29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

INVESTIGATION OF ADAPTIVE WING BENEFITS FOR TRANSPORT AIRCRAFT

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Keywords: *aerodynamic effectiveness, adaptive wings, single- and multi-point optimization*

Abstract

One of the promising ways to increase aerodynamic effectiveness of the advanced civil aircraft assumes an introduction of the so-called adaptive wings which can alter their geometry depending on the flight condition. In spite of a large number of publications and patents concerning adaptive wings there is no established point of view upon both the possible benefits of wing adaptation for transonic transports and the procedure of its in-flight utilization. This paper deals with applied theoretical and practical aspects of wing adaptation for the next generation of transonic airliners. An aerodynamic optimization algorithm was used to assess an adaptive wing concept for drag reduction at transonic speeds. Full adaptation wing concept assess was done through solving a sequence of single point optimization problems, while multi-point optimization procedure was used for justification of partially adapted wings. A new way of using adaptation advantages is proposed by taking modest speed shockless wing as a basic one and trying to mitigate sharp drag rise at off-design regimes with the aid of partial adaptation.

1 Introduction

In the last quarter of the 20th century progress in the field of civil aircraft aerodynamics was provided, basically, by introduction of supercritical wings. In principle supercritical wings allow significant increase in airplane cruising speed. Actually they were utilized in another way: speed of cruise flight had not been changed, but the relative thickness had increased and sweep value had decreased, that permitted to design wings with a larger aspect ratio and a smaller induced drag.

The potential of supercritical wings with fixed geometry is close to its limit at present, so it is necessary to search for new ways of aerodynamics improvement. One of the promising directions is connected with the introduction of the so-called adaptive wings [1-3] which can minimize aerodynamic drag by alteration their geometry depending on the flight condition. It is possible to consider two scenarios on application of adaptive wings in transport aircraft: optimistic (regarding full shape adaptation which looks semi-fantastic now but is probably possible in the future with application of some absolutely new constructive materials and effective actuators) and realistic one (regarding rather limited shape adaptation by wing leading edge and trailing edge deflections and, probably, some deformations in spoiler area [2]).

In spite of a large number of publications and patents on adaptive wings there is no established point of view neither upon the possible benefits of wing adaptation for transonic transports nor upon the procedure of its in-flight utilization.

This paper deals with both applied theoretical and practical aspects of wing adaptation for the next generation of transonic airliners. An aerodynamic optimization algorithm is used to assess an adaptive wing concept for drag reduction at transonic speeds. Full adaptation wing concept assess is done through solving a sequence of single point optimization problems, while multi-point optimization procedure is used for justification of partially adapted wings. On the example of generic transport aircraft it is shown that the effectiveness of the partial shape adaptation is equal approximately to two thirds of the full adaptation that makes the last one not reasonable in our opinion.

A new way of using adaptation advantages is proposed by taking modest speed shockless wing as a basic one and trying to alleviate sharp drag rise at off-design regimes with the aid of partial adaptation.

Two wings for advanced regional jet with natural laminar flow on the outer wing are considered. In spite of the low sweep angle (15° at quarter chord) the design Mach number is as high as M=0.78 and 0.79 correspondingly. The former wing has fixed shape while the latter is based upon the partial adaptive concept to relieve drag rise in the vicinity of design flight regime.

The aerodynamic model of the regional jet with the first wing has been designed, manufactured and tested at cruise regimes in TsAGI's wind tunnel. Selected results of the experimental studies are presented in this article. The second wing with changeable leading and trailing edge parts is under construction now.

2 Aerodynamic design procedure and an efficiency criterion for adaptive wings

A number of design flight regimes (characterized basically by M&Cl pairs) rather than a single one should be taken into account by a designer of a flying vehicle. It is valid not only for maneuvering combat aircraft, but even for long haul passenger airplane with the dominant cruise regime. The wing of the fixed form cannot have optimum performance at all conditions. From here naturally emerges an idea of adaptive wing utilization for the best fit to the various flight conditions. The aviation history is full of examples concerning adaptive geometry of lifting surfaces, for example, high-lift devices for take-off and landing regimes as well as variable-sweep wings of some supersonic aircraft. Variable camber maintaining "laminar bucket" at required Cl coefficient is a standard technology for modern sailplanes to trade off different flight regimes. Significant performance improvements in terms of drag rise and buffet boundaries expansion were shown to be realized by maneuvering flaps and slats for fighters and trainer aircraft. Smooth variable camber wing concept for military airplanes reached culmination in Mission Adaptive Wing (MAW) demonstrator program on the basis of TACT F-111 testbed in the late seventies (see, for example [2]), but has not received practical implementation, probably because of design complexities.

