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The studies on low-noise laminar wing regional aircraft

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Abstract

Presented are recent studies conducted in TsAGI on regional and short range low-noise aircraft with natural laminar flow (NLF) transonic wings. At designing of such wings a distinct trade-off between laminar and turbulent mode of a flow, between viscous and wave drag amount and also between NLF and high lift characteristics has to be considered. A description of the special multicriterion optimization procedure for aerodynamic design of laminar wings developed in TsAGI is given. Several aerodynamic models were designed and manufactured for transonic wind tunnels testing including configurations with over-wing-trailing-edge engine arrangement which can reduce community noise and open the road to fuel-efficient ultra-high-bypass-ratio turbofans with large fan diameter on short range planes. Selected experimental results are also presented.

INTRODUCTION

Stringent environmental requirements are formulated in the USA, Europe (see NASA and ACARE visions in [1]) and Russia to technical indicators of aircraft of the near future to provide the predicted sustainable growth of air transport. In particular, the goal is to substantially reduce emissions of carbon dioxides (by ~50%), nitrogen oxides (by ~80%) and to decrease community noise. Thus the development of more environmentally friendly, fuel efficient transport aircraft is a major challenge to the aircraft industry and research. Such ambitious goals can't be matched with small improvements on existing aircraft designs but are only possible with leaps in technologies. That is courageous ideas have to be considered on introduction of radically new technologies and configurations and search has to be conducted by the wide front.

Laminarization is currently the only technology in aerodynamics which promises two-digit percentage improvement in fuel burn [1]. Despite of the long history of studies on this technology [2-5] it still is waiting for active implementation into airplane design. Today, laminar airfoils are widespread used in sailplane, UAV and light aircraft designs, but practically all applications of laminar flow technology put into operation so far are restricted to straight wings flying at low Reynolds and Mach numbers. This is because only one transition phenomenon, namely Tollmien-Schlichting instability (TSI), exists. The situation becomes more complicated for transonic swept wings for which two more transition phenomena, i.e. crossflow instability (CFI) and attachment line transition (ALT), come into effect [6]. In order to limit the growth of crossflow instabilities and prevent early transition the leading edge sweep of the wing shouldn't be higher than 18-20 degrees. It is common opinion that due to this restriction the reduction of cruise Mach number to about 0.75 is inevitable [4, 7], however such small speed poorly agrees with modern route networks served by high speed (M = 0.78-0.8) current fleet of regional and short/medium range aircraft like A-320 and B-737. Forward swept wings are offered by DLR for achievement of the necessary speed and still keeping the demanded small leading edge sweep [7], however other shortcomings of the forward sweep most likely outweigh its advantages.

TsAGI for many years investigates various aspects of a laminarization, and in recent years these studies received a new impulse. The NLF airplanes considered in TsAGI possess wings with small backward sweep, however they reach high Mach numbers of about M = 0.78 due to utilization of advanced supercritical profiles along span. At designing of such wings it is necessary to consider a strong compromise between laminar and turbulent mode of a flow, between viscous and wave drag amount at transonic speeds and also between natural laminar flow (small leading edge radius) and high lift characteristics.

Several aerodynamic models with low-sweep wings were designed for testing in transonic wind tunnels including configurations with over-wing-trailing-edge engine arrangement. Such a layout promises a reduction in community noise [8-11] and opens the road to fuel-efficient ultra-high-bypass-ratio turbofans with large fan diameter on short range planes. Selected experimental results are also presented.

1 MULTICRITERION OPTIMIZATION PROCEDURE FOR AERODYNAMIC DESIGN OF NLF WINGS

According to present-day views natural laminarization is possible for small Reynolds number and sweep value wings (Fig. 1 from [6]), i.e. for regional or short range aircraft.

