AN EXPERIENCE IN AERODYNAMIC DESIGN OF TRANSPORT AIRCRAFT

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This paper gives brief description of the author's experience in aerodynamic design of wings and other layout elements of subsonic transport aircraft. It describes general trends in development of aircraft aerodynamics, applied computational methods and design techniques, offers some recent examples, outlines future objectives.

Introduction

Currently all over the world investigations on reaching essential progress in the efficiency of air transport and in minimization of its negative environmental effect are carried on [1, 2]. Ambitious objectives on further increase of flight safety, appreciable reduction of fuel consumption, significant decrease in CO_2, NO_x and other emissions, substantial community and cabin noise decrease are planned.

Seeking to diminish technical and financial risks, the basic manufacturers of transport airplanes continue to improve performances of the classical configuration. Having arisen in the middle of last century this configuration still has certain reserves for perfecting and, probably, will be dominating in the first decades of 21-st century. However, the further advance in improvement of technical and ecological performances of trunk-route airplanes, most likely, is impossible without transition to different layouts of flight vehicles, such as "flying wings" or some other configurations.

The role and place of aerodynamics in advanced airplane projects depends on the configuration under study: classical or non-traditional. For the classical layout the principal subject of aerodynamicist's care is a wing, as the element almost completely defining aerodynamics of the airplane. Here significant experience is collected and a direction of the further advance is linked most probably with flow control. For non-traditional layouts multidisciplinary approaches are of primary importance. In this area integrated studies are necessary for creating scientific-and-technological know-how.

This article presents a condensed review of the author's experience in aerodynamic design of civil transports, accumulated in TsAGI during development of the latest Russian airplanes. The description of applied computational methods and design techniques is given and a number of real-life examples are presented.

1. Mainline airplanes aerodynamics – tendencies of development

Introduction of so-called supercritical profiles and wings became the largest achievement of aerodynamics in the last quarter of the 20-th century, allowing postponing wave crisis to higher Mach numbers [3]. Due to application of such profiles it is possible to increase relative thickness of a wing and/or to reduce its sweep at fixed cruise Mach number. The gain in wing structure weight received in this way may be "exchanged" for an increase in aspect ratio and total lift-to-drag ratio because of lowering induced drag. For example, the Russian civil planes of the fourth generation designed according to this principle (Ilyushin-96, Tupolev-204, λ =9-10) considerably exceed the predecessors (Ilyushin-86, Tupolev-154, λ =7-8) on lift-to-drag ratio value. The following step of increase in wing aspect ratio from λ =9-

10 to λ =11-12 and more is possible because of application of composite materials. Manufacture of a wing from composites is envisioned, for example, in the project of the next generation Russian middle-haul airplane MS-21 (Fig. 1).

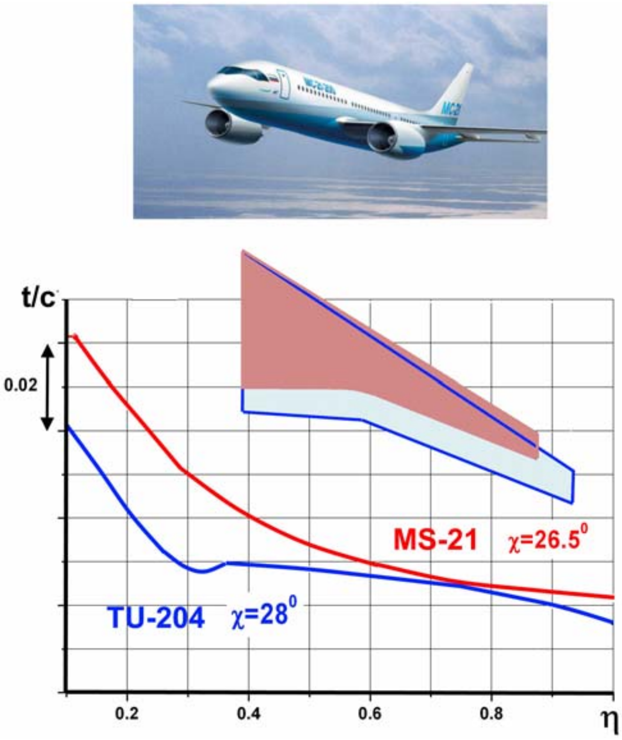

Fig.1. Next generation MS-21 airplane

The basic direction of development of supercritical wings for mainline aircraft is an achievement of small wave and profile drags at high cruise lift coefficient $Cl \geq 0.55-0.60$ to realize entirely advantages of large-aspect-ratio wings. It forces to use more aggressive wing pressure distributions with the augmented extent of a supersonic zone on the upper surface and unfavorable pressure gradients near the trailing edge. Besides, for safe cruise flight with high Cl's it is necessary to ensure sufficient buffet margins. Especially buffet problem is actual for high-aspect-ratio wings (λ =11-12) with a high cruise Mach number (M=0.82-0.85).

