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The numerical and experimental studies on the over-wing-engine configurations aerodynamics

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Abstract

Environmental requirements, such as community noise and emission limits will play an ever increasing role in the foreseen future of the civil aviation. Options are limited for reducing noise from the current configuration, hence new radical green designs may be required to meet the severe next-generation aircraft targets, claimed at present by NASA, ACARE and other organizations.
Engine noise is one of the most dominant factors of the whole aircraft noise. While current trend of an increase in by pass ratio leads to the noise reduction by itself, possibility to accommodate large engines under wing are restricted. An over-wing-engine mounting can both help to solve this problem and further reduce the community noise due to the shielding effect. TsAGI carries out systematic investigations on the “silent” aircraft with engine noise shielding by the airframe parts. Various configurations with different engine arrangement and propulsion system architecture have been studied. A description of the aerodynamic peculiarities of an each scheme alongside with the details of aerodynamic design procedure is given in this paper. Selected results of the experimental studies are presented.

1. Introduction

The dominant configuration in the world aviation fleet is the classic swept-winged aircraft with turbofan engines mounted under the wing or on the rear fuselage. At the same time it is rather seldom to see airplanes with engines mounted over wing. Why such an arrangement is unpopular? Firstly, there is an essential risk of unfavorable aerodynamic interference, especially at transonic speeds: strong shock waves may appear in the vicinity of pylons and nacelles due to increased velocities on the upper wing surface. Secondly, the cabin noise amplifies as compared with an under-wing engine configuration, and that would demand an additional weight of sound-absorbing material. Moreover, thrust vector biases upwards and hence leads to an undesirable negative pitching moment, both in take-off and cruise conditions. Many questions arise about reasonable design of the wing-pylon-nacelle structure and its aeroelastic behavior. Finally, engines maintenance becomes noticeably complicated.
Meanwhile, the over-wing engine configuration possesses a number of advantages. Thus, nacelle diameter increase does not result in landing gear lengthening, hence there is a possibility for very high-bypass-ratio engines to be mounted. Air inlets are better secured from foreign object damage which can occur on airfield runways of poor quality. There are no slat cut-offs as compared to an engine-under-wing arrangement. Jet exhausts do not interfere with flaps. Finally, the engine upper arrangement is very promising as regards considerable community noise reduction. The last issue seems to be of the highest priority for next generation commercial airplanes. For business and small regional jets the engine arrangement over the wing ensures an enlargement of cabin volume due to elimination of carry-through structure required to mount the engines on the rear fuselage.
In the USA and Europe have been initiated intensive studies on “silent” aircraft configurations [1-8] to meet the stringent NASA and ACARE environmental requirements for the next decades. TsAGI carries out systematic investigations on this subject matter as well [9], trying to take account of necessary technologies development in different disciplines, especially in aerodynamics and propulsion system, since aerodynamics is the main bottleneck that slows down the over-wing-engine configuration introduction. Various arrangements with different engine installations and propulsion system architecture have been studied. Several aerodynamic models with upper engine arrangement have been designed, manufactured and tested in TsAGI’s large transonic wind tunnels. They include conventional “tube and wing” configurations as well as non-conventional business-jet and “flying wing” layouts. Descriptions of the aerodynamic peculiarities of the each scheme are given in this article alongside with the aerodynamic design principles. Selected results of the experimental studies (including those of flow visualization) are presented and compared with CFD data.

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2. Aerodynamic design of the over-wing-engine configurations

An unfavorable aerodynamic interference of engines with wing surface is one of the main technical barriers to over-wing-engine configurations adoption. The engine disposed over the upper wing surface operates in a field of increased velocities and, accordingly, an unfavorable aerodynamic interference can exhibit. Especially strong interference is peculiar to configurations with front engines, since it is near the leading edge of the wing where the highest negative pressure is realized. For instance, in European Project ROSAS [1] the engines mounting over the wing leading edge was found unacceptable due to the occurrence of intense shock waves (Figure 1 from [1]).