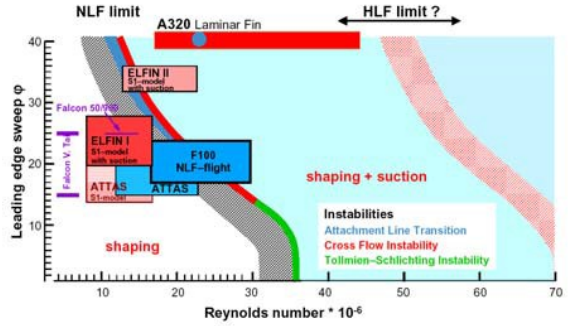

Fig 1: The frontiers of laminarization [6]

Basing upon different flight experiments it was revealed that the leading edge sweep of the wing shouldn't be higher than approximately 18-20 degrees to prevent early transition. Due to this restriction it was considered necessary for a long time to reduce cruise Mach number to values of 0.75 and even less, but such small speed poorly agrees with modern route networks served by high speed (M = 0.78-0.8) current fleet of regional and short/medium range aircraft. Modern supercritical wings do permit obtaining high Mach numbers without excessive sweep [12,13], thus omitting CFI and ALT risk, but they rely heavily on the so called "turbulent" pressure distribution, featuring rather high leading edge velocity peak continued by supersonic zone with moderate negative velocity gradient terminated by a weak shock. An aerodynamic model of the short range airplane with turbulent reference low-sweep wing ($\chi_{1/4}$ = 15°) and under-wing through-flow nacelles is shown in Fig. 2. The model was tested in the large transonic TsAGI's wind tunnel T-128 and showed satisfactory high speed properties, proving the possibility of obtaining M_{cruise} = 0.78.

Fig 2: Aerodynamic model with low-sweep wing

Laminar airfoils, on the contrary, require mild positive velocity gradient on the upper surface, stabilizing Tollmien-Schlichting instability. As can be seen from Fig. 3, taken from [4], this immediately results in loss of lift, loss of the airfoil thickness and increase of negative pitching moment coefficient. Besides, small leading edge radius of the laminar airfoil is a reason of poor high-lift capability and this may be another crucial point taking into account an impossibility of slat utilization.

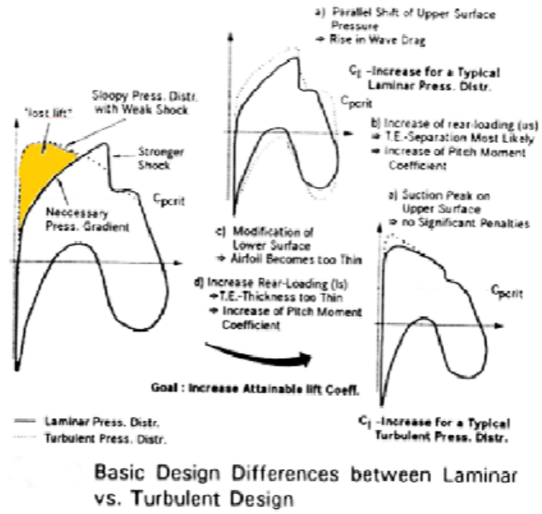

Fig 3: Basic differences between laminar and turbulent design [4]

Summing all the listed drawbacks of the laminar wings it is obvious that some multicriterian design procedure should be used to resolve several trade-offs in a rational way. The main trade-offs are between profile and wave drag of the transonic wing and between cruise lift-to-drag ratio and high-lift capability. An additional compromise is related to the behaviour of the laminar wing under fully turbulent conditions and choice of necessary preflight fuel reserve because premature transition may occur due to insect, dirt or ice contamination. Such compromise was considered, for example, in [14], but in two-dimensional formulation. The Pareto front of laminar vs turbulent efficiency of the airfoil was constructed, and a conclusion was drawn that extreme edges of the front are poor choices for the practical design.

In this article usual aerodynamic design procedure for transport aircraft [15] is extended to include possibility of designing natural laminar flow transonic wings. The cornerstone of the procedure is a multicriterian optimization block providing simultaneous wing cruise and high-lift characteristics optimization. Fast transonic and subsonic analysis methods permit numerous flow evaluations in optimization loops without excessive time consumption. The objective function is presented by the linear combination of lift-to-drag ratios (L/D) at several cruise regimes and the maximum lift coefficient Cl_{max} at low speed. Among cruise regimes are considered both full turbulent and free transition modes with corresponding weight factors determining relative position on the Pareto front. More conservative but reliable approach consists in choosing turbulent regimes more weighty – in this case there is no loss against turbulent counterparts at all, while the possibility of significant drag reduction (∆Cd~0.0015-0.0020) exists due to laminarization of the (upper) wing surface.