Deriving of wing geometry with the mentioned pressure distribution is fulfilled by means of computational aerodynamics methods. Still important role at creation of new concepts of wings is played by experimental studies in wind tunnels, including cryogenic and pressurized wind tunnels capable of reaching high Reynolds numbers.

For wings of very large aspect ratio aeroelastic problems are in the foreground. General aero-strength optimization of a wing from the very beginning demands realization of a bulk of joint aerodynamic and strength calculations. The essential role at definition of an optimum construction is played by active and passive load alleviation systems applied recently on mainline airplanes. All it leads to that the former principle of consecutive design of "external" aerodynamic contours and then of "internal" structure of a wing, mismatches modern requirements, and should be substituted by a principle of simultaneous optimal multidisciplinary design.

Besides increase in wing aspect ratio also the tendency of engine bypass ratio growth is clearly tracked. It is known, that the bypass ratio increase leads to lowering of engine fuel consumption and noise, but aggravates conditions of its integration on the airframe. Not to lengthen excessively landing gears, the designer tries to place an engine nacelle more close to a wing. Thanks to wide CFD application the distances from an engine nacelle to a wing were considerably diminished at planes of last generations in comparison with the previous projects. Reduction of interference drag and also weakening of unfavorable effect of a large engine nacelle on an efficiency of wing high lift devices continues to remain the important problem of aerodynamic design in classical layout.

The perspective solution from the point of view of noise abatement is the arrangement of the engines over the fuselage or on the upper wing surface (Fig.2).

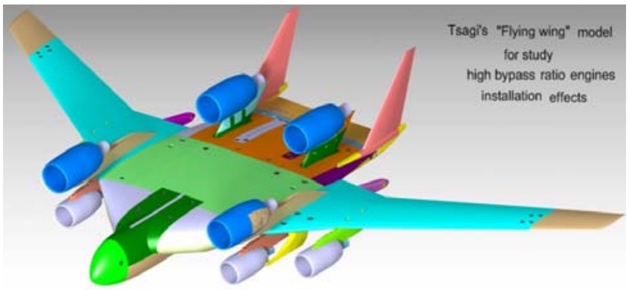

Fig.2. "Flying wing" aerodynamic model

In more remote perspective significant effect can be expected from the deep integration of propulsion system with an airframe. Such so called distributed propulsion system concepts are studied actively now by engineering community [4].

2. Numerical methods of aerodynamic design

Modern achievements in computational aerodynamics methods and continuous growth of available computer power enable radical changes in the process of aerodynamic design of transport aircraft. Besides simple increase in amount of alternative versions of configurations under study the possibility of using special design methodology, including inverse and optimization methods permits a designer to reach his targets more quickly and straightforwardly. With the aid of approved numerical methods search of the optimal geometry is carried out and the subsequent wind tunnel experiment serves, basically, to check an achievement of desired aerodynamic properties and to create a.c. bank of the final configuration.

The aerodynamic design procedure used in TsAGI consists of four basic components [5]: geometry manipulation system, direct methods for the analysis of aerodynamic characteristics, inverse methods for construction of geometrical shapes with desired pressure distributions and optimization methods, allowing a designer to maximize the selected objective function (for example, lift-to-drag ratio) by a geometry variation at the imposed constructive and aerodynamic restrictions.

The key to success of the aerodynamic design process is a **direct analysis method.** Efficiency of all design stages depends on its reliability, accuracy, robustness and speed.

For many years TsAGI's specialists have been creating various codes for the aerodynamic analysis of transport aircraft. Of great value was a creation and continuous perfecting of software package BLWF (see [5]). This package is intended for the fast analysis of transonic flow over various configurations of flight vehicles on the basis of iterative quasi-simultaneous algorithm of strong viscous-inviscid interaction of external flow and a boundary layer on lifting surfaces. Full-potential and recently Euler equations are solved in the outer region within few seconds on a modern PC. Three-dimensional computational grid of C-O type over a wing-fuselage configuration is generated automatically using simple algebraic technique. An inclusion of nacelles, pylons, empennage and winglets is possible on the basis of "chimera" procedure. Thus, practically entire airplane configuration (Fig.3) can be analyzed.