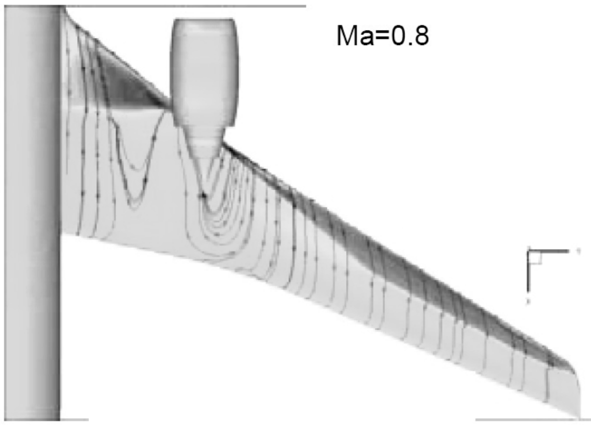

Figure 1: Shock-induced separation inboard of the pylon on the over-wing-nacelle configuration

The authors experienced the same troubles with the “flying wing” (FW) configuration (Figure 2) in TsAGI. Both calculations and experiments showed the presence of the intense shock waves even though nacelles proportions to the local chords were small enough as well as the local lift coefficients.

Figure 2: TsAGI “Flying Wing” aerodynamic model with the upper nacelles forward position

The engines mounting over the wing trailing edge is much better because local velocities do not considerably exceed the free stream speed. Moreover, in cruising flight modes the engine slows down the flow in front of itself, and the nearby wing sections operate as if at the lower Mach numbers, i.e. we have the example of positive aerodynamic interference here. Business jets developers have long been familiar with this issue [10]. It is even possible to use it for some thickening of the rear spar, but some caution should be exercised because with a stretched version of an airplane creating and engines removing from the wing trailing edge the positive decelerating effect would disappear and a sufficiently strong shock wave could develop on the wing and lead to the shock-induced separation (Figure 3).

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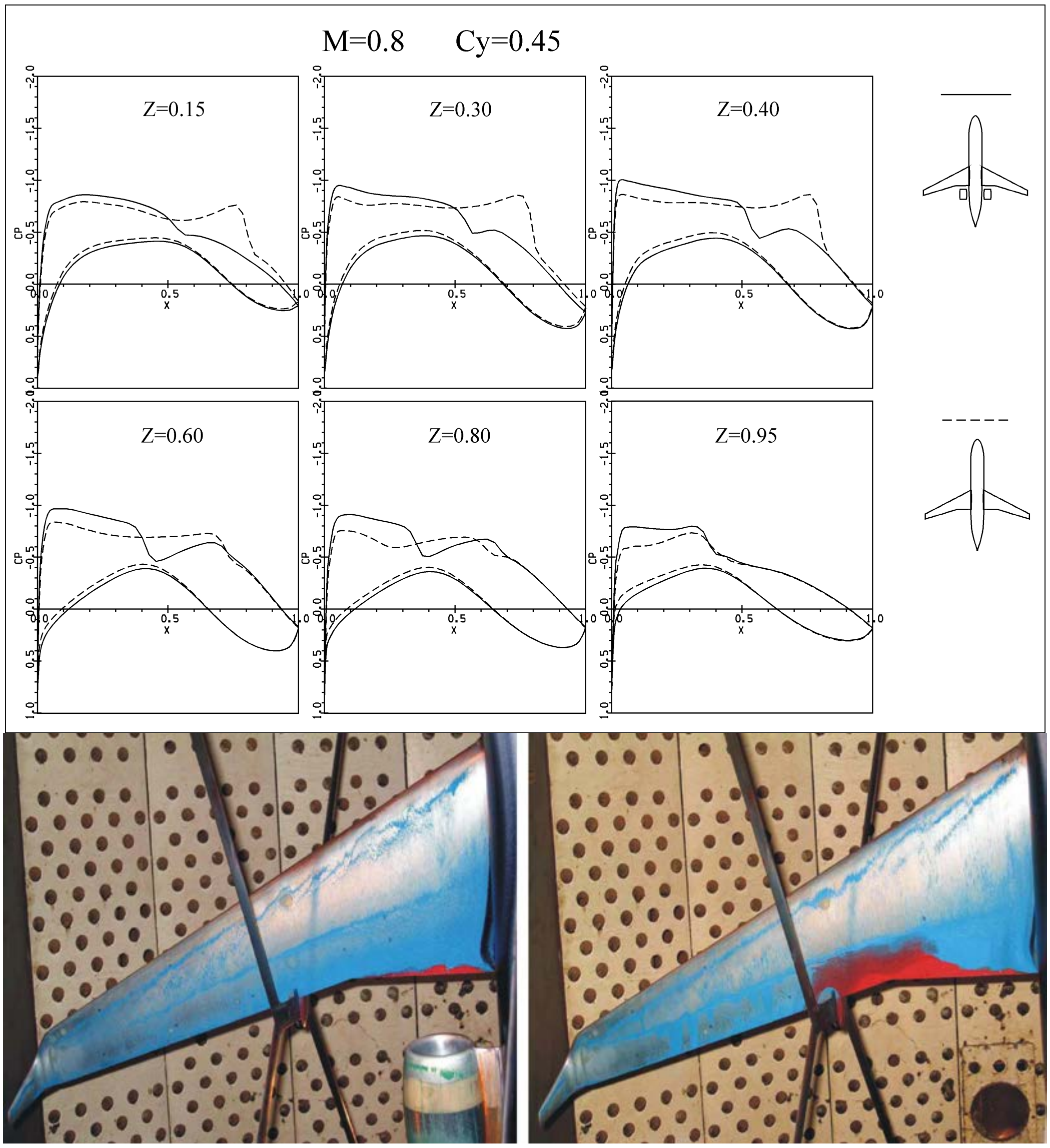

