and taper.

Terms, responsible for longitudinal moment behavior at low speed were added to the objective function and the optimization procedure was conducted with total number of 34 geometry variables.

Despite the approximate character of the low-speed computational method it provides more or less accurate estimation of the lift and pitching moment behavior at high angles of attack (Fig. 17), at least up to stall and a bit further. In the plots the pitching moment is referred to the centre of gravity allocated at neutral point position. The maximum lift (stall) is achieved when the separation zone reaches approximately the middle of the chord of the outer wing. The maximum pitch-up is achieved later, when the whole outer wing is separated entirely and looses lift. Unfortunately the recovering of the pitching moment to the second stable region is not captured by the solver (Compare Fig. 15 and 17).

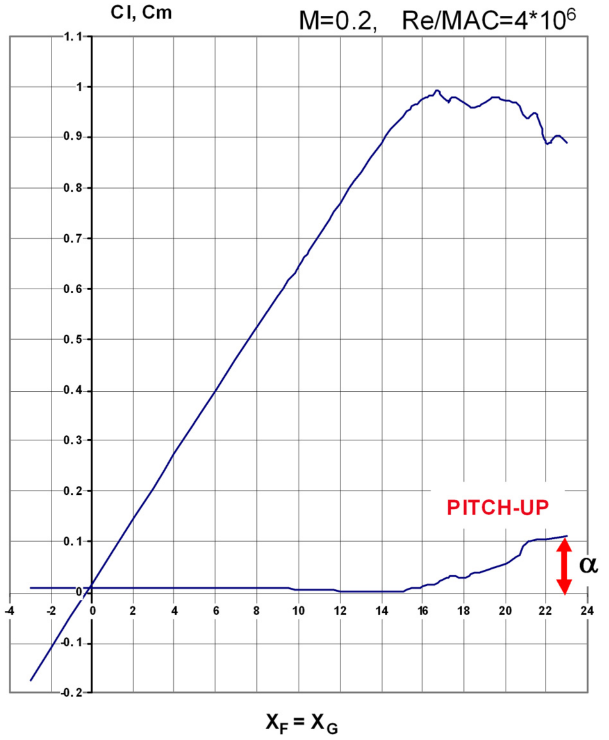


Fig. 17. WSEP results for Flying Wing

The sensitivity of the pitch-up characteristics to variations of the selected “critical” parameters (outer wing sweep, taper ratio, wing tip section washout) were specially investigated for better understanding of optimization task. The dependencies demonstrate the clear behavior and are simply interpreted from physical point of view. For example, the magnitude of the pitch-up decreases monotonously with outer wing sweep decrease (Fig.18) – it is explained mainly by a reduced distance between the centre of gravity position and outer wings.

Based on the optimization results the recommendations on Flying Wing aerodynamic model geometry (Fig.14) have been formulated. The model is now under manufacturing and tests are to take place by the end of 2010.

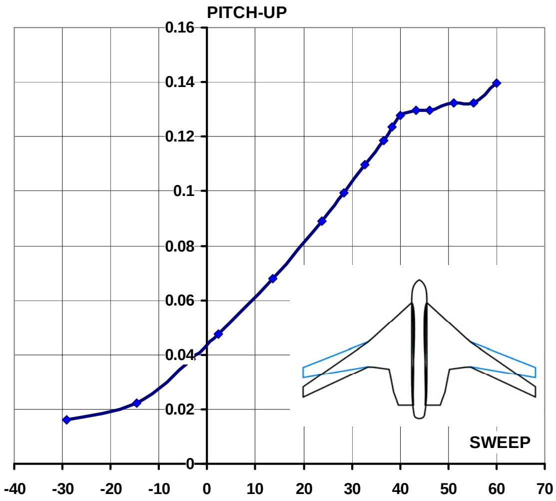


Fig. 18 The sensitivity of the pitch-up characteristics to variations of outer wing sweep

4 Conclusions

The engineering procedure is presented for accounting simultaneously cruise and low-speed characteristics of a wing in the course of the aerodynamic design by optimizing common multi-objective function. The examples shown demonstrate the potential for using the developed procedure as a practical and efficient design tool despite of the simplicity of the approach accepted. The experimental data confirm advance in cruise and low-speed aerodynamics of the medium-haul aircraft provided by multiregime optimization. The Flying Wing design example illustrates the applicability of the method for taking into account aircraft longitudinal stability characteristics.

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