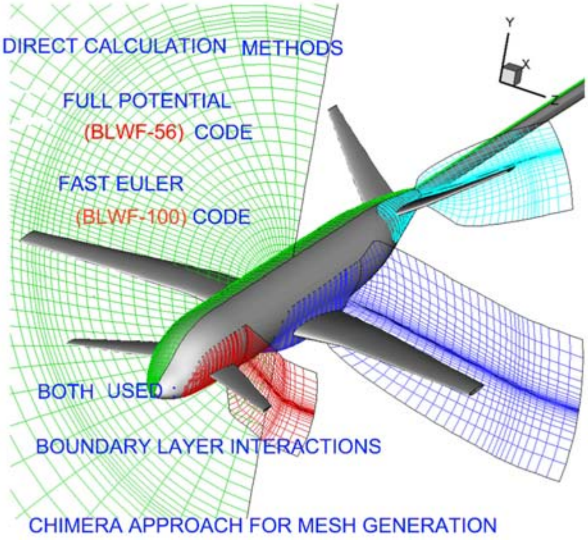

Fig.3. BLWF code methodology

From the beginning of 90-ies BLWF code is widely used in TsAGI and other world aviation centers [6] for the aerodynamic analysis of transonic transport aircraft. The program has passed wide approbation and its results were compared many times with the result of experiments, with calculations fulfilled not after but before wind tunnel tests. Fast response time of the code ensures the good fundamentals for its application in iterative inverse and optimization design procedures. The code is permanently upgraded and extended. At present BLWF software package allows to take into account influence of structure elasticity, analyze non-stationary transonic flows, consider different vehicles with multiple lifting surfaces (Fig.4) etc.

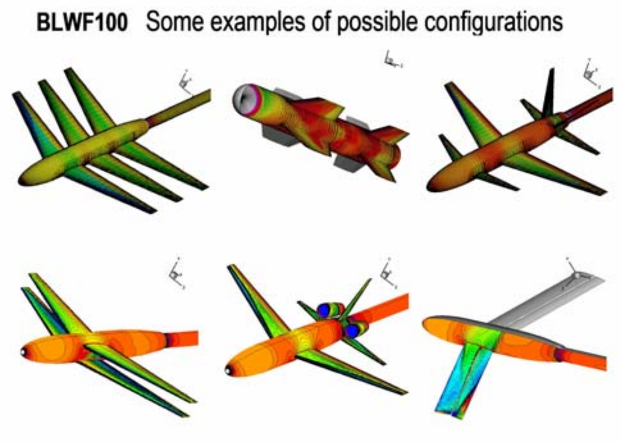

Fig.4. Possible configurations for BLWF code analysis

Techniques and codes for the solution of the Reynolds-Averaged Navier-Stokes (RANS) equations are also actively developed and applied in TsAGI. For correct analysis of three-dimensional configurations grids with size not less than 10-30 million nodes are required. Therefore in practice of aerodynamic design these methods are usually applied at the final stage when the airplane geometry is basically frozen and only local refinements are required. The example of flow calculation over MS-21 airplane on a hybrid grid with ~ 20mln nodes is presented in Fig. 5.

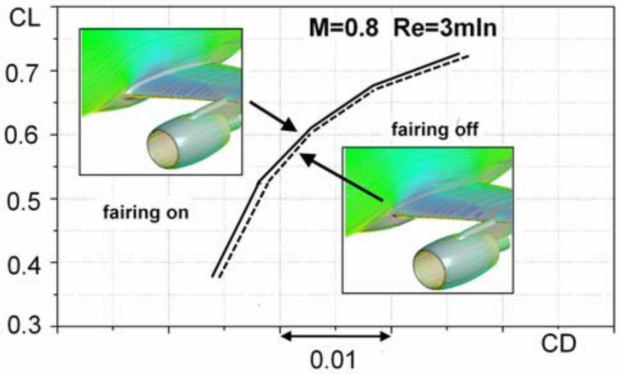

Fig.5. Analysis of wing-fuselage fairing by Navier-Stokes solver

Inverse methods of aerodynamics are the well-known and effective instrument of aerodynamic design. They allow to eliminate or weaken shocks, to reduce level of perturbations of a flow in the right place, to realize pressure distributions favorable for development of a laminar or turbulent boundary layer. Certainly, not any desired pressure distribution can be realized physically as generally the inverse problem is ill-conditioned. Therefore for real transonic three-dimensional flows use of engineering approaches is inevitable.

The availability of powerful inverse method makes it possible to build so-called "equivalent" wing. This wing has the same pressure distribution as initial one, but under other conditions. Such a trick is useful, for example, for "transferring" good pressure distribution from a successful prototype for fast design of initial geometry of a new wing. The concept of equivalent wings can be used for flow simulation in a wind tunnel with different boundary conditions or even for compensating of thick boundary layer influence at small Reynolds numbers [7].