Transport aircraft have not so wide flight envelope, but even a few percent of improvement in fuel consumption substantiate introduction of the newest technologies such as variable camber or more broadly speaking "intelligent wing". That is why a lot of inventors propose original, often very refined [4,5] engineering solutions on adaptive wing structure, but occasionally not withstanding critics even at the superficial analysis. In our opinion it happens because such inventors simply solve the set design task on a wing geometry modification, not having right thoughts about possible aerodynamic benefits.

The task of this work included a theoretical justification of adaptive wings utilization expedience for perspective transport aircraft and a comparison of full adaptation wing concept vs partial adaptation wing concept, implying wing leading and trailing parts deflection and, probably, some deformation in spoiler area.

For an estimate of aerodynamic performance full-potential+boundary layer code BLWF-28 [6,7] has been used, which received wide application in TsAGI and other world aviation centers due to a fast response time and automatic generation of an algebraic mesh.

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. Three-dimensional computational grid of C-O type over a wing-fuselage configuration is generated using simple algebraic technique. Inclusion of nacelles, pylons and tail fins is made on the basis of "chimera" procedure.

The calculation of a compressible laminar and turbulent boundary layer on a surface of a wing is carried out by finite-difference technique. Cebeci-Smith algebraic model as well as a non-equilibrium Spallart-Almares model of turbulent viscosity are utilized. The transpiration effect of a boundary layer on an external flow is modeled by an appropriate modification of the boundary conditions on the surface of a wing.

The coupling of inviscid external flow and viscous flow is carried out on the basis of a quasi-simultaneous algorithm which provided fast convergence of viscous - inviscid iterations both for attached flow regimes and weak separation. As a rule, five viscous - inviscid iterations for the achievement of full convergence are sufficient. Single run of wing+fuselage transonic flow calculation on modern PC takes about 10sec.

The code delivers values of Cl and Cm as a result of pressure surface integration, and also total drag value components: an induced drag defined in Trefftz plane; a wave drag defined by shock relations over all flow field super-/sub-sonic boundaries; and profile drag of a wing defined by approximate Squire-Young formula, basing on three-dimensional boundary layer trailing edge parameters. For the best agreement with wind tunnel results the computed wave drag is usually multiplied by empirical coefficient 1.5. It is the authors' opinion that, although the results of our study were received with the help of the specific code, the final conclusions have more general character.

The geometry of the wing is defined by our customary design procedure, consisting of three phases [7]: choosing of an initial geometry, refining of pressure distribution at the main on-design cruise point with the aid of inverse method and utilization of optimization procedure for final definition of the base sections shapes. At optimization two methods – gradient procedure and, by virtue of speed of a direct method, even genetic algorithm can be used. Typical number of design variables (local smooth bumps and global contour variations, such as change of section twist, camber, crest position, etc.) for a wing specified by 4-8 baseline sections is about 10 per each section.

Principal choice of the aerodynamic design methodology concerns the number and (M&Cl)-values of the operating points considered during optimization stage. If only single operating point is taken into account then the danger exists of obtaining too sensitive shockless solution which immediately breaks even at weakening of the regime severity, i.e. M or Cl value decreasing (Fig. 1). For obtaining robust design it is necessary to consider several operating points, i.e. to apply multi-regime optimization. Performance in the main point can thus be compromised, but the large scoring is received at off-design conditions and in total. In real designs of the modern wings of trunk-route airplanes the authors usually use simultaneous optimization of aerodynamic performances at 6-8 regimes corresponding to full-scale conditions, and also include one-two regimes corresponding to wind tunnel environment. As a rule, we optimize weighted value of lift-to-drag ratio taking into account various restrictions depending on a specific target. The design point appropriate weights are not known a priori and are tuned by a designer in the outer loop of optimization procedure.