Figure 3: Suppression of the shock-induced flow separation by the nacelle installation
(the T-106 wind tunnel experiment)

With an engine arranging behind a trailing edge some exacerbations arise as to the static strength and aeroelasticity issues. For them to be weakened the engine nacelles need to be shifted upstream, again into the zone of the strong adverse interference. A powerful kit of aerodynamic design tools is necessary for this problem to be solved satisfactorily. The kit should include a detailed direct analysis method which takes into account all geometry features, an optimization procedure and an inverse method [11] which allows to build the surface of an aircraft element according to a given pressure distribution. In their practice, the authors use the original version of the residual correction method [12] in which the upper level presents the RANS-approach and based on the full potential method [11] inverse approach is used as the corrector.

Thus, the procedure for the aerodynamic design of configurations with over-wing engines consists of four stages:
- the selection of suitable configurations with the minimal adverse aerodynamic interference;
- the designing of the initial geometry of the wing, the pylon and the engine nacelle with separation of disturbances from the elements; the principle of separation of disturbances is one of the most fruitful in designing complex configurations with a large number of elements;
- the refinement of the wing/pylon/nacelle contours by using the inverse method;
- the geometry parametrization and the utilisation of the multiregime optimization of the aerodynamic characteristics.

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3. The studies on low-noise laminar wing regional aircraft

TsAGI studied the aerodynamic interference between a wing and over-wing-trailing-edge engines for a long-range aircraft with a high cruise Mach number and for a short-range aircraft with a 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 appears 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 makes it possible for the wing surface to be designed and optimized with more credibility. The thorough studies of this configuration reveal unexpected aerodynamic benefits: due to decelerating influence of the engines and lack of landing gear fairings at the wing-fuselage junction (landing gear is reasonable to be placed in the lower part of the massive engine pylon) the wave crisis can be postponed to the higher Mach numbers – that is what we want to justify the natural laminar flow (NLF) wing without a reduction of the desired Mach number of M = 0.78. Several low-sweep ($\chi_{1/4}$ = 15°) wings LSW-1, LSW-2, LSW-3 (Figure 4) were tested in the T-128 wind tunnel in 2015-2017. The aerodynamic studies have revealed satisfactory transonic aerodynamic characteristics (Figure 5), including the possibility of significant laminar runs on the outer parts of the wing. On the last model outstanding lift capabilities at low speed have been obtained as well.

