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NOVEL CONFIGURATION OF A BUSINESS JET WITH A DROP-SHAPED FUSELAGE

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Abstract

This paper deals with computational and experimental aerodynamic studies of a small business jet designed for 4-8 passengers. The novel layout with drop-shaped fuselage provides considerable improvement of passenger comfort and achievement of maximum flight speed, corresponding to Mach number M = 0.8 even with simple straight wing. An aerodynamic model of the airplane has been designed, manufactured and tested in TsAGI wind tunnels. The results of the experimental studies alongside with accompanying detailed CFD calculations which were initiated to clarify the physics of a flow at high velocities and high angles of attack are presented. The paper concludes with suggestions for the possibilities of improving the configuration and proposals for future research.

1 Introduction

Market surveys show that demand for comfort, in particular a large cabin, is critical to the success of a business-jet. In order to satisfy this demand a wing is usually shifted away from the fuselage in a typical business-jet configuration that leads to the need of a large belly fairing (Fig. 1). Such configuration is a typical example of an unfavourable aerodynamic interference with poor drag-rise characteristics due to wing staying in an accelerated flow region.

Fig. 1. Typical business-jet layout

On the contrary, wing located in a decelerated flow zone where local Mach number is less than free stream value might cause drag-rise postponement to higher velocities. Well-known “area rule” for near sonic aircraft is based on this principle, but for subsonic vehicles it is as well expedient. Original “area ruling” has been used by the authors at designing of a new layout of a small business jet “Tadpole” (Figs. 2,3) [1] destined for 4-8 passengers. The drop-shaped fuselage allows to improve comfort of passengers considerably (the maximum height of interior H = 1.9 *m* is the greatest among analogues) and to receive favourable aerodynamic wing-fuselage interference.

Additional deceleration of the flow in a wing root region is obtained by traditional placing of engines on the aft fuselage near the wing trailing edge. All of this make it possible to reach the maximum speed corresponding to M = 0.8 with entirely unswept wing having usual relative thickness distribution (t/c = 15-11% at the root and tip accordingly). Use of a straight wing simplifies and lightens the structure, allows obtaining high lift in the absence of slats and promotes natural laminar flow of a wing at high Mach number cruise.

The aerodynamic (1/7 scale) model of the "Tadpole" has been designed, manufactured and tested at cruise and low speed regimes in TsAGI's wind tunnels (Figs. 2,3). The main task of the experimental program was to prove the ability of reaching high Mach number at cruise as well as to investigate longitudinal and lateral stability&control characteristics (especially at high angles of attack) for proper sizing of the empennage and control surfaces. The results of the experimental studies alongside with accompanying detailed CFD calculations are presented.

Fig. 2. The aerodynamic model in the low speed wind tunnel T-102

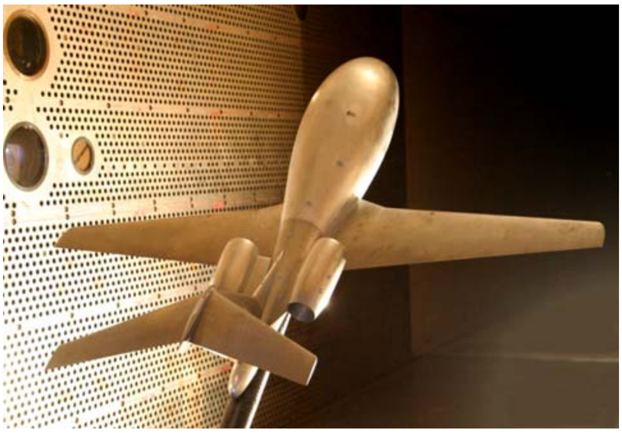


Fig. 3. The aerodynamic model in the transonic wind tunnel T-128

2 Brief description of the model and wind tunnels

Basing upon previous theoretical background [1] an aerodynamic 1/7 scale model of the "Tadpole" has been designed and manufactured in TsAGI. General view of the model in the low- and high-speed wind tunnels is shown in Figs. 2,3. The model is characterized by stated below dimensions:

- Fuselage length $L_F = 1.586\ m$;
- Wingspan $L_W = 1.895\ m$;
- Wing trapezium area $S_W = 0.409\ m^2$;
- Mean aerodynamic chord $MAC = 0.242\ m$;
- Outer wing leading edge sweep $\chi = 9.5°$;
- Aspect ratio of the wing $\lambda_{tr} = 8.5$;
- Taper ratio $\eta_{tr} = 3$;
- Angle of wing inclination $\alpha_{root} = 1°$.