In TsAGI three-dimensional inverse iteration methods TRAWDES-1 and TRAWDES-2 are developed (Fig.6 [5]), both belonging to the class of so called residual-correction methods. In the course of iterations the wing geometry is altered to reduce a residual between the specified and current pressure distributions. Both methods differ only in geometry correction blocks and use a direct method of aerodynamic analysis as “a black box” which can be, if necessary, easily replaced by another one. In the TRAWDES-1 code the geometry corrector is the wing inverse subsonic method, while in the TRAWDES-2 code for this purpose the inverse two-dimensional transonic method is used. Except purely inverse problems also the solution of the mixed problems is possible, when one part of a wing, for example torsion box, is fixed, and on the other part the desired pressure distribution is prescribed. The inverse method is used also for the aerodynamic design of winglets.

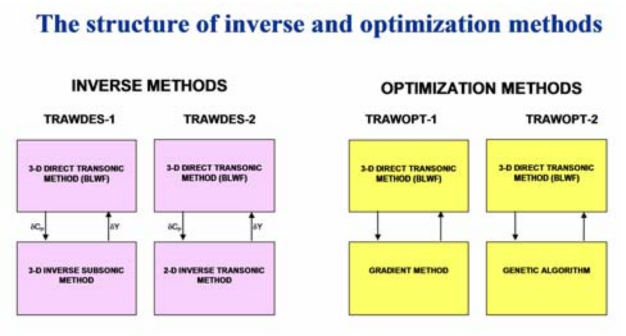

Fig.6. Structure of inverse and optimization methods

One of the principal deficiencies of inverse methods is the uncertainty in defining "optimal" target pressure distribution. Usually this choice is based upon the designer's experience but it is natural only for large-aspect-ratio wing and can be done hardly for other elements or in case of strong interaction between airplane parts. Besides, inverse method is rather difficult to apply in a situation when there are numerous restrictions of a constructive and aerodynamic origin. In these cases application of numerical optimization methods is necessary.

Numerical optimization methods are formally the most suitable methods for design as they allow easily to change objective functions, to consider numerous geometrical and aerodynamic constraints, and also to conduct multipoint optimization. The procedure of numerical optimization is based on coupling of a direct method for aerodynamic analysis, a set of geometry variations and the optimization module. Variation of the shape of base sections of a wing is made by means of global (relative thickness, twist, camber, crest position, tail inclination etc.) and local variations. It is possible to vary a wing plan form also. At high transonic Mach numbers variations of fuselage geometry are applied.

In the optimization block TRAWOPT developed in TsAGI two methods - a classical gradient method and genetic algorithm have found application. Use of the last became possible due to fast direct method BLWF utilization. Besides, the authors have developed the hybrid two-level genetic algorithm [8], allowing reducing a required estimated time approximately in 3 times.

Basic advantage of design optimization techniques is its capability of the simultaneous account of aerodynamic performances on several conditions of flight, i.e. multimode or multicriteria optimization. Supercritical wings of last generations possess high sensitivity to flow conditions. It is really easy to achieve practically isentropic flow at one design regime, but shocks may appear at off-design regimes even at lower M or Cl. That is why the wing which has been optimized at only one condition will, as a rule, lose to a wing at which design several conditions (Fig.7) have been considered. In our practice we use simultaneous optimization of aerodynamic characteristics at 4-5 regimes corresponding to full-scale conditions, and also add one-two regimes corresponding to wind tunnel conditions. Scalar value of the weighted average lift-to-drag ratio is usually optimized, or whole Pareto-front may be considered (Fig.8).