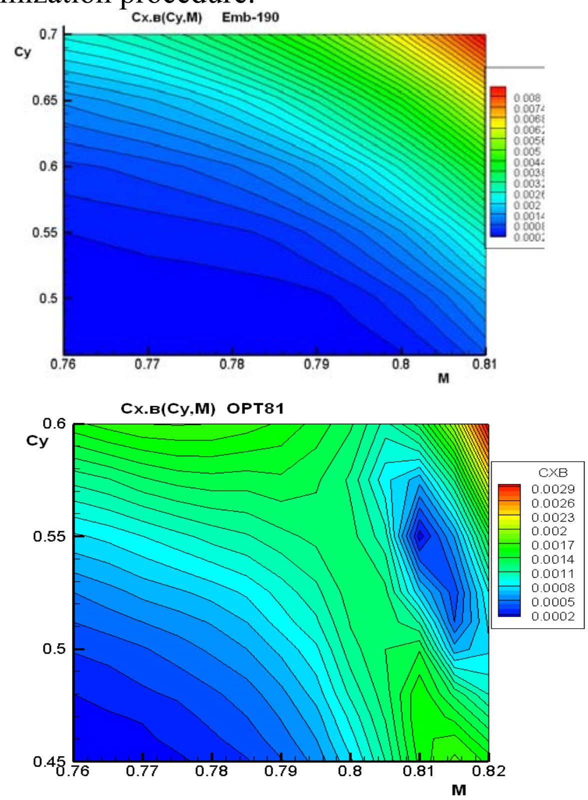


Fig. 1. Comparison of conventional and single-point-optimized wing wave drag reliefs

Shockless solutions which are typical results of one-point optimizations represent natural aims for adaptive wings. However Mach numbers for which shock-free solutions exist (for the sweep angle and relative thickness of the wing fixed) are not arbitrary large [3, 8, 9] - at increasing Mach number over some limit the possibility of obtaining shock-free solutions disappears. The potential speed gain can be taken as a good efficiency criterion for adaptive wings (Fig. 2). Also, as well as in the case of supercritical wings the potential of velocity increase can be exchanged for reducing sweep of a wing or increasing its thickness.

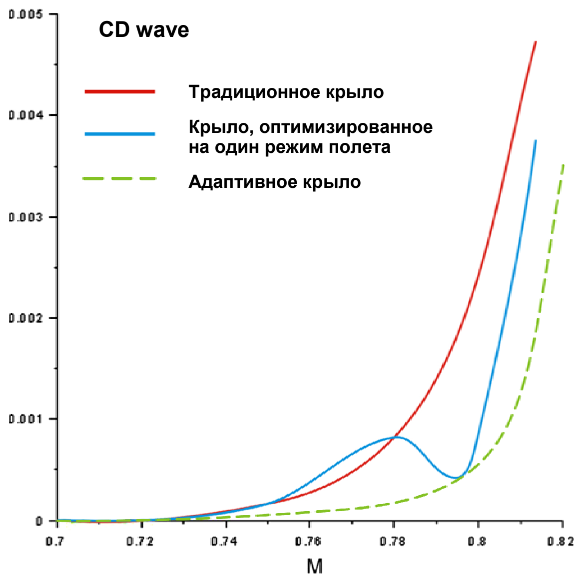


Fig. 2. Utilizing of adaptive wing for increasing cruise speed

3 Assessing of the full adaptive wings potential

For the analysis typical wing+fuselage configuration of the modern regional jet similar to Embraer 190 has been selected. The wing with trailing edge kink and a sweep of $\chi_{1/4}$=23.7 ° is defined by 4 base sections (Fig. 3) with the relative thicknesses t/c=15 % (root) ÷ 12 % (kink) ÷ 11 % (end of flap) ÷ 10% (tip). Linear lofting of the geometry is assumed between baseline sections. During the optimization the planform and the relative thickness of the wing did not change.

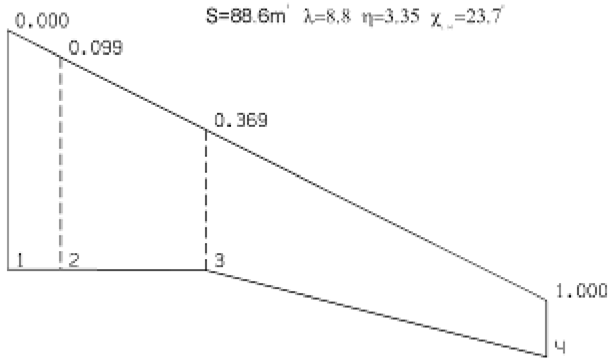


Fig. 3. Wing planform and its baseline sections

Base wing of modern style was designed according to the procedure described above with 5-point optimization, the main cruise regime being M=0.79, Cl_{trap}=0.55 (that is equivalent to Cl~0.5 relative to full wing area) and Re=20mln basing on MAC. Profiles of the wing named *modern79* are shown in fig. 4.