The key to success of the aerodynamic design process is the fast direct transonic analysis method – BLWF code [15]. 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 few seconds on modern PC. Thanks to small CPU time requirement and also to the built-in automatic procedure of grid generation, the BLWF code is widely used in TsAGI and other world aviation centres for aerodynamic design purposes.

Initially only fixed transition calculation mode was available in the BLWF code. Several attempts to include transition prediction capability were undertaken, for example semi-empirical e^N method is studying. For low-sweep wing it was found adequate to use simple two-dimensional empirical criterion of Granville [16]. Calculated with the help of this criterion a transition line on the low-sweep wing (see Fig. 2) agrees satisfactorily with the experimental one, visualized by the liquid crystal technique (Fig. 4). Calculation with free transition is done in iterative way. Initial pressure distribution is calculated with forward prescribed transition, after that the position of new transition line is defined by the analysis of a set of pressure distributions along span and sent with some relaxation to direct code, and so on. Up to ten iterations is necessary to reach a converged solution. Simultaneously angle of attack value is tuned to reach the prescribed lift coefficient during the optimization process.

Usually we consider several fully turbulent and a few free transition design regimes. Changing relative weights of different regimes in the composite objective function it is possible to obtain more knowledge about problem of interest basing on a feedback provided by the optimization results and to come finally to well-balanced problem specification. Fast turnaround computation time is of paramount importance for the success of the optimization procedure. Pareto fronts are particularly useful in revealing different trade-offs, but even with very fast direct methods they can be constructed for simple model problems only.

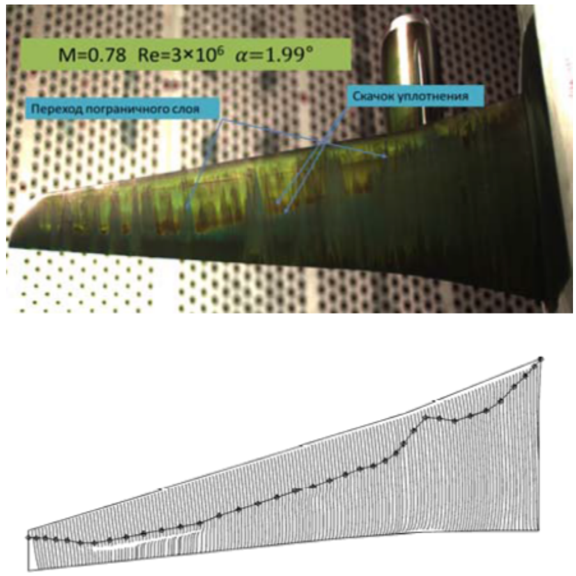

Fig 4: Experimental and calculated transition position

2 OVER-WING-TRAILING-EDGE ENGINE CONFIGURATIONS

Over the last years there was a boom in publications [8-11] concerning over-wing-trailing-edge engine configurations. The main driven forces of this new surge in interest are the expectations of fuel-efficient ultra-high-bypass-ratio turbofans (or superfans) advent in the near future with a corresponding provided drop in fuel consumption and jet noise. Large fan diameter makes it difficult to mount engines in the conventional under-the-wing configuration, whilst over-the-wing engines have no constraints on their dimensions. Besides, the wing would shield fan-to-ground noise which is the main noise source for superfans. A number of additional merits exist, to mention a few: reducing hazard of foreign objects penetration into the air intake, possibility to truncate landing gears, lack of a gap of the leading edge high-lift devices etc. Some disadvantages exist as well, for example, increased cabin noise level, likely necessity of T-tail and so on.