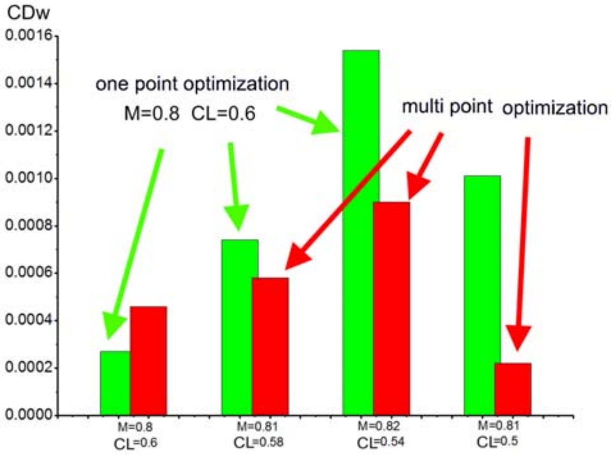

Fig.7. Comparison of one-point and multi-point optimization

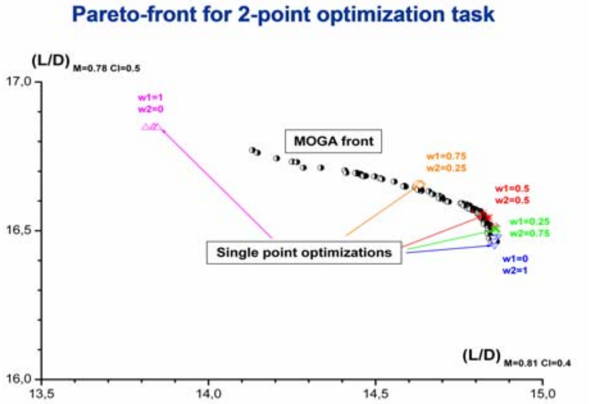

Fig.8. Pareto-front for two-point optimization task

New more efficient optimization techniques are continuously searched for by TsAGI's specialists. Two-level schemes based upon different surrogate approximation on the lowest level are among the most perspective approaches. Adjoint methods for shape optimization also attract great attention because of their ability to obtain gradient information in one run. Both techniques promise full exploitation of RANS methods in the advanced aerodynamic design procedures.

3. Technique and examples of aerodynamic design

The following procedure of aerodynamic design [5] is accepted now in TsAGI. At the first stage the initial wing geometry corresponding to chosen cruise Mach number is selected basing upon statistics (a planform, sweep angle, mean relative thickness etc.) and appropriate prototype. Then, by means of an inverse method the new geometry with advanced pressure distribution on the basic cruise regime is generated. At this stage the data about pressure distribution rather than the geometry of the prototype are more valuable. If necessary, inverse methods are applied also to formation of the fuselage variations and generation of “aerofunction”, i.e. variations of geometry causing desirable changes in pressure distributions. At the third stage the parametric variation of the configuration obtained is made, and the optimization procedure defines an optimal set of parameters which maximizes the selected objective function with the account of aerodynamic and constructive restrictions. This stage is rather labor-consuming, because of repeated refinements of a kind of objective function and restrictions adopted for reaching of global efficiency of the project by many criteria. Tuning of local aerodynamics is made at the fourth - the last stage of a design, which main task is to take everything out from the configuration and preservation of base aerodynamic performances from technology simplification factors influence. At this stage Navier-Stokes solvers and experimental tools are applied, including those at increased Reynolds numbers on large-scale half-span models (Fig.9).

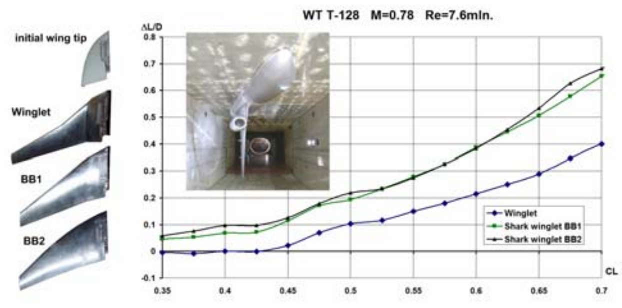

Fig.9. Large-scale half-span model of SSJ-100

The wing surface of the modern trunk-route airplane has, as a rule, very complicated shape dictated by a desire to ensure favorable aerodynamic performances in a broad band of conditions of cruise flight, and also to satisfy strength and constructive constraints. By means of computational methods all wing sections are tuned to a particular configuration of a developed vehicle and a flow condition, including multi-regime considerations. Such technique allows designing wings with performances, close to the best possible from the point of view of lift-to-drag ratio, speed of flight, the maximum lift etc.

The described technique has been used for aerodynamic design of modern Russian regional airplane SSJ-100 (Fig.10), developed by Sukhoi Civil Aircraft Corporation. The plane is intended for transportation of 98 passengers on the range to 3500km. High lift-to-drag ratio at M_{cruise}=0.78 and favorable unseparated flow at M_{MO}=0.81 was the purpose of aerodynamic design.

Fig.10. SSJ-100 airplane

One of the most difficult problem in designing SSJ-100 configuration was the canceling of unfavorable interference of a wing with long duct close-coupled nacelle. Like famous DLR-F6 configuration, SSJ-100 airplane initially had a strong shock wave on the pylon and wing lower surface at a climb condition. Moreover the upper surface of the wing was also significantly influenced by the presence of the nacelle causing shock waves at cruise conditions. Therefore the design of the wing was started at once taking into account an interference with the nacelles. The design problem became complicated by the requirement of manufacturability of a wing surface.

Thanks to application of the technique described it was possible to eliminate practically a harmful interference with nacelles and to reduce time of the wing design considerably. The wing geometry has been practically “frozen" after testing of only two aerodynamic models in a wind tunnel. Pylon modification has been also fulfilled basing upon the principle of “separating of mutual perturbations from various elements”. Thus, the pylon shape was altered so that to diminish its own perturbation in a zone of the maximum thickness of a lower surface of a wing. As a result of rather small changes it became possible to augment considerably lift-to-drag ratio of the model (Fig.11).