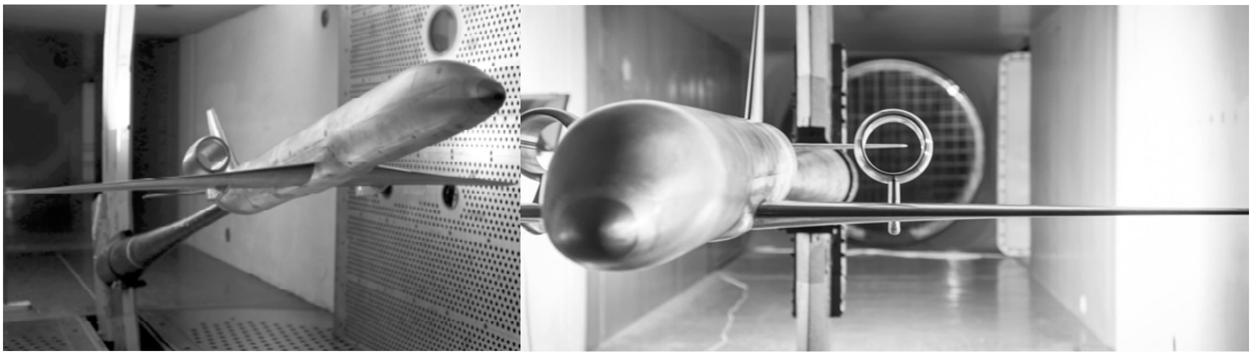

Figure 4: The aerodynamic models of low-sweep wing (LSW-2, LSW-3) regional aircraft with over-wing nacelles

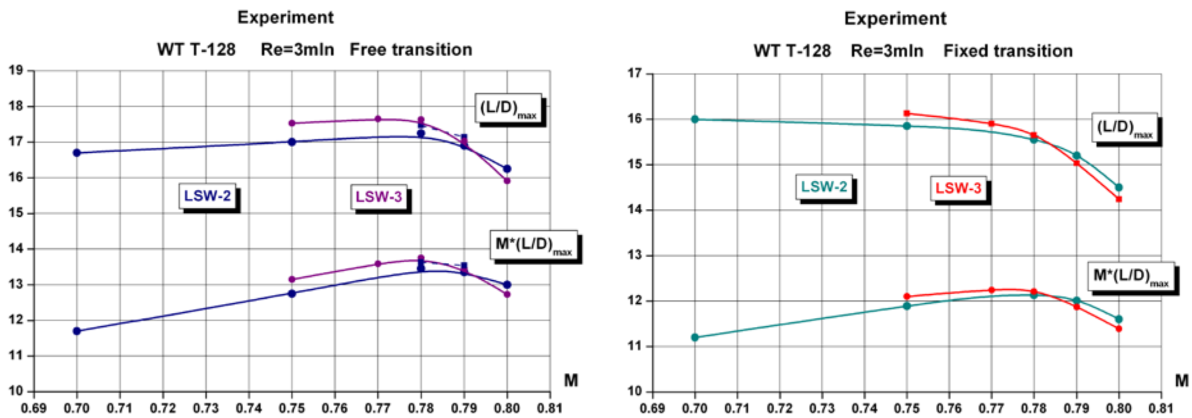

Figure 5: Experimental characteristics of the aerodynamic models

The diversified studies of the last configuration are still continued. Large half-model is being created with the aim of checking laminar testing possibilities of the T-128 wind tunnel at high Re numbers, just as it was done for the cryogenic wind tunnels in [13, 14]. First tests of the semi-span model are planned for the end of the year 2019.
The detailed studies of the aeroelastic structure are aimed at finding rational pylons geometry with tolerant weight penalties.