The dimensions of the model give a possibility to test it in several large sub- and transonic wind tunnels. The model can be tested in different variants, from isolated fuselage till complete configuration, to single out the contributions of the various parts of the layout and to measure their mutual interference. Besides, there is a possibility to change an inclination angle of a stabilizer for trimming studies. Under fins of considerable size and area can be installed for pitch and yaw stability enhancement.

The "Tadpole" model was tested in two wind tunnels: low-speed T-102 (Fig. 2) and large transonic pressurized T-128 (Fig. 3).

Relatively cheap low-speed wind tunnel T-102 with open oval working section 4 by 2.5 meters is designed for model studies at velocities up to V = 50 *m/sec* at wide range of attack and slip angles. The model is installed on strip suspensions of outer electromechanical balances.

Relatively small number of runs were performed in much more expensive T-128 at free transition of boundary layer on the model. Aerodynamic wind tunnel T-128 represents a closed-loop variable-density tube with main drive gear power of 100 *MW*. The size of its working section with adjustable wall perforation is 12 by 2.75 by 2.75 meters. Wind tunnel can be pressurized up to 4 *atm* at low speeds and up to 2 *atm* at transonic speeds. Tests are usually carried out by separate polar runs with a possibility to maintain the given Reynolds number ($3.5*10^6$ in our case) automatically through air density control in the working section. Model is mounted on a tail frame with internal balances. Passive vibration dampers are applied for suppressing model oscillations on separated flow regimes.

3 Selected results of experimental studies

The main task of the experimental program was to prove the ability of reaching high Mach number at cruise as well as to investigate longitudinal and lateral stability&control characteristics, especially at high angles of attack, for proper sizing of the empennage and control surfaces.

Aerodynamic characteristics were obtained in different wind tunnels al low speeds (Re ~ 1mln), and their comparison is given in Figs. 4-6.