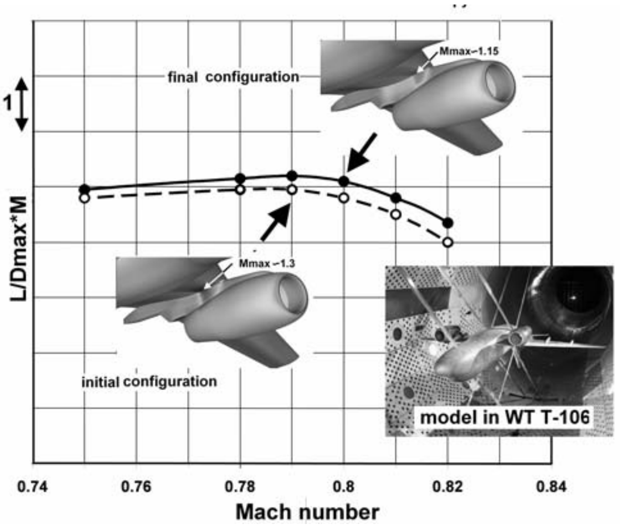

Fig.11. Pylon modification

An experience collected at the development of SSJ-100 aerodynamic configuration became a good basis for the aerodynamic design of its successors – SSJ-NG and next generation middle-haul airplane MS-21. Due to composite structure of a wing of these planes there exists a possibility to increase aspect ratio considerably, but cruise Cl coefficient increases also, so the task of minimizing wave drag exaggerates. Throughout the years studies of large-aspect-ratio transonic wings have been carried out in TsAGI for perspective trunk-route airplanes with different cruise Mach numbers (Fig.12).

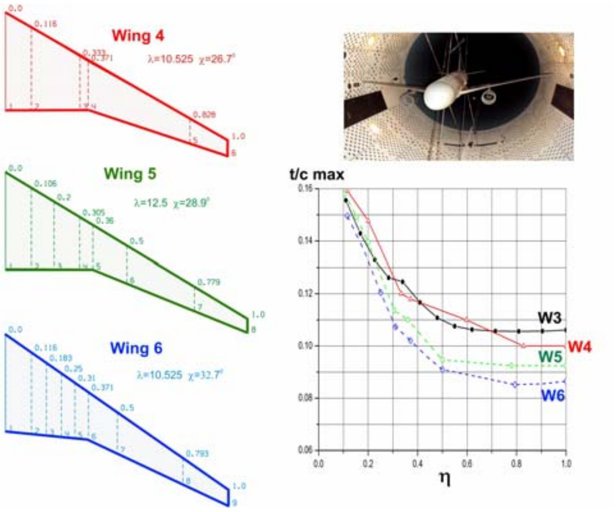

Fig.12. Research wings for different Mach numbers

Nacelles of different by-pass ratio were tested experimentally to obtain reliable data about interference peculiarities. Conducted investigations make it possible to recommend rational aerodynamic configuration for the IRKUT design team with minimal technical risk.

One more compromise really meeting in practice of aerodynamic design is the compromise between cruise and take-off and landing performances of the airplane. At present it is possible to predict numerically the lift capabilities of the isolated wing with sufficient accuracy but not with high-lift devices deployed. However, good lifting properties of a wing itself reduce demands to the high lift devices and, hence, simpler devices can be used reducing weight, price and maintenance costs of the whole system. Therefore, in our design practice the technique of the simultaneous account of cruise performances on high speeds and lifting performances of a wing at the low speeds is introduced [9]. It has been tested experimentally on the model of middle-range mainline airplane (Fig.13).

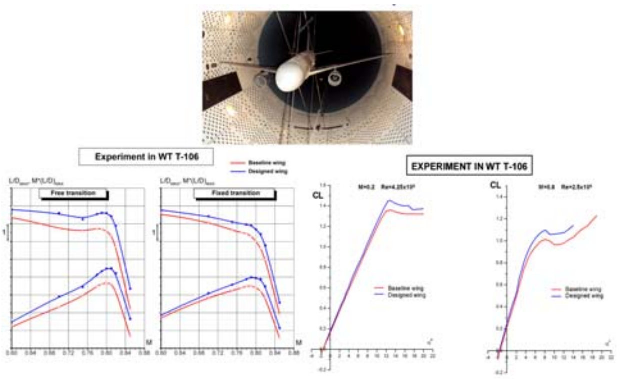

Fig.13. Comparison of lift-to-drag and lift characteristics

The following example concerns studies of aerodynamic configuration of long-haul aircraft with high cruise Mach numbers. The comprehensive investigations conducted earlier in TsAGI, have displayed that at modern level of technologies appreciable aggravation of direct operation costs begins after M=0.9, therefore different versions of the aircraft with M_{cruise}= 0.85 ÷ 0.90 were studied. Three research configurations with progressively increased M_{cruise}=0.85, 0.88 and 0.9 were computationally designed, manufactured and tested in the large transonic wind tunnel T-106. All the layouts use the same simple cylindrical non-“area-ruled” fuselage. At present it is commonly agreed that although very beneficial for favorable interference with the wing, “area-ruling” of the fuselage brings additional complexity and weight together with complicating passenger accommodation.