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4. The studies on a business jet with high passenger comfort

For a number of years, TsAGI has been conducting studies of a so called “Tadpole” business jet configuration with a drop-shaped fuselage [15], providing high comfort level for passengers and a favorable interference with the wing installed in the local decelerated zone of the flow behind the fuselage mid-section. An 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 makes it possible to reach the maximum speed corresponding to M = 0.8 with an entirely unswept wing having usual relative thickness distribution (t/c = 15-11% at root and tip 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 the wing at high Mach cruise. The tests carried out in the T-128 wind tunnel (Figure 6) fully confirmed the high speed characteristics of the configuration.

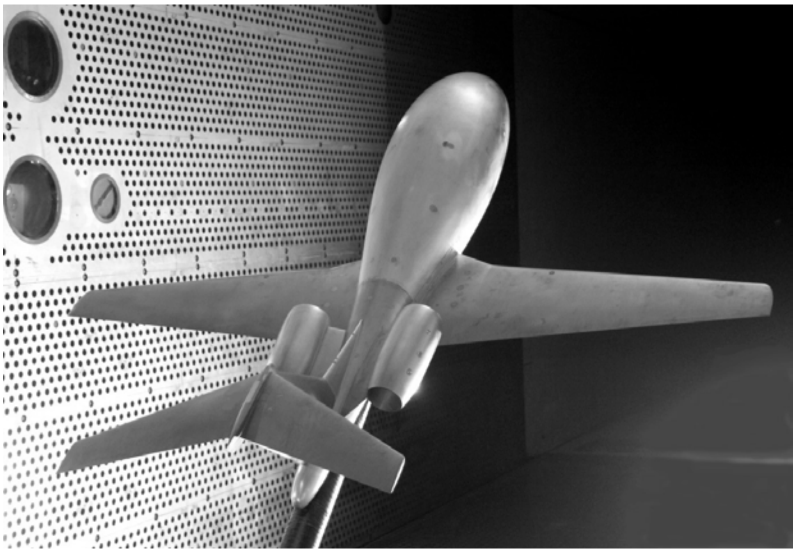

Figure 6: The “Tadpole” business jet aerodynamic model with straight wing ($M_{cruise} = 0.8$)

Design studies of the configuration have been recently continued towards an engine over-wing arrangement. Such a tendency was inspired by the successes in the laminar wing regional aircraft aerodynamics that were described in the previous section. However, the main incentive was the desire to enlarge the cabin volume like in the Honda jet [16]. Besides, moving nacelles to the wing eliminates the hazard of the root separated flow penetration to the inlets at high angles of attack.

The new wing has a small sweep (actually the wing trailing edge is perpendicular to the free stream) and is designed for a high speed cruise Mach number M = 0.82. The model was tested with the same fuselage, both in full configuration and without tail unit (Figure 7).