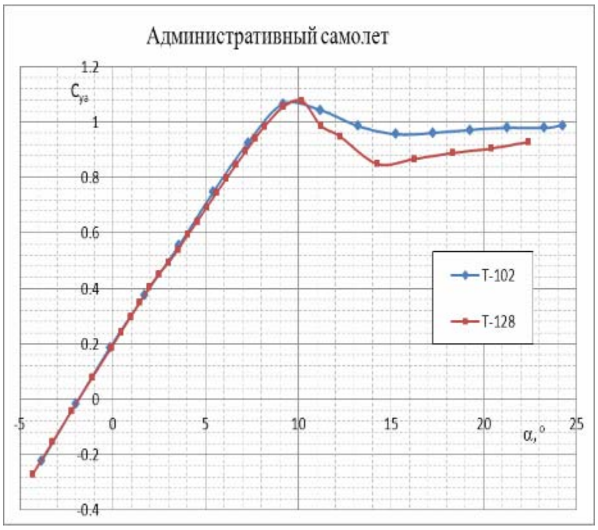


Fig. 4. Comparison of lift characteristics at low speeds

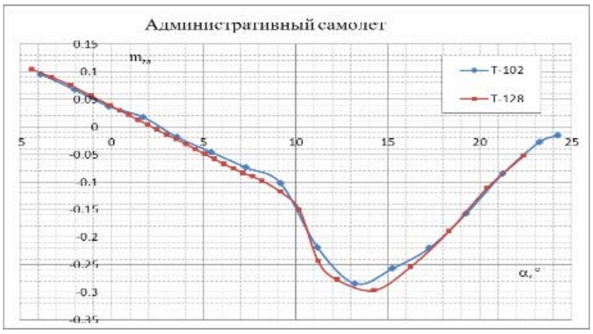


Fig. 5. Comparison of pitching moments

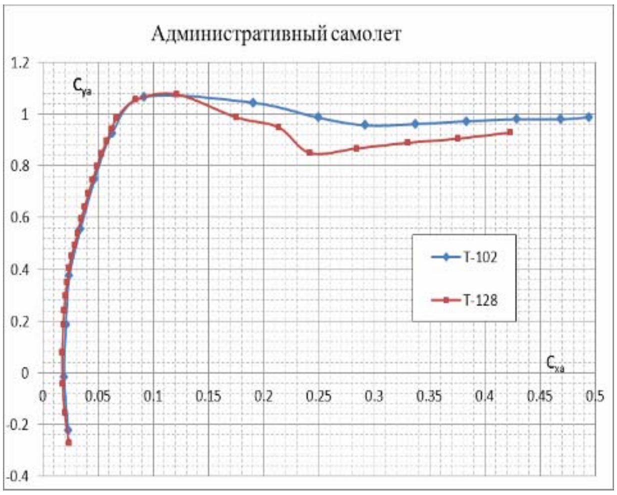


Fig. 6. Drag polars comparison

Pitching moment after stall is characterized by a considerable nonlinearity in spite of the unswept wing usage. In the very onset of stall, tail wash reduces and moment tends to decrease; then, separated flow covers the tail causing loss of its efficiency and the model configuration becomes unstable up to very high angles of attack. It is the typical pattern of the so-called “deep stall” for airplanes with T-tail. For moment pitch-up to reduce under fins are wise to install.

Reynolds number increase due to pressurization in T-128 leads not only to the lift characteristics enhancement but also to the moment nonlinearity onset shifting to higher angles of attack (Figs. 7,8).

Experimental values of the model lift-to-drag ratio at cruise speeds are shown in Fig. 9. High aerodynamic efficiency keeps up to M ≈ 0.8, so the main aim of the aerodynamic design is achieved.

