On the utilization of low-sweep transonic wings

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Abstract

Capabilities of achieving high-speed flight with low-sweep supercritical wings are considered. The techniques of aerodynamic design of such wings are described briefly. Examples of designing of high-speed wings of a small sweep for various airplanes are given. It is shown that for perspective airplanes with M_{cruise}≈0.75-0.76 and less it is rational to apply straight high-speed supercritical wings, using their advantages in simplicity and a structure weight, take-off and landing characteristics etc.
At definition of a vehicle general layout on early design stages it is necessary to choose such configurations in which adverse aerodynamic interference is reduced to a minimum. On the contrary, on the layouts characterized by a favorable aerodynamic interference it is possible to achieve an additional gain of speed in comparison with a "pure" wing.
Further increase of aerodynamic efficiency can be reached by means of the adaptive supercritical wings realizing optimum pressure distribution not only at single cruise condition but also at the whole envelope of flight.

1. Introduction

Wing sweep increase as well as relative thickness reduction is used traditionally by aerodynamicists for aircraft speed augmentation due to wave drag rise delay, but weight penalties are inevitable for swept wing. Modern supercritical airfoils allow increasing flight speed considerably in comparison with airfoils of the previous generations (fig.1 [1]) practically without incurring weight degradations. Thus, there is a capability to reduce wing sweep considerably without loss of a speed. However, basing upon former experience, designers reluctantly want to implement low-sweep wings. Sometimes it can be explained by specific features of a design, for example, convenience of accommodation of a landing gear behind a rear spar of a swept wing. Unfortunately, absence of the information on last achievements in the field of transonic aerodynamic design may also affects. Some conventional "wisdoms" play a role, for example that unswept wings can be applied at speeds not above M_{cruise}≈0.7. As a result, not only the plane of 70-s – Yakovlev-42, but also more modern Russian planes - Beriev-200, Tupolev-334 etc., have too much sweep. Moreover, even now the authors often encounter with projects of advanced aircraft having wings with too excessive sweepback.