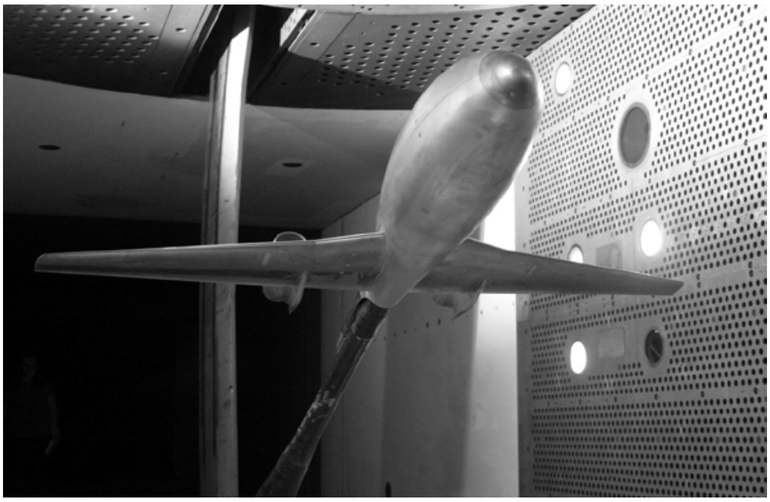

Figure 7: The business jet aerodynamic model with engine over-wing arrangement

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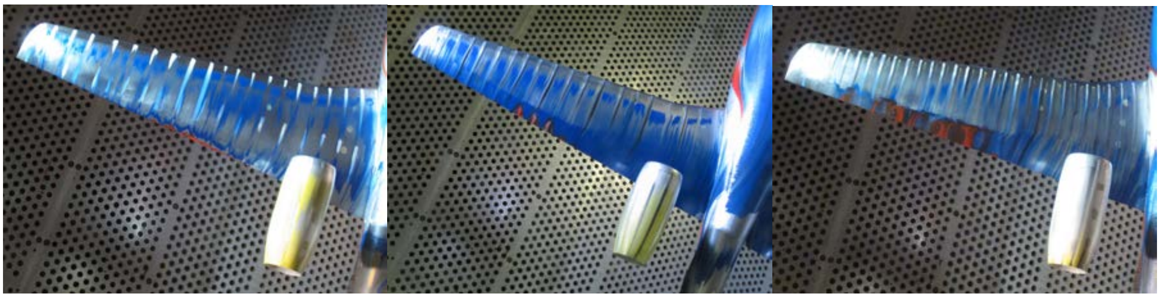
The tests confirmed the results of preliminary calculations. Any adverse features in the aerodynamic characteristics were noticed neither at transonic flight speeds nor at low speeds at high angles of attack. There was the flow visualisation with using the colored oil film technique (Figure 8) alongside with the balance tests. It can be seen that the flow separation development (changing from a trailing-edge type to a shock-induced one at increasing Mach number) occurs approximately in the middle of the console span where the inhibiting effect of the engine nacelle no longer exists.



M = 0.8 M = 0.82 M = 0.85

Figure 8: The flow visualization at different Mach numbers (α = 1.5°) by colored oil film technique

5. Flying Wing layout with upper engine location

“Flying Wing” (FW) or Blended-Wing-Body (BWB) configurations are considered as a serious alternative to conventional airplanes by aviation community [2, 8, 17]. Despite the long list of the shortcomings, FW/BWB passenger configurations have, at least potentially, three serious advantages: higher lift-to-drag ratio due to decreased relative wetted area, favorable load distribution along span and a significant community noise reduction possibility due to engines shielding in case of their upper location. It is the latter advantage that attracts a particular attention due to the desire to create a real “silent” aircraft which is virtually imperceptible to human ears.
However, placing the engines above the center wing section has many disadvantages, such as an increased maintenance complexity, due-to-thrust raised pitching moment, and especially an adverse aerodynamic interference with the airframe. Tests of the previous FW aerodynamic model in TsAGI showed that with Mach number increasing the drag growth of the nacelles located on the upper surface (both in front and rear positions, see Figures 2, 9) is significantly higher as compared with classic, engine-under-wing arrangement.