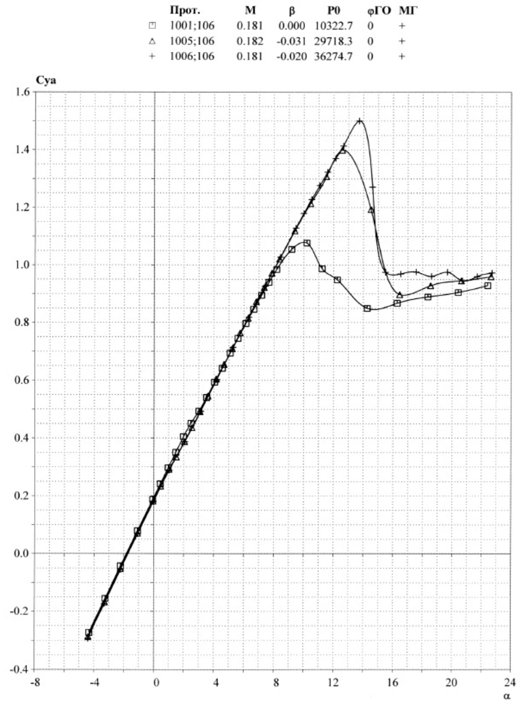


Fig. 7. – Reynolds number influence on lift at M=0.18

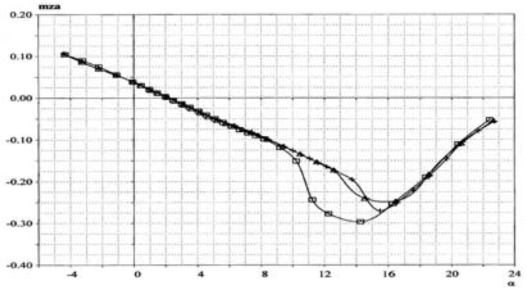


Fig. 8. – Reynolds number influence on pitching moment

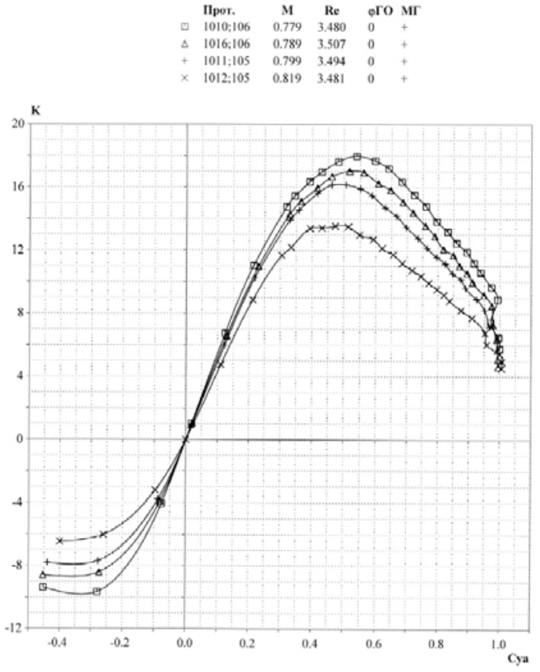


Fig.9. Model lift-to-drag ratios at high Mach numbers

4 RANS calculation results

Three-dimensional time-accurate compressible RANS equations are solved using finite volume method based on body fitted multiblock structured point-to-point grid with 48 million nodes. The size of the first cell from the surface corresponds to $y_+ \approx 1$. Coefficient of cell growth in normal direction is approximately 1.2. The topology of the mesh in symmetry plane is visualized in Fig. 10.

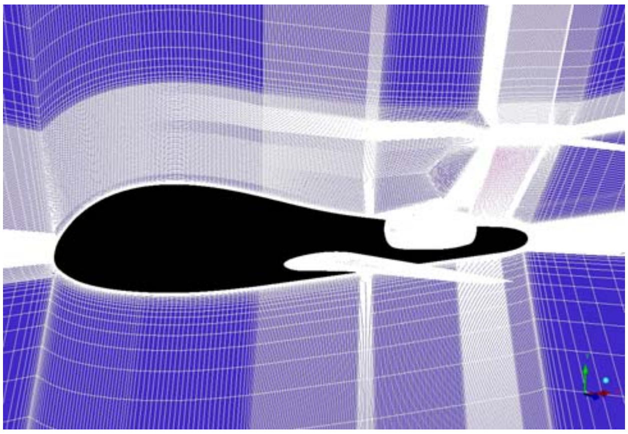
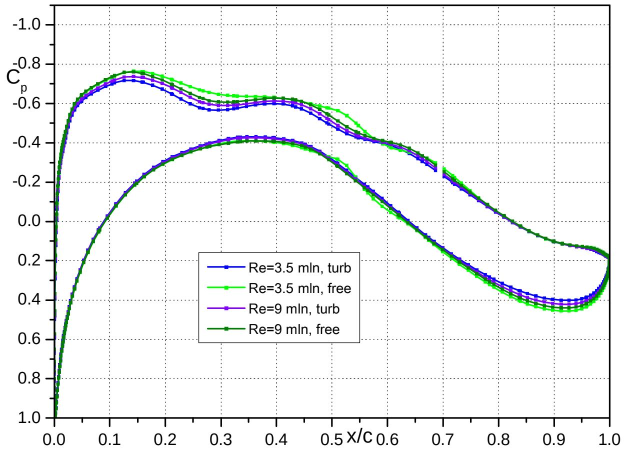


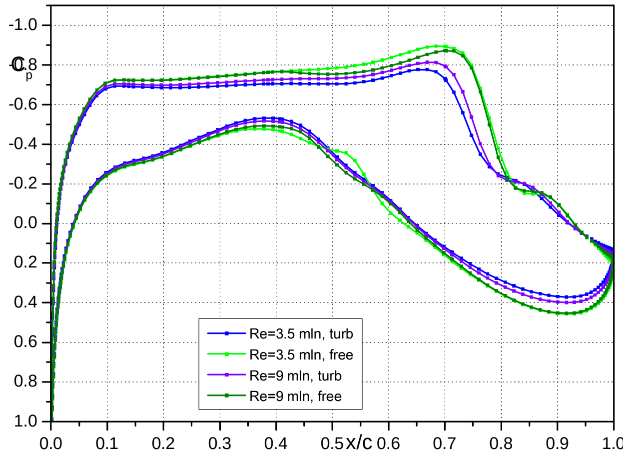
Fig. 10. Grid topology in plane of symmetry

For simulations presented here, spatial discretizations of the convective fluxes are done with second-order upwind Roe's finite-difference splitting scheme, whereas the viscous fluxes are discretized with second-order central difference scheme. Dual time stepping method is employed to advance the solution in time, while multigrid and local time stepping are introduced in the sub iterations to accelerate the convergence. The two-equation k-ω SST turbulence model is used.