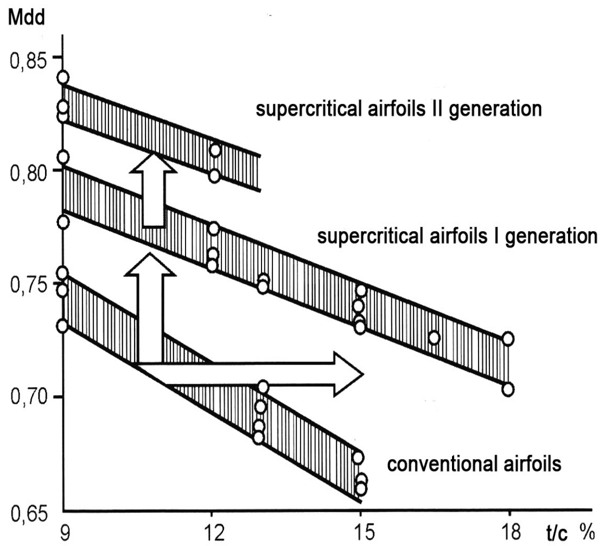

Figure 1: Mach-Thickness relationship for airfoils

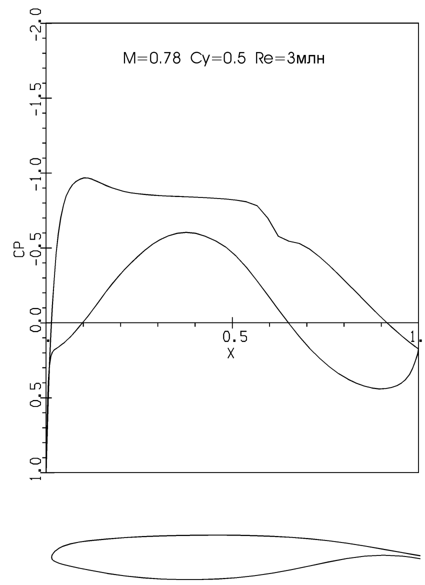

Figure 2: Modern supercritical airfoil

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The work presented herein explores the possibility of refining and extending some commonly accepted limits related to an application of low-sweep transonic wings. Similar ideas may be found in the recent foreign publications [2-4]. For example, in [3] it is asserted, that if the designers of the Boeing 737 and the Airbus A-320 aircraft had access to the modern supercritical wing technologies they might have elected to use wings with significantly less sweepback. In the European program NACRE [4] low-sweep wing of the advanced short-haul airplane with slightly reduced M_{cruise}=0.76 is combined with a natural laminar flow control and the use of very-high-bypass-ratio turbofans or even open rotors.

Efficient high-speed low-sweep transonic wings may be created with the help of the modern aerodynamic design procedure based upon state-of-the-art CFD methods linked with inverse and optimization routines. Brief description of the techniques used is given. The examples from the author’s practice of high-speed low-sweep wing design for different purpose vehicles are described. Some transonic wind tunnel data aimed to verify computational achievements are included also. It is emphasized that along with optimal shape of the wing the conditions of favorable aerodynamic interference with the fuselage and engine nacelles are of the same importance. Besides, additional speed increment may be achieved by the concept of adaptive transonic wing realizing optimal pressure distribution not only at single point but in the whole region of flight regimes.

As a prime conclusion it is argued that for future designs with cruise Mach number no more than M≈0.76 it is rational to choose unswept wings making good use of their simplicity, weight advantages, high-lift aerodynamics etc.

2. Technique of aerodynamic designing of transonic configurations

Computational Fluid Dynamics (CFD) plays an important role in aerodynamic design of an airplane elements as well as a whole configuration. Basing upon significant progress in computer power and numerical methods, CFD has passed a big way from the first modeling of inviscid/incompressible flow over 2-dimensional airfoils to detailed solutions of viscous compressible gas equations over a complete airplane configuration. Modern achievements in CFD methods have allowed to change cardinally process of aerodynamic design not only due to simple increase of considered alternatives or shortening the design development process, but also due to improving the quality of a design with the help of built-in design capabilities. It is necessary to notice, that cost of computations continuously reduces all last years whereas expenses for carrying out wind tunnel tests tend to increase all over the world.

For the effective organization of aerodynamic design procedure presence of four basic components is necessary [5]: geometry control and manipulation system, direct methods for the analysis of aerodynamic characteristics, inverse and optimization methods, predicting the necessary geometry shape changes to obtain desired pressure distribution or to optimize certain flow characteristics (e.g. drag) at the imposed numerous constructive and aerodynamic constraints.

The key to success of the aerodynamic design process is a <u>direct analysis method</u>. Efficiency of all design stages depends on its reliability, accuracy, robustness and speed. For many years different direct codes have been created at TsAGI. The great value had a creation and continuous perfection of the BLWF code [6]. This code is intended for an operative analysis of transonic flow over a wing-body combination and more complex configurations on the basis of iterative quasi-simultaneous strong viscous-inviscid interaction of external potential flow and a boundary layer on lifting surfaces. The solution of transonic flow over entire airplane is provided within one minute on modern PC. Thanks to small CPU time requirement and also to the built-in automatic procedure of grid generation not demanding direct intervention of the user the BLWF code is widely used in TsAGI and other world aviation centers (see for example [7]) for designing of efficient commercial transport.

<u>Inverse methods</u> are intended for generating wing geometry with specified (target) pressure distribution. In hands of skilled aerodynamicist inverse methods are powerful tools of aerodynamic designing. They allow him to eliminate or weaken shock waves, to reduce level of disturbances of a flow in the predetermined region, to realize the pressure profile favorable for development of a boundary layer. Possessing of robust inverse method it is possible to transfer “good” pressure distribution from a successful prototype for fast designing of the initial geometry.

