AERODYNAMICS OF STOL AIRPLANES WITH POWERED HIGH-LIFT SYSTEMS

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Keywords: *short takeoff and landing, aerodynamic characteristics, powered lift systems*

Abstract

Presented in the paper are results of studies on aerodynamics of short takeoff and landing (STOL) transport aircraft with various types of powered lift systems (PLS), performed at the Central Aerohydrodynamic Institute (TsAGI), named after Prof. N.E. Zhukovsky.

The test results obtained in the TsAGI T-101 large wind tunnel correspond to the experimental aircraft "Photon" with wing jet high-lift systems, a twin-engine transport aircraft's large-scale model with the wing upper surface blowing by exhaust gases of full-scale turbofan engines and models of four-engine aircraft with wing blowing by exhaust flow of super-high bypass ratio (BPR=16-18) turbofans and slipstream of high-loading coaxial propfans. The features have been revealed and general regularities established in relation to the influence of engine jets on the aerodynamics of aircraft. The problem of STOL flight safety in case of an engine failure is considered.

Possibilities of the use of tangential engine bleed air blowing over the upper wing surface for suppression of shock-induced flow separation at cruise transonic speeds and for increasing aircraft lifting capabilities on takeoff and landing using blown plain flaps are demonstrated.

New conceptual aerodynamic configurations of STOL aircraft with distributed power plants are offered. The estimates of flight performances of STOL transports with various types of PLS are given.

1 Introduction

Short takeoff and landing (STOL) aircraft is a special class of airplanes able to use short concreted or soft-surface runways (RW) 600-800m in length. The application of STOL technologies can provide:

- essential growth in air traffic volumes due to increase in aircraft payload capacity, operations from short, including poorly prepared unpaved runways, as well as increasing the throughput of existing airports,
- reducing the time of passenger and cargo «door to door» delivery due to proximity of STOL airfields to settlements,
- reducing the noise level in the vicinity of airports owing to steep takeoff and approach paths,
- flight safety enhancement during takeoff and landing operations due to reduction of operating speeds.

Radical improvement of aerodynamic and flight performances of aircraft is possible due to application of the so-called powered lift systems (PLS) [1-3]. Accordingly to the aerodynamic effects and the level of power expenses the PLS can be divided into two groups:

- jet-blowing wing high-lift devices ,
- external wing blowing by turbofan and turboprop jets.

Calculated and experimental researches have shown possibilities of significant improvement in the aerodynamic and flight performances of aircraft of different purposes owing to PLS employment. However the practical realization of PLS demands solving a number aerodynamic and design problems.

The basic aerodynamic problems to be solved are [4]:

- increase of PLS effectiveness by optimization of system parameters and minimization of power expenses;
- counteracting significant nose-down pitching moments due to PLS use;
- increase of control surfaces' effectiveness at low flight speeds;
- ensuring the stability and controllability of aircraft at various flight regimes and asymmetric engine failure for aircraft with over high-lift wing blowing by engine jets.

To address the practical implementation of PLS in some countries developed and implemented comprehensive programs that include exploratory research at the choice of rational configurations of aircraft with PLS, testing of the elements of these systems in full-scale setups, and flight-test aircraft demonstrators. In the 70-80s of the last century have been performed at NASA programs to develop an advanced medium military transport aircraft for the operation from runway length as short as 600m (Advanced Medium STOL Transport - AMST) and a quiet (low-noise) transport aircraft (QSRA program). On the basis of experience in the development of the McDonnell Douglas YC-15 experimental aircraft (1975), the C-17 operational-strategic military transport aircraft, able to operate from shortened runways, was created in 1991. It was fitted with slotted flap system blown by jets of four turbofans, located under the wing [5]. Currently in Europe the AIRBUS company has developed the A-400M medium military transport aircraft shortened takeoff and landing with propfan engines.

Similar researches were carried out for many years in the USSR and Russia. As a result of the researches performed at the Central Aerohydrodynamic Institute (TsAGI), extensive experimental data obtained on airfoils, wings and complete models of aircraft with different types of PLS. Much of these data was obtained in the large wind tunnel (WT) T-101 on full-scale planes or large-scale models. This experimental data, together with the developed effective theoretical methods, is the scientific basis needed for shaping STOL aerodynamic configurations for different purposes.