TsAGI studied aerodynamic interference between wing and over-wing-trailing-edge engines for long-range aircraft with high cruise Mach number and for short-range aircraft with smaller M_{cruise}. Calculations and wind tunnel experiments showed that large wing sweep of high speed aircraft makes it difficult to mount engines over the wing in the vicinity of planform kink because intense negative aerodynamic interference appeared not only at near-the-nacelles regions but along the whole wingspan. Besides, flow over the wing is strongly sensitive to the cruise mass flow ratio through the engines.

Small sweep, on the contrary, causes more local interference between the wing and the over-wing engine that allows designing and optimizing wing surface with more credibility. Thorough studies of this configuration reveal unexpected aerodynamic benefits: due to decelerating influence of engines and lack of landing gear fairings at the wing-fuselage junction (landing gear is reasonable to locate in the lower part of the massive engine pylon) the wave crisis may be postponed to slightly higher Mach numbers – exactly that we want to justify NLF wing without reduction of the desired Mach number of M=0.78. Aerodynamic studies in the T-128, held in 2015 with the initial wing LSW-2 (Fig.5), designed without accounting free transition regimes, showed satisfactory transonic aerodynamic characteristics, including the possibility of obtaining significant laminar runs on the outer parts of the wing. Of the main drawbacks were poor lift capabilities at low speed.

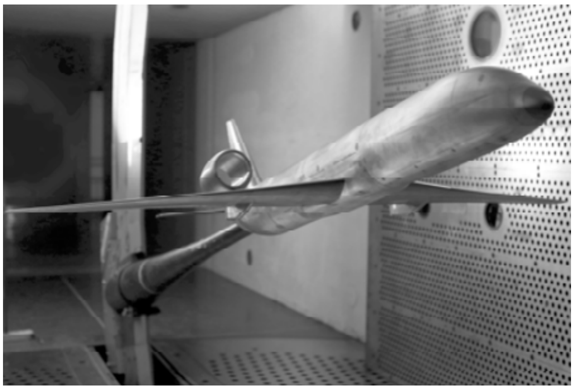

Fig 5: The aerodynamic model of low-sweep wing (LSW-2) aircraft with over-wing nacelles

After that new design procedure, described in the previous section, has been used for the design of the wing 3 (Fig.6). Leading edge kink was canceled for simplicity reason. It was assumed that the wing 3 is equipped with Krueger flaps across the span and there is no laminarization of the lower surface.

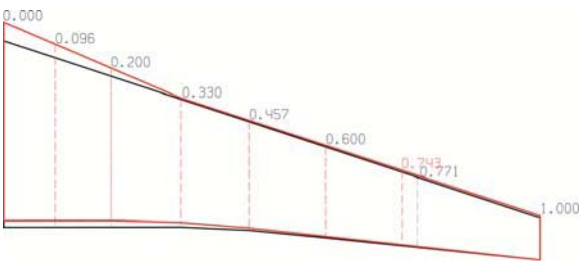

Fig 6: A comparison of wing planform between LSW-2 (red) and LSW-3 (black)

This assumption makes it possible to increase lift characteristics by drooping leading edges of the airfoils slightly. In addition, laminar flow is hardly achievable in the root regions of the wing, because of the large local Reynolds number and strong influence of the fuselage and nacelles. Besides, the optimization indicates that for root sections it is more appropriate to have front loading to improve speed characteristics and to weaken negative pitching moment of the wing. Thus, when designing LSW-3, in comparison with LSW-2 the following goals were stated:

- increase L/D-ratio at free transition condition
- lose a little at fully turbulent flow condition
- increase lift characteristics at low speed.

The aerodynamic model with wing 3 (LSW-3) was tested in the first half of the year 2017 (Fig.7).