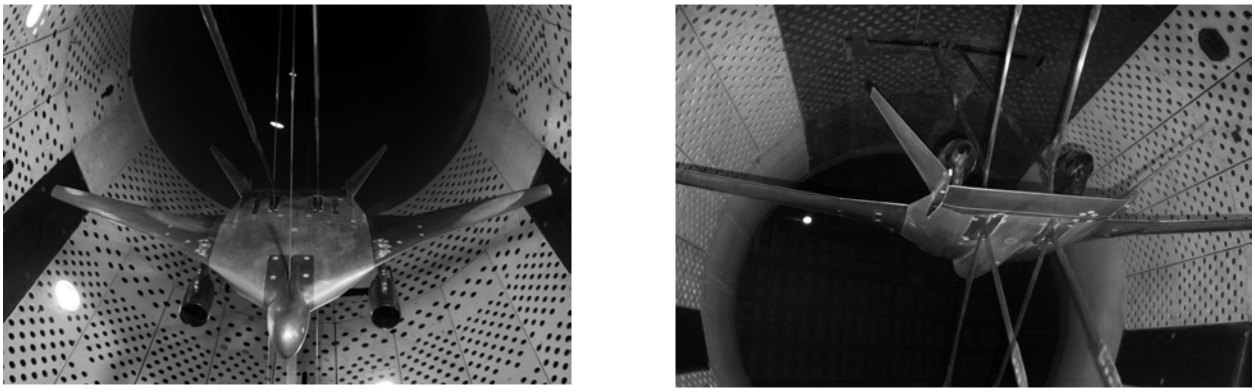


Figure 9: The FW aerodynamic model with forward under-wing and rear over-wing nacelles arrangements

Several different ways were considered to reduce the adverse interference. Acceptable, although limited, results have been achieved by using inverse methods to change the geometry of the wing upper surface in the interference zone. The local flow can be additionally decelerated with the second passenger deck of the central body terminating in front of the nacelles. This idea is similar to that of using a drop-shaped fuselage on the “Tadpole” configuration which provided a favorable interference. Thus, the one-and-a-half deck configuration of the central body that reminds the B-747 Jumbo jet fuselage has been got as a result. Such an addition of the upper deck improves the distribution of cross-sectional areas along the length of the aircraft and thus facilitates the cruise speed enhancement.

Calculations show that the adverse aerodynamic interference has been greatly attenuated and shocks on the pylons have been eliminated (Figure 10). Besides, incorporation of a second deck improves longitudinal mass distribution on the aircraft and reduces both the relative weight of the structure and wetted area per passenger that leads to the increase of the configuration efficiency.
The special FW aerodynamic model with flexible arrangement of tail units, wing tips and nacelles has been designed and is currently in the stage of manufacture. Wind tunnel tests of this new model are planned for the next year 2020.

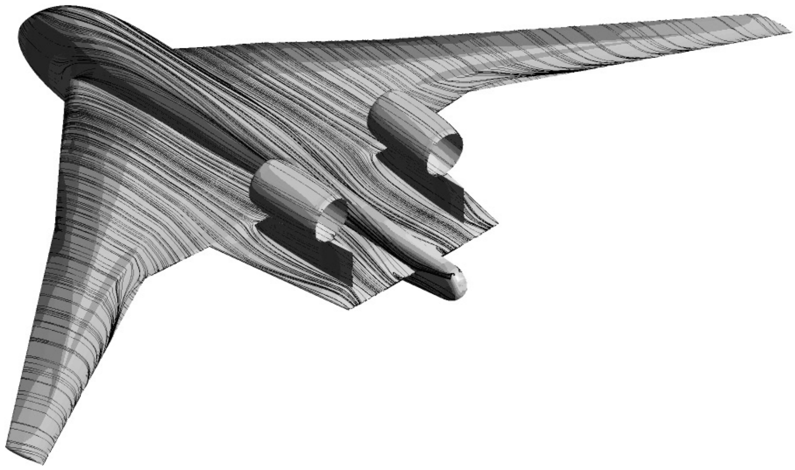


Figure 10: CFD flow field visualization over a novel FW configuration

Conclusions

The peculiarities of aerodynamic design of over-wing-engines aircraft configurations are indicated. In general, their aerodynamics is more complicated due to the possibility of an adverse aerodynamic interference caused by increased flow velocities over wings. Therefore, it is necessary to search for such configurations where this risk is minimized or there could even be some positive interference. In the design of complex airplane geometries it is necessary to apply the most advanced CFD methods with careful modeling of the main elements of a configuration: wing, fuselage, nacelles, pylons, fairings, etc. – and with the supplementation of the wide application of inverse and optimization techniques.
The design examples from TsAGI' experience are given. They include conventional "tube and wing" configurations as well as non-conventional business-jet and "flying wing" layouts. Selected results of the experimental studies (including those of flow visualization) are presented.

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