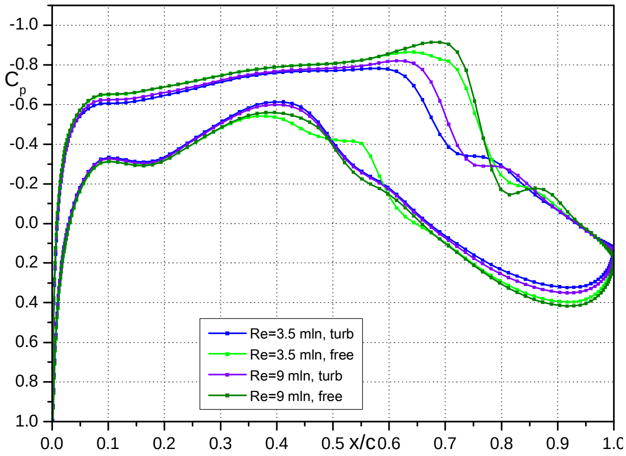
Fully turbulent calculations as well as free transition (Langtry-Menter model [2]) calculations at Mach number M = 0.8 and two Reynolds numbers Re = 3.5 mln (wind tunnel conditions) and Re = 9 mln (flight conditions) were carried out for clarifying the results of transonic wind tunnel campaign. Corresponding pressure distributions over wing at different positions along span are shown in Fig. 11. Favorable pressure gradients assisting natural laminarization are seen at both surfaces of the wing. According to calculation, the flow in the wind tunnel is laminar on the considerable part of the model surface (Fig. 12), which explains the high values of experimental lift-to-drag ratios. At flight conditions laminar regions shrink (Fig. 13), so the calculated polar shifts right (Fig. 14) in spite of Reynolds number increase.