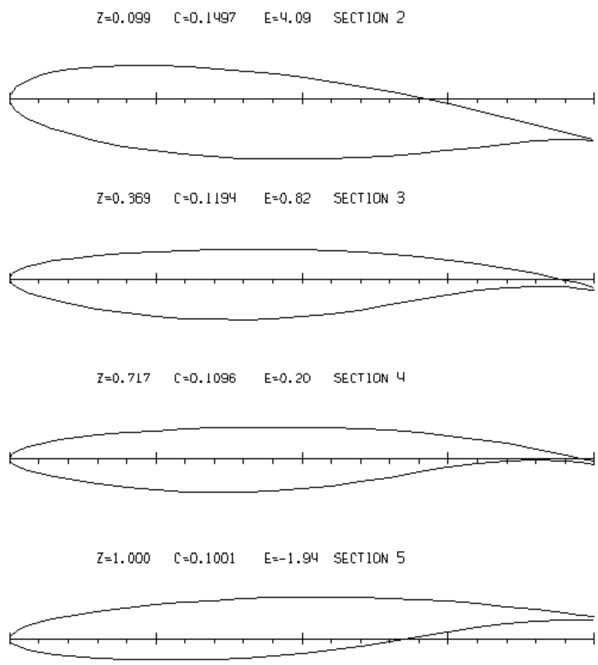


Fig. 4. Airfoils of *modern79* wing sections

Figure 5 shows calculated pressure distribution along wing span at flight regime M=0.79 Cl=0.55, it doesn't contain shocks. Creep drag at Cl=0.55 is also hardly observed.

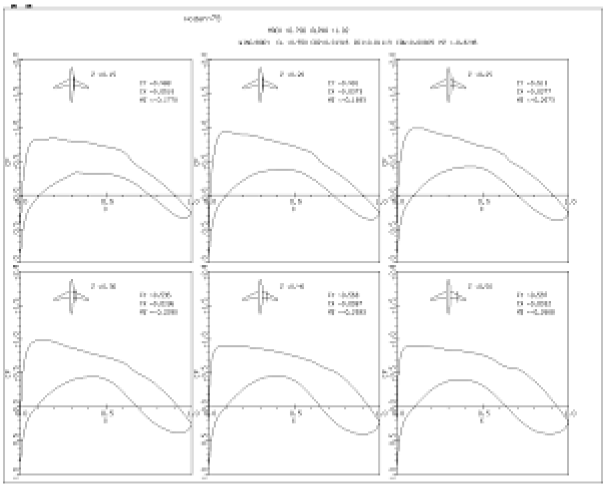


Fig. 5. Wing pressure distribution at M=0.79 Cl=0.55

Further a sequence of single-point optimization problems has been solved at the same lift coefficient Cl=0.55 but at continuously increasing Mach numbers. Base wing geometry *modern79* was taken as an initial one during optimizations and 40 design variables were created for use in optimizations. The goal was to maximize the lift-to-drag ratio of the hypothetical airplane at each operating Mach number, for this result some constant drag coefficient was added to the computed Cd as an estimate of fuselage viscous effects as well as nacelles, pylons and empennage drag.