Some drawbacks are inherent to inverse methods also. They are difficult to apply, for example, to designing of multi-regime vehicle, or in the presence of numerous geometrical restrictions. Besides, in case of strong aerodynamic interference between different elements adverse pressure distribution on some element can be a result of influence from another one, and attempts to use an inverse method directly are not always rational. For example, poor wing-fuselage fairing can distort wing pressure distribution over large part of a span, Venturri effect can provoke shocks on engine pylons, massive sponsons can cardinally change a flow pattern on the lower wing surface of a high-wing monoplane etc. Especially large interference effects are inherent to flows at large near sonic Mach numbers. For the solution of interference problems it is recommended to use a principle of separation of disturbances from various elements of the aircraft.

Numerical optimization methods are most adapted for design purposes allowing easily change of objective functions, consideration of numerous geometrical and aerodynamic constraints and conduction of multipoint optimization. Procedure of numerical optimization is based on coupling of a direct method for aerodynamic analysis, a set of geometry variations and the optimization block. Change of the base sections of a wing is made by means of global (twist, camber, crest position $Y_{MAX,}$ etc.) and local variations. It is possible to vary a wing planform and a mutual position of different elements of a layout. At large Mach numbers variations of fuselage geometry are often applied.

In the optimization block two methods – gradient method and owing to speed of a direct method even genetic algorithm, can be used. The last is a variant of a method of random search with the self-training simulating the process of natural survival in wildlife. The typical number of design variables for a wing set by 5-7 base sections, is equal approximately 50. As a rule, lift-to-drag ratio taking into account various constraints is optimized. From aerodynamic values it is often necessary to restrict pitching and bending moments. Geometrical restrictions allow meeting constructive and manufacturing requirements. For example, for obtaining technology acceptable wing surface it is expedient to limit curvature of box panels along span.

Basic advantage of optimization techniques is a capability of multimode or multicriteria optimization. Modern supercritical wings are strongly sensitive to flow conditions. If at a single flight condition it is possible to achieve practically shockless flow, the off-design characteristics may be poor even at reduced M or Cl regimes because of shocks appearing. Single-point optimized wing will lose to a wing at which designing several conditions have been considered. Additional consideration of a low speed regimes allows to find the rational compromise between cruise and take-off and landing characteristics of a wing [8,9].

At present the authors use a four-stage aerodynamic design procedure [5]. At the beginning the initial wing geometry is selected with chosen on a conceptual design stage planform, sweep and mean relative thickness. Then, by means of an inverse method new geometry is generated with improved pressure distribution and small wave drag at basic cruise regime. At the third stage the parametric variation of the configuration obtained is made, and the optimization procedure defines an optimum set of parameters which maximizes chosen objective function with the account of numerous restrictions of different origin. This stage is labour-consuming, not only because search of an extremum demands large computing expenses, but also owing to numerous repeated changes of a kind of object function and restrictions for achieving maximum project efficiency by many criteria. Fine "tuning" of configuration by the inverse and optimization methods can be carried out in a number of successive cycles. After the third stage usually the manufacturing of aerodynamic model is started to receive experimental confirmation of estimated characteristics. At last, local aerodynamics adjustment is made at fourth stage (fairings, fillets, wingtips etc.) which task is to unveil the last reserves of configuration and to prevent deterioration of prime aerodynamic characteristics owing to technology factors. Here it is possible to use not so fast computational methods (for example, RANS-methods) with detailed modeling of all airplane elements, as well as wind tunnel studies.

3. On the selection of wing sweep for subsonic aircraft

Let's consider two-dimensional airfoil flow - it depends on a condition - (M, Cl) and airfoil geometry. According to empirical relations in order to increase speed by $\Delta M\approx 0.01$ with other things being equal it is necessary to reduce a relative thickness of an airfoil by $\Delta(t/c)\approx 0.01$ or to reduce lift coefficient by $\Delta Cl\approx 0.1$. Existence of these simple relations allows cutting down all variety of parameters to one combination (M, Cl, t/c). It is common practice to consider airfoils with relative thickness t/c=0.12 and Cl=0.5. From figure 1 it is seen that modern supercritical airfoils with such parameters can ensure cruise Mach number as high as M_{cruise}~0.78-0.79. The geometry of a typical supercritical airfoil obtained by means of described above design procedure and its pressure distribution at M=0.78 are shown in fig. 2. It is visible, that the significant part of lift is generated by rear loading on the lower surface, yielding negative pitching moment. On the upper surface there is an extensive supersonic zone terminated by a weak shock. Leading edge of the airfoil is drooped slightly downwards for enhancing lifting properties at low speeds.