2y/span = 0.2



2y/span = 0.5



2y/span = 0.8

Fig.11. Pressure distributions at different spanwise positions

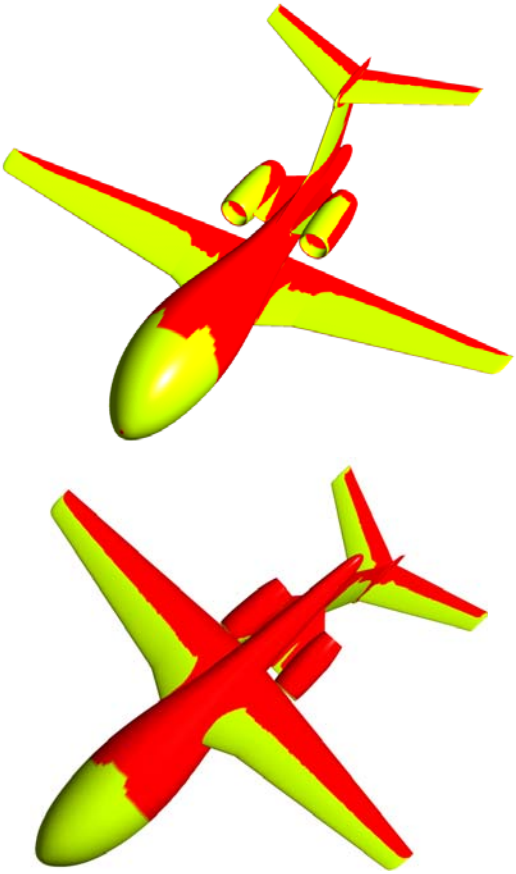


Fig. 12. Laminar and turbulent regions at WT conditions

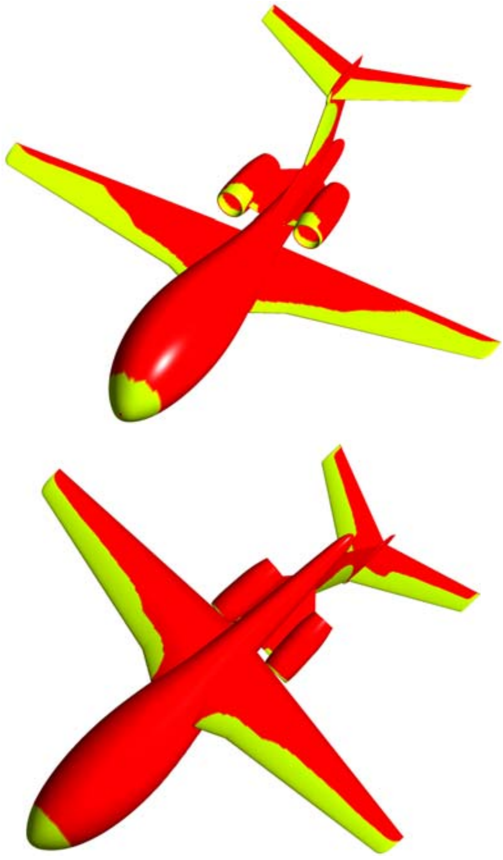


Fig. 13. Laminar and turbulent regions at flight conditions

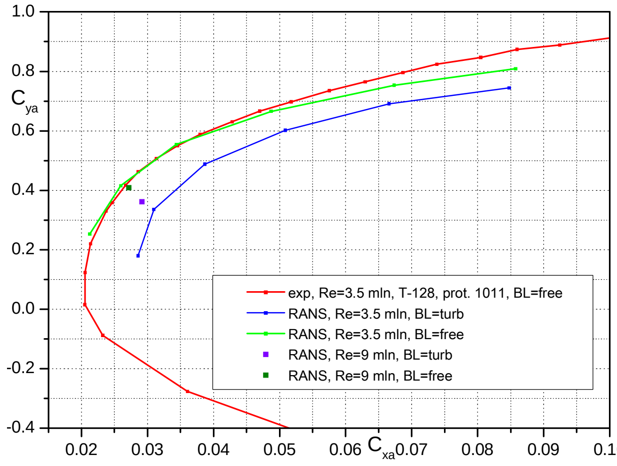


Fig. 14. Calculated and experimental drag polars

Conclusions

The original scheme of a new business jet with a drop-shaped fuselage and straight wing is proposed. It enables considerable improvement of passenger comfort and, due to favorable aerodynamic interference, the realization of maximum flight speed, corresponding to M = 0.8.

Comprehensive numerical and experimental studies of the proposed business jet have been carried out in TsAGI to reveal all the aerodynamic peculiarities of the configuration and substantiate its utilization.

The tested configuration possesses the high lift-to-drag ratio at cruise regimes due to long runs of natural laminar flow on the wing and other elements of the airplane. Even higher Mach numbers can be reached by a slight increase of the wing sweep (say, up to $\chi \sim 20°$) without cutting off flow laminarization, because the drop-shaped fuselage is shock-free flown around up to M=0.86.

Sufficiently high lift coefficient is reached ($C_{Lmax} \sim 1.5$) even without high-lift devices. Pitching moment characteristics are typical for T-shaped tail configuration and can be improved at high angles of attack by installing under fins of appropriate sizes.

Detailed RANS-calculations are of great value for critical flow peculiarities around unconventional configurations understanding and for rational choosing of layout and aerodynamic decisions.

References

[1] Bolsunovsky A.L., Buzoverya N.P., Chernavskikh Yu.N., Chernyshev I.L., Dunaevsky A.I., Gurevich B.I. *Study on a concept of a business jet with high passenger comfort*. EUCASS 2011, St. Petersburg, Russia.

[2] Langtry R.B., Menter F.R. *Correlation-Based Transition Modeling for Unstructured Parallelized Computational Fluid Dynamics Codes*. AIAA Journal, vol. 47, No 12, 2009.

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