We will briefly stop on the results of the fastest version with M_{cruise}= 0.90. Both sweep angle ($\chi_{1/4}$=38.5°) and thickness-to-chord ratio have been chosen close to that of the B-747 wing with the thought in mind to preserve satisfactory take-off&landing performances by using conventional (slat/flap) high lift devices. It was required to redesign also the shape of a nose of a fuselage, having made its more blunted. The photo of aerodynamic model MS-90 in the T-106 wind tunnel is shown in Fig.14.

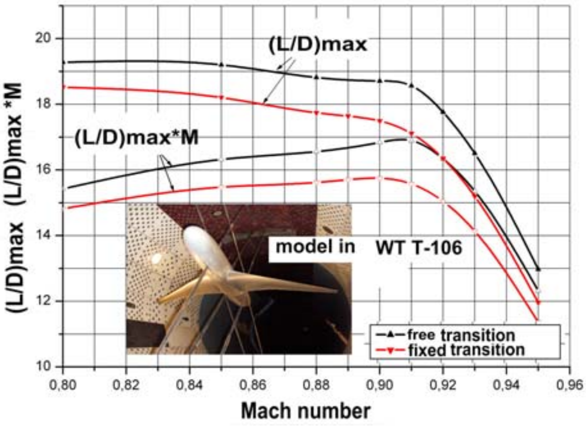

Fig.14. Aerodynamic model of long-haul aircraft with M_{cruise}=0.9

Given are also experimental values of lift-to-drag ratio of the model and range parameter $(L/D)_{Max}\cdot M$. It is visible, that the given aerodynamic configuration really ensures the desired M_{cruise}=0.9-0.92. The further advancement on speed can be achieved by “area-ruling” of the fuselage [10].

It should be noted that a principle of "area-rule", valid for near-sonic speeds, is possible to use also for smaller speeds achieving favorable interference between vehicle elements. Original "area ruling" has been used at designing of a new layout of a small business jet "Tadpole" designed for 4-6 passengers (Fig.15).

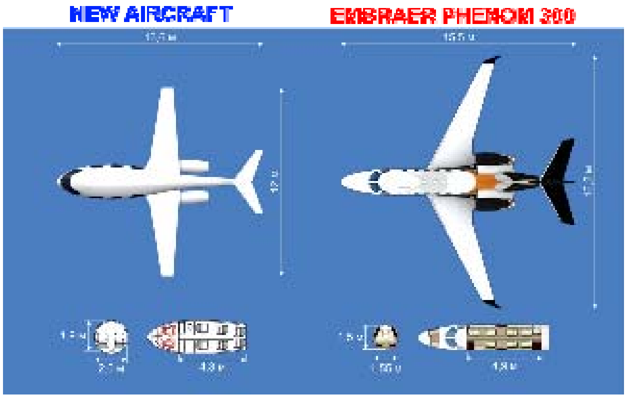

Fig.15. Small business jet “Tadpole”

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.16) 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).

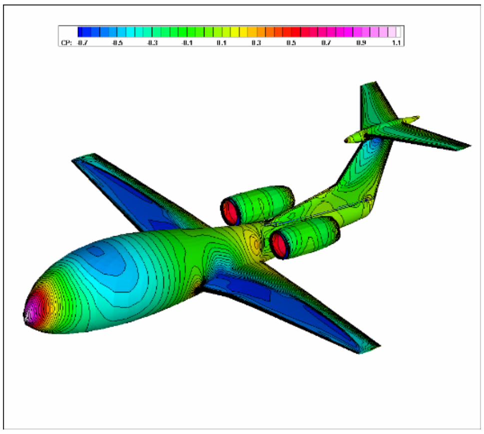

Fig.16. Pressure distribution over the surface

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.

4. Basic directions of developing aerodynamics of civil transports

It is expected, that by ~2025 the necessary technological breakthroughs will be collected, allowing to pass to the next generation of civil transports. In the near-term outlook the following problems will probably become aggravated: a problem of organic fuel resources, a problem of global warming and influence of mankind activity on a climate, a problem of throughput of the airports at steady traffic growth, a community noise problem. The indicated problems will make the direct impact on development of the civil aviation. The main tasks which will be necessary to solve are: further increase of an air safety due to comprehensive introduction of automatic control systems; the next appreciable reduction of fuel consumption in comparison with the modern planes; lowering of harmful emissions and optimization of emissions on the altitude; noise abatement on the ground and in interior [11-14].