Modern transonic wings have a mean relative thickness about 12 %, and a mean flight lift coefficient $Cl\approx 0.5$. Thus, it is possible to take directly previous results on airfoils for an estimation of high-speed properties of a low-sweep wing. We have to consider inevitable losses of lift near wing tips and lift loss on a horizontal tail at trimming of the steady plane of the normal scheme. As a result of simple estimations we will receive that a straight wing with typical distribution of relative thickness $\bar{c}$=15÷12÷9 % at root, kink and tip accordingly, can ensure M_{cruise}=0.76-0.77.

The high-speed wing of a small sweep ($\chi_{1/4}$=8°) was designed by the authors for M-60CP airplane being investigated by Myasishchev design bureau (fig.3). During the optimization following flight conditions were considered: M=0.76 Cl=0.575; M=0.77 Cl=0.55; M=0.78 Cl=0.525; M=0.76 Cl=0.6 and M=0.76 Cl=0.55. The mean relative thickness of the wing equals t/c=11.5 %. According to the calculations, the designed wing really guarantees small level of wave losses at prescribed regimes. On the basis of the fulfilled studies the mathematical model has been developed and the aerodynamic model has been manufactured. Tests of this model in TsAGI's wind tunnel T-106M are planned for the middle of 2011.

Let's ask a question why at really flying planes wing parameters are far from above estimations. In our opinion here it is possible to indicate two main reasons. First, the potential of the advanced transonic airfoils is not fully used. Secondly, it is very often observed an adverse aerodynamic interference with other elements of an airplane (fuselage, fairing, pylons, engine nacelles, sponsons and so forth), not allowing to realize capabilities of a "pure" wing. The adverse interference is caused either by the underestimation or the wrong account of interaction of separate elements at designing (for example, earlier a wing was designed without accounting an interference with engines), or selection of irrational layout at the beginning.

As a typical example of irrational aerodynamic layout small executive airplane may serve. As a rule for space saving in a saloon a wing is placed below the fuselage (fig. 4) and the large fairing is required. In this case on the lower surface of a fairing there is an additional acceleration of a flow leading to generation of negative lift and, what is even more important, increasing local Mach number significantly $M_{local}>M_{\infty}$. Thus, disturbances from separate elements summarize resulting in essential losses of Mdd.

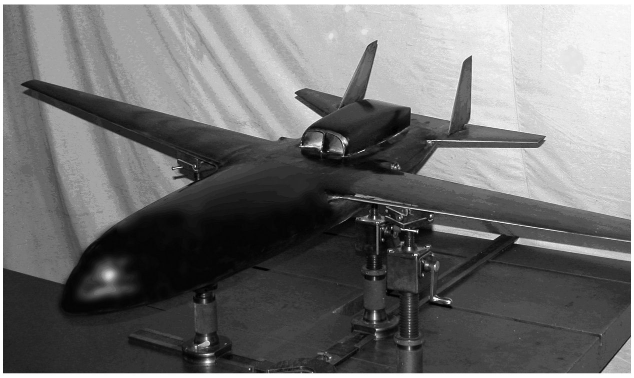


Figure 3: The aerodynamic model of M-60CP airplane

Figure 4: Premier 1A business jet

Configuration without a fairing, even at larger diameter of a fuselage possesses considerably better interference. Calculations show, that the fairing influence is equivalent to huge increase of root relative thickness - Δ(t/c)≈0.05. The designer should understand clearly consequences of an adverse aerodynamic interference from the beginning to make selection in favor of this or that principal layout.