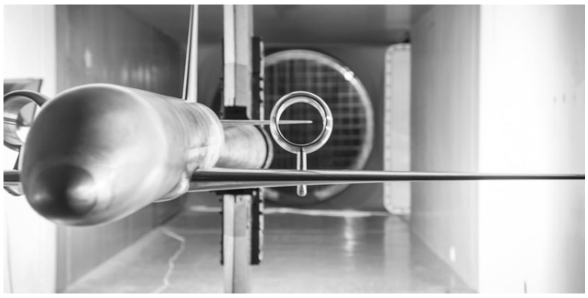

Fig 7: The aerodynamic model of short range aircraft with wing 3 in the T-128 wind tunnel

Almost all the design goals were met. Especially impressed was an increase in maximum lift, much higher than predicted by the theory (Fig.8). For insurance, repeated testing in another wind tunnel was even fulfilled.

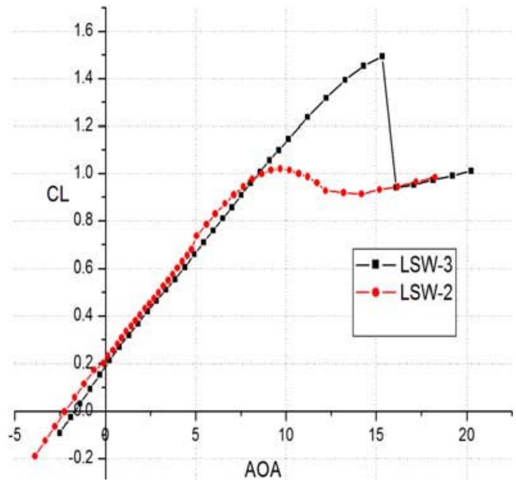

Fig 8: Comparison of experimental lift characteristics (M=0.2 Re=0.8mln)

Studies of this layout will be continued from different directions. Large half-model is creating with the aim of checking laminar testing possibilities of the T-128 wind tunnel at high Re numbers, just as was done for the cryogenic wind tunnels in [17,18]. Aerostructural detailed studies will be aimed at finding rational geometry pylons. The current pylons (Fig.9) seem too delicate for the structure strength adequacy.

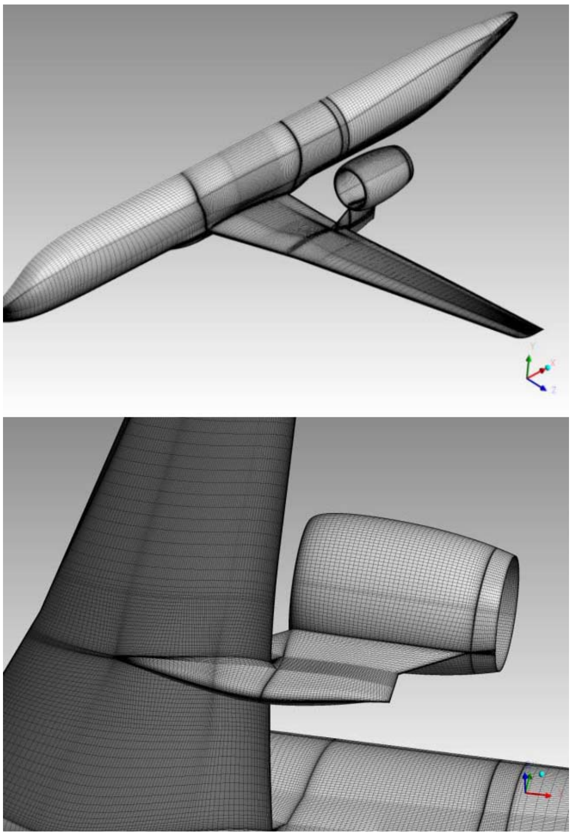

Fig 9: Details of wing-pylon-nacelle zone of the model

CONCLUSION

Natural laminar flow low-sweep wings can be designed for advanced regional and short-medium aircraft without reduction of cruise Mach number typical for modern airplanes. At designing of such wings it is necessary to consider a compromise between laminar and turbulent mode of a flow, between viscous and wave drag amount and also between natural laminar flow (NLF) and high lift characteristics. Special multicriterion optimization procedure for aerodynamic design of laminar wings has been created and used for designing several low-sweep wing aerodynamic models, including those with over-wing-trailing-edge engines. Wind tunnel results obtained up to date are very encouraging and stimulate further studies of the concept.

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