The classical layout of the airplane will remain, apparently, dominating in the nearest future. It has certain reserves, including aerodynamic which can be scooped out by the following perspective techniques:

- new types of wing tips;
- new types of high-lift devices;
- application of adaptive elements;
- laminarization of an empennage, engine nacelles, and then wings;
- flow monitoring and control (most likely, nonstationary) with the help of mini-and micro-devices;
- application of active high-speed load alleviation systems in the whole flight envelope;
- application of thrust vectoring;
- transition to small static instability.

At the same time there are several promising non-traditional configurations which can make in the future a competition to the classical layout. They may be BWB configurations (Fig.2), quiet planes with the upper engine arrangement (Fig.17), “lifting fuselage” layouts (Fig.18) or some other futuristic hybrid designs (Fig.19).

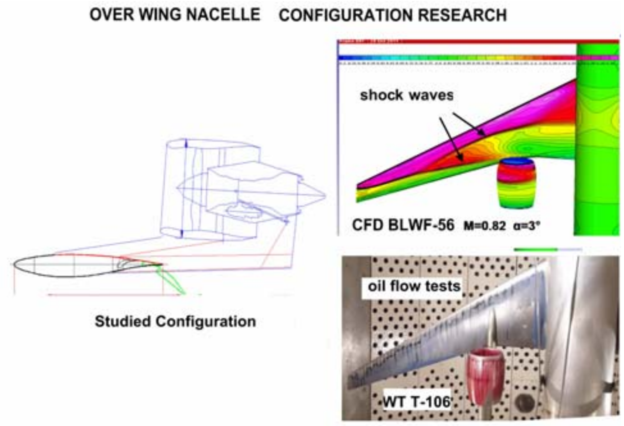

Fig.17. Configuration with over-the-wing engines

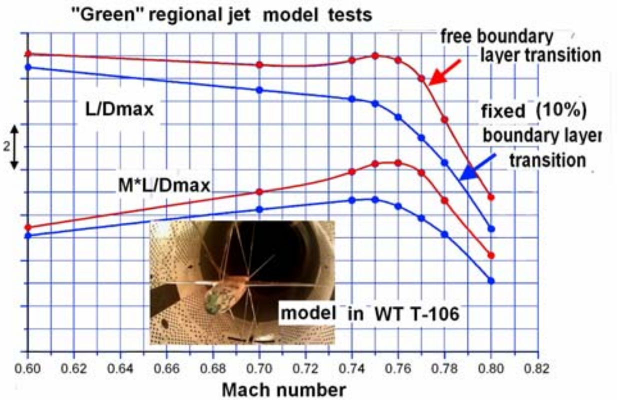

Fig.18. Lifting fuselage configuration

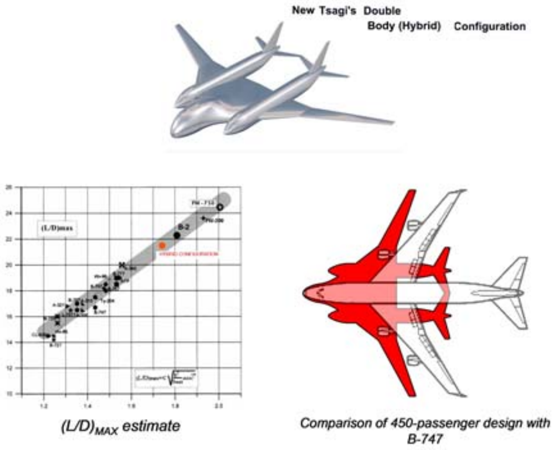

Fig.19. Triple-body airplane

The subjects of aerodynamic researches should concern the following questions:

-working out of highly effective systems and technologies of drag reduction;

-theoretical and experimental methods for a prediction and control of boundary layer development;

-aerodynamics of controls, including non-traditional tools;

-use of adaptive wings and other elements;

-new concepts of creation high lift at low speeds;

-new techniques on improvement of propellers and engines performances;

-further development of computational methods, in particular with reference to high-lift devices;

-development of multidisciplinary design methods.

The conclusion

The next year's development of aerodynamic configuration of trunk-route aircraft will go within the limits of the classical layout, relying on the advances in the field of composite materials, turbofan engines of superlarge by-pass ratio and aerodynamics of advanced supercritical wings with increased aspect ratio. Advanced investigations in various areas for creation of technological breakthroughs are necessary.

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