The scheme "high-wing monoplane" is even more problematic for aerodynamic designing because an adverse interference appears on the upper - more critical wing surface. Numerical and experimental studies have shown that with the "natural" form of the fairing it is typical situation that the strong shock exists near the axis of the fuselage causing flow separation and falling of aerodynamic efficiency long before design Mach number M=0.78, whereas outer wings exhibit quiet subcritical flow. With successfully designed fairing the wing with a smaller sweep can enter in crisis even after more swept wing (fig.5,6). The more the length of a fairing, the better, with other things being equal, flow in a vicinity of a centre wing and higher drag divergence Mach number Mdd, however weight of a skin of a fairing also increases. Understanding inevitability of extended upper fairing, the designer should envision on an early design stage reasonable use of created additional volumes, for example, for a fuel tanks.

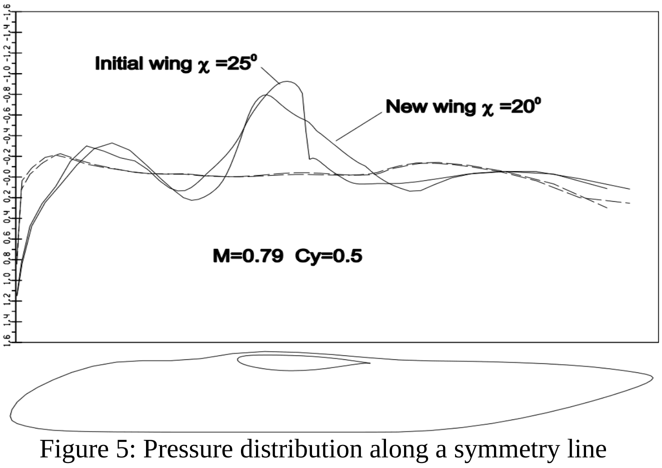


Figure 5: Pressure distribution along a symmetry line

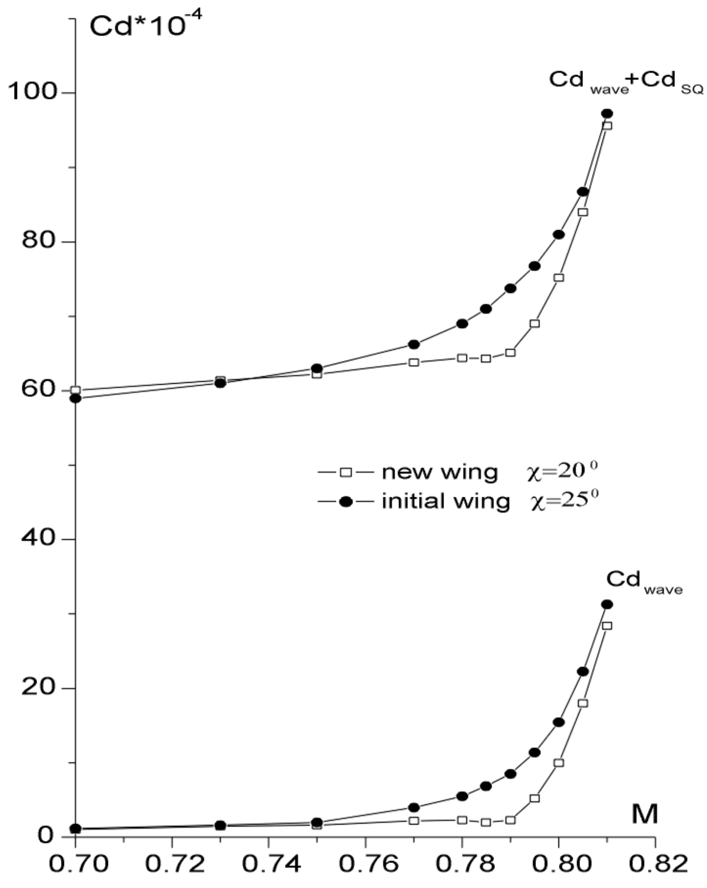
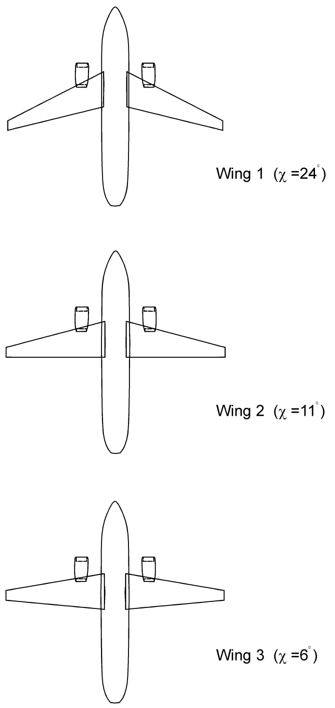