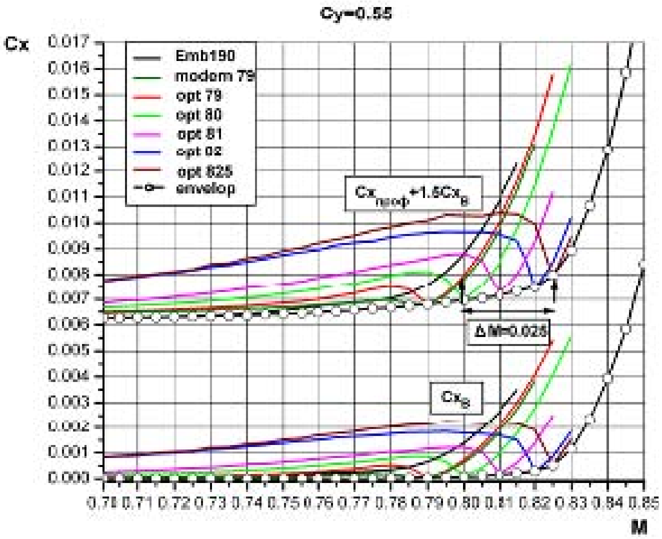


Fig. 6. Drag vs Mach number dependencies

The results of fulfilled single-point optimizations are illustrated in fig. 6. The higher Mach number of one-point optimization design, the higher is the so-called creep drag at off-design conditions. The shock-free flow can be reached up to Mach number M≈0.82. Total envelope, i.e. performance of ideal full adaptive wing gives an increase in $\Delta M_{dd} \approx 0.025$ in comparison with *modern79* wing that agrees with the estimates of the other authors. One-point design nature reflects in wave drag polar too (fig. 7), i.e. reduction of Cl from base value Cl=0.55 also leads to drag creep.

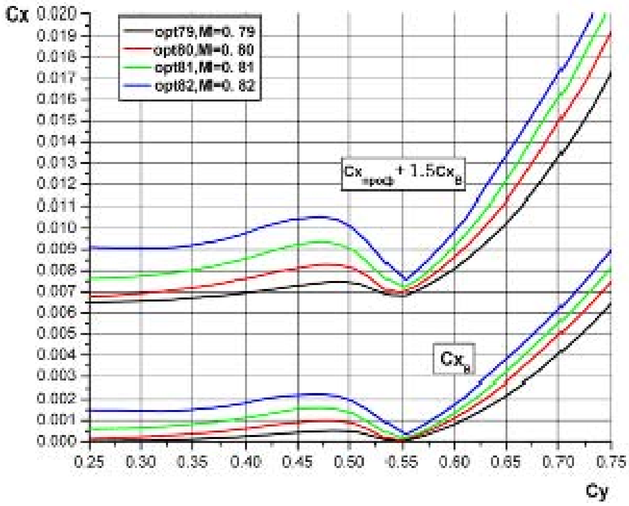
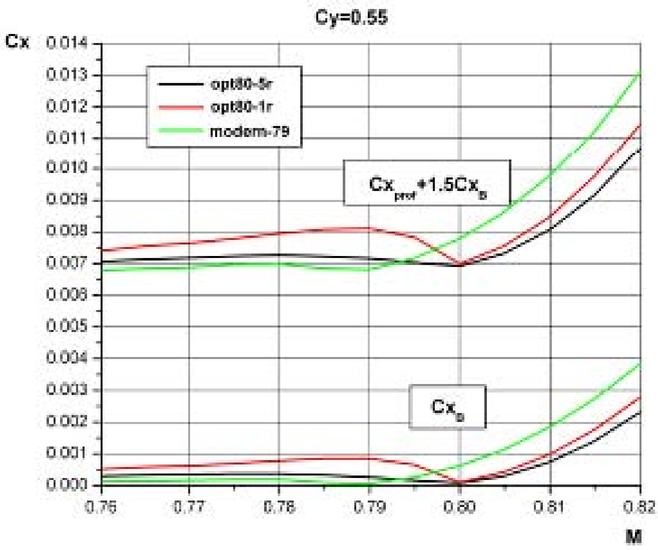


Fig. 7. Wave and wave&profile wing drag polars

Multi-point optimization can relieve off-design performance. Thus, a wing optimized on a 5-point template (M=0.8, Cl=0.55; ΔM = ±0.005; ΔCl = ±0.05) OPT80-5r has much more acceptable off-design performance, than the single-mode wing OPT80-1r (Fig. 8).