The most extensively studied areas are the boundary control systems (BLC) which have been used in a number of serial and test military aircraft MiG-21, MiG-23 and others. Long-term operation of these aircraft showed high efficiency and reliability of BLC systems for improvement in takeoff and landing performance. The wing upper surface blowing system by turbofan jets is used on the serial "Antonov-72" light transport aircraft (1977). The use of intensive blowing over the high-lift wing by slipstreams of coaxial propfan engines is the characteristic property of the "Antonov-70" medium transport aircraft (1994) with a unique takeoff and landing performance (Fig.1).

Fig.1. STOL military transport "Antonov-70"

This aircraft with a takeoff gross weight (TOW) of more 100t can takeoff from a soft-surface runway 600-800m in length, transport 20t of payload over a range of up to 3000кm at cruise Mach number of M=0,7, and to land on an unimproved runway of the same length.

Presented in the given article are some results on STOL transport investigations carried out in TsAGI. On the basis of a generalization of existing experimental and theoretical results, some general regularities of various types of PLS impact on aircraft aerodynamics were revealed, comparative analysis of the effectiveness of different PLS performed and recommendations prepared for the choice of a rational type of PLS to provide the required STOL performance.

2 The Investigations of the Wing Jet High-Lift Systems.

Detailed parametrical investigations of the wing jet high-lift systems were carried out in the TsAGI T-101 wind tunnel on experimental aircraft "Photon" [3] (Fig. 2a), designed and manufactured in the Moscow aviation university accordingly to the TsAGI technical assignment. Modularity of the wing design have allowed to study the different variants of jet blowing system (Fig.2b):

-boundary layer and circulation control (BLC/CC) by means of tangential jet blowing of compressed air from a slotted nozzle over plain flaps deflectable within an angle range of 0 to 180°,

-boundary layer control (BLC) on the wing upper surface by means of tangential jet blowing from a slotted nozzle at leading edge,

-circulation control (CC) by means of tangential jet blowing from a slotted nozzle at the wing rounded trailing edge (RTE) in a wide range of the trailing edge radius R and width of the slotted nozzle h_j related to wing chord c: $R/c=0.01\div 0.04$ and $h_j/c=(0.3 \div 2)\ 10^{-3}$.

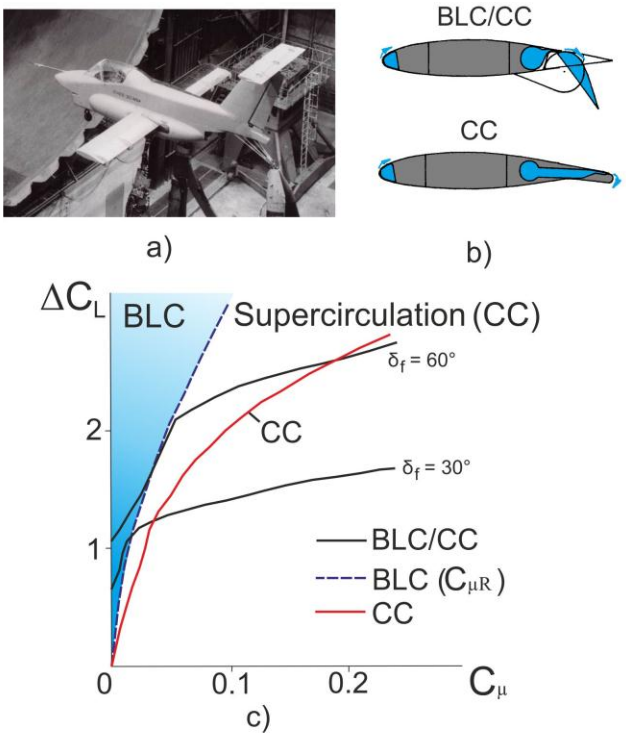


Fig. 2. Experimental studies of high-lift systems on the aircraft "Photon" in the TsAGI WT T-101