Figure 6: Drag dependence vs Mach number

It is necessary to optimize simultaneously wing and fillet shapes - only in this case it is possible to compare correctly wings of a different sweep. Conducted for perspective transport studies show that decrease in a sweep from $\chi_{1/4}=24°$ to $\chi_{1/4}=6°$ (straight rear spar) (fig.7) reduces cruise speed of flight only by a ~25km/hour, providing weight saving and simplicity of a design and improving take-off and landing characteristics.



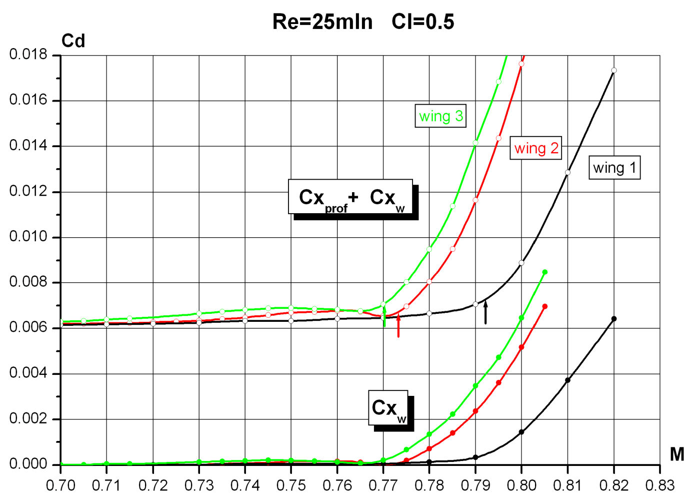


Figure 7: Comparison of wings with different sweep

The aerodynamic interference may be not only negative, but positive also. It is useful to put, for example, a wing in a zone of decelerated flow where a local Mach number is less than M_∞. Well-known "area rule" for near sonic aircraft is based on this principle, but for subsonic speed vehicles it is expedient also. Except waisting of a fuselage in a wing zone there are other tools for flow slowdown, for example, engine nacelles placed in a tail part of a fuselage. At cruise the relative air flow through the engine is less than unit, therefore in front of the engine the flow is decelerated. The effect of flow deceleration is especially strong on high-speed business jets, where distance from a trailing edge of a wing to the lip of engine nacelles is small.

Original "area ruling" has been used at designing of a new layout of a small business jet "Tadpole" (fig.8). According to estimations the maximum take-off weight of the plane is within 5700kg, while range reaches 3200km with 6 passengers and 4200km with 3 passengers. The drop-shaped fuselage allows to improve considerably comfort of passengers (the maximum altitude of interior H=1.9m - the greatest among analogues) and to receive favorable aerodynamic wing-fuselage interference (fig.9) making it possible to reach the maximum speed corresponding to M=0.8. Notice, that wing is entirely unswept with usual relative thickness distribution (t/c=15-11 % in root and tip sections accordingly). Use of a straight wing simplifies and lightens the design, allows obtaining high lift in the absence of slats and promotes natural laminar flow of a wing at speedy cruise.