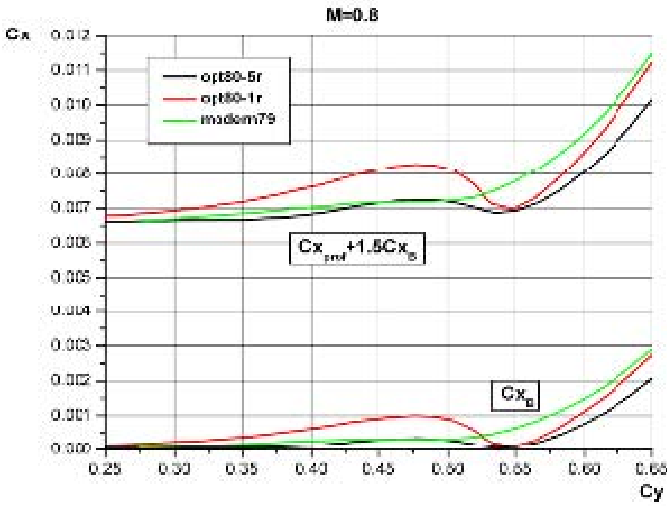


Fig. 8. Comparison of single- and five-point optimized wings

4 Partially adapted wings

Let's call as partially adaptive such wings which have fixed box with a possibility to deflect slightly nose and tail parts at cruise (Fig. 9 [2]). Mentioned in [2] spoilers of the changeable form can be useful to the future laminar wings for which the shock closing supersonic zone on the upper surface is disposed just around spoilers and doesn't move essentially along chord. For turbulent wings the movement of a shock is much larger, and efficiency of the bump in the given fixed place is reduced.

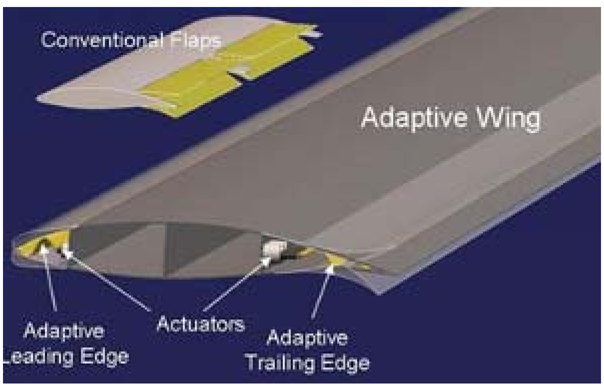


Fig. 9. Adaptive leading and trailing edges

Let's take wing OPT80-5r received earlier as the base one. We will introduce possibility of the smooth deflection of the nose and tail parts divided each into three segments spanwise. Not going into technical details of a design, we will mark that some ideas have been considered in [1] and [2]. Besides, it is known, that small discrete ($\Delta\delta = \pm 1.5°$ through 0.5 °) changing of a flap position at cruise is possible in the newest planes Boeing 787 and A-350.

Totally there are 3+3 variations of wing geometry (Fig. 10) which we will use for optimization of the off-design performance at each deviation of Cl or M from the base regime M=0.8 Cl=0.55. During optimization three tail alone variations, three nose alone variations and all six variations were applied.

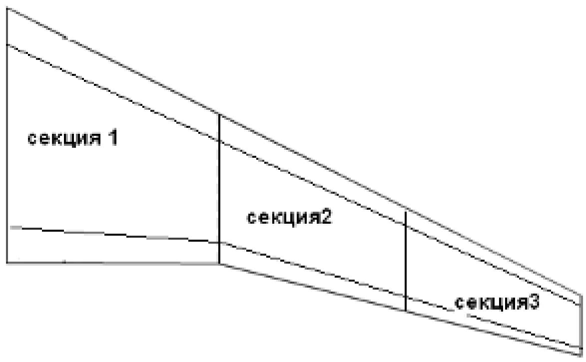
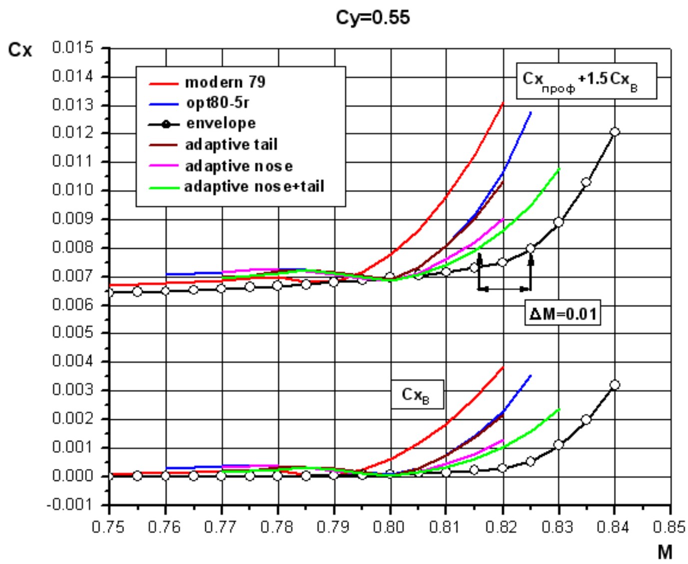


Fig. 10. Segmented nose and tail parts of the wing

Performance benefits due to partial adaptation of the OPT80-5r wing are illustrated in fig.11.



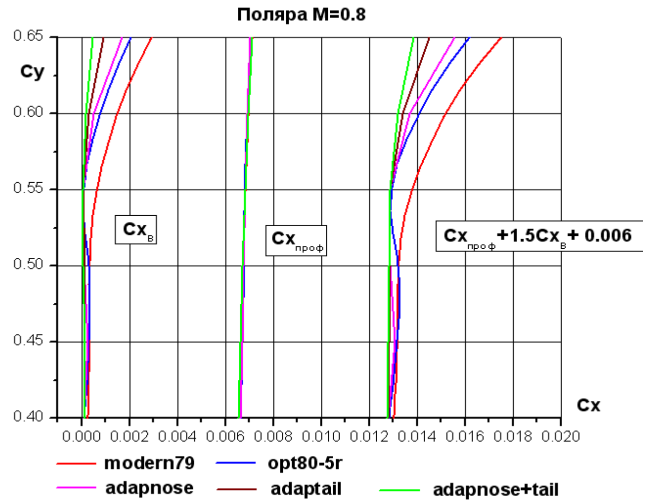


Fig. 11. Partial adaptation benefits

It is visible that deflection of the leading edge is more effective for speed enhancement. On the contrary, deflection of trailing-edge parts shifts “shockless bucket” more effectively over Cl-range. Both ways are not very effective for damping "creep" drag at smaller Mach numbers.

As a whole, the total adaptation by means of deflecting leading- and trailing-edge parts allows additional progress of ΔM≈0.005 in comparison with the fixed wing OPT80-5r. It means that partial adaptation permits to reach cruise Mach number which is only by ΔM≈0.01 less than at the full adaptation of wing geometry. In our opinion this remaining potential of ΔM≈0.01 does not justify construction complication of full adaptation concept affecting wing box.

Thus, as it seems to us, one of the rational procedure to use adaptation advantages for transport aircraft is by taking modest speed shockless wing as a basic one (a la OPT80-5r) and trying to alleviate sharp drag rise at off-design regimes with the aid of partial adaptation. In this way the aerodynamic range parameter, i.e. M*(L/D) product can be augmented by ~1.5-2% in comparison with conventional fixed geometry wing.

5 Experimental verification of partially adaptive wing concept

Verification of the concept of partially adaptive wing has been decided to carry out on an example of the perspective regional jet with a low-sweep wing. Basing on achievements of the modern CFD and aerodynamic design methods [9,10,11], it is possible to reach as high Mach numbers as M=0.78 at a small sweep of the leading edge χ_{le} <17-18°, necessary for preventing growth of cross-flow and attachment line instabilities. Laminarization is another perspective technology which may find its place in next generation airplanes.

Two wings for advanced regional jet with natural laminar flow on the outer wing are considered. In spite of the low sweep angle (15° at quarter chord) the design Mach numbers are as high as M=0.78 and 0.79 correspondingly. The former wing has fixed shape while the latter is based upon the partial adaptive concept to relieve drag rise in the vicinity of design flight regime.

The aerodynamic model of the regional jet with the first wing has been designed, manufactured and tested at cruise regimes in TsAGI’s wind tunnel T-128 (Fig. 12). It was proven experimentally that wing 1 ensures the achievement of prescribed M=0.78. The second wing with changeable leading and trailing parts is under construction now.

Fig. 12. Aerodynamic model of the regional jet with low-sweep wing in T-128 wind tunnel

Conclusions

An aerodynamic optimization procedure was used to assess an adaptive wing concept for transport aircraft. Full adaptation wing concept assess was done through solving a sequence of single point optimization problems, while multi-point optimization procedure was used for justification of partially adapted wings. It was shown that an additional potential of full adaptive wings in comparison with partially adaptive wings is rather small that makes them not reasonable in our opinion. A new way of using adaptation advantages is proposed by taking modest speed shockless wing as a basic one and trying to mitigate sharp drag rise at off-design regimes with the aid of partial adaptation**.**

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