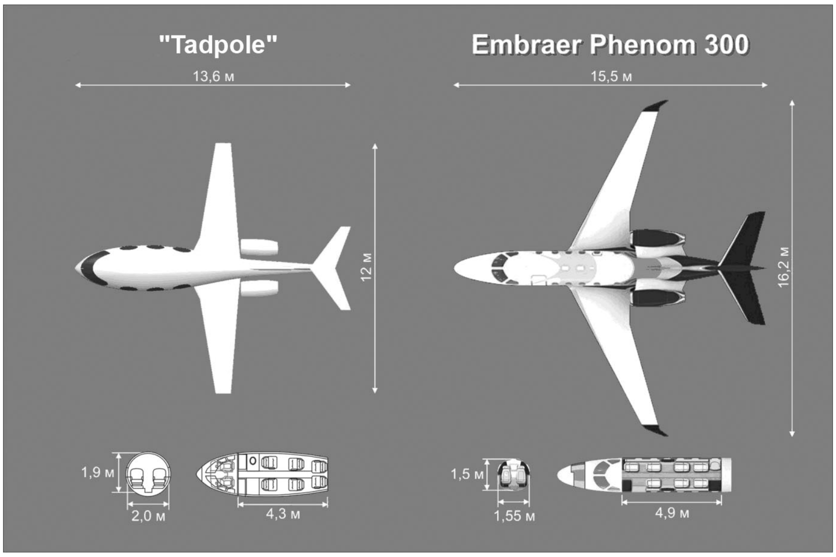


Figure 8: Comparison of business jet configurations

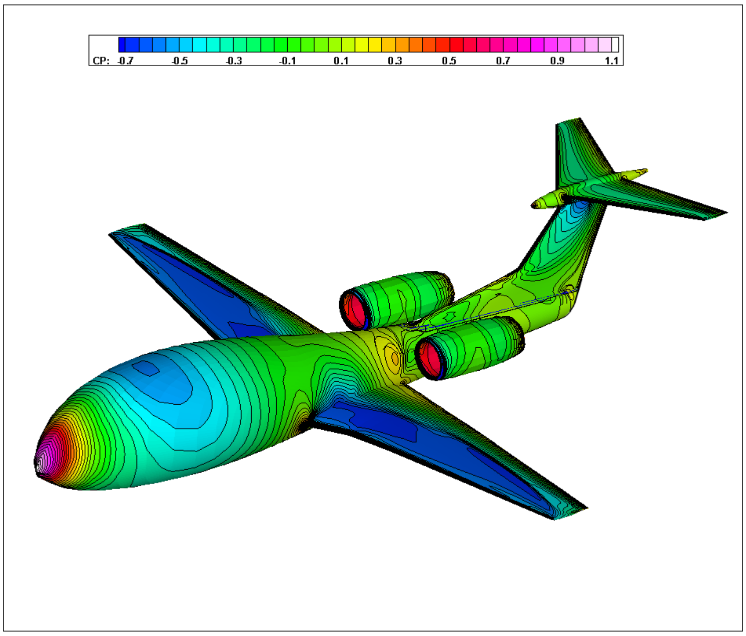


Figure 9: Surface pressure distribution at M=0.8 Cl=0.35 regime

One of possibilities to increase aerodynamic efficiency of high-speed wings further is the application of so-called adaptive wings [10,11]. Unlike the usual wings forcedly designed for several modes of flight and having some losses on each particular mode, adaptive wings allow passing on an envelope of optimal points. The potential of increase M_{cruise} by using adaptive wings is estimated by an expert value of ΔM_{cruise}~0.015÷0.02. Similarly to supercritical wings it is possible to use the adaptive wings not only for increase in a cruise Mach number, but also for sweep decrease at M=const. Within the adaptive wing concept it is not unlikely to imagine advanced short-haul airplane with $M_{cruise} \approx 0.78$ and a wing leading edge sweep $\chi \leq 18^{\circ}$ that allows the designer to hope for additional decrease in drag due to laminarization of the slats of outer wings. Thus, the total potential of the concept of adaptive wings is estimated at 3-4 % of fuel consumption without implementation of radical changes into a plane design. It is noteworthy value to conduct thorough computational-experimental studies on the given subjects.

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