A comparison of aerodynamic characteristics of the aircraft "Photon" with tangential blowing over flaps and the wing rounded trailing edge with optimum parameters ($h_j=1\div2.5\%R$ and $R=2\div4\%c$) has shown (Fig. 2c):

- the lift coefficient increment ΔC_L of the aircraft depends essentially on jet momentum coefficient $C\mu = J/q_\infty S_0$, where J - the jet momentum, q_∞ - the freestream dynamic pressure, S_0 - the reference wing area, corresponding to the flap or RTE span;
- the relationships between the lift coefficient increment ΔC_L and the jet momentum coefficient $C\mu$ for blown flaps essentially differs from the corresponding relationships ΔC_L ($C\mu$) for the CC system on the wing rounded trailing edge. With blown flaps there is an intensive increase of the lift coefficient increment at values of jet momentum coefficient $C\mu \leq C\mu_R$, corresponding to flow reattachment on flaps. Then there is an abrupt reduction of the lift coefficient increment rate, associated with the jet influence on a flow speed circulation over the wing (supercirculation effect). With jet blowing over the wing rounded trailing edge, there is a monotonous increase in the lift coefficient approximately proportional to $\sqrt{C\mu}$.

The values of the lift coefficient increment of the wing with BLC on flaps at jet momentum coefficients $C\mu_R$ and all investigated angles of flap deflection ($\delta_f \leq 75°$) exceeds the values of ΔC_L on the wing with CC system on RTE;

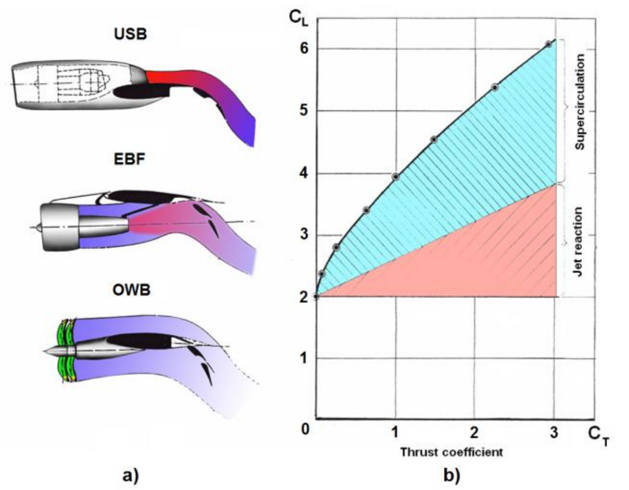
- the aerodynamic center of the wing with the CC system is in a more downstream position from a leading edge ($x_{ac} \approx 0{,}55c$), than with the BLC system ($x_{ac} \approx 0{,}45c$); as a result, the problem of longitudinal trimming of the aircraft with the CC system becomes more complicated;
- the thickening of the wing trailing edge to values $R/c \leq 0.02\div0.03$ in test conditions in the WT at low flow speeds (V=40 m/s) and Reynolds number of $Re\approx3\cdot10^6$ only insignificantly influences the aircraft drag both without jet blowing and at with it on RTE ;
- BLC application at the wing leading edge increases the maximum lift coefficient by 20-25% and a critical angle of attack by 6-8deg.

at jet momentum coefficients Cμ ≤ 0.05 for the aircraft both with blown flaps and with the CC system at the wing rounded trailing edge as a result of flow reattachment on the wing upper surface.

Thus, the investigations have shown that both the systems are effective, however they possess a number of specific features which are necessary to take into account in deciding on the PLS type for an aircraft.

3 STOL Aircraft with Over - the -Wing Blowing by Engine Jets

Increase in aircraft’s lifting capabilities with high-lift wing blowing by engines jets (Fig. 3a) takes place owing to improvement of flow over the wing and flaps, the effect of supercirculation and deflection of the engine thrust vector (Fig. 3b). The lift increment depends mainly on the effective angle of the thrust vector deflection and on the engine thrust coefficient $C_T = T/q_\infty S$, where T - thrust, S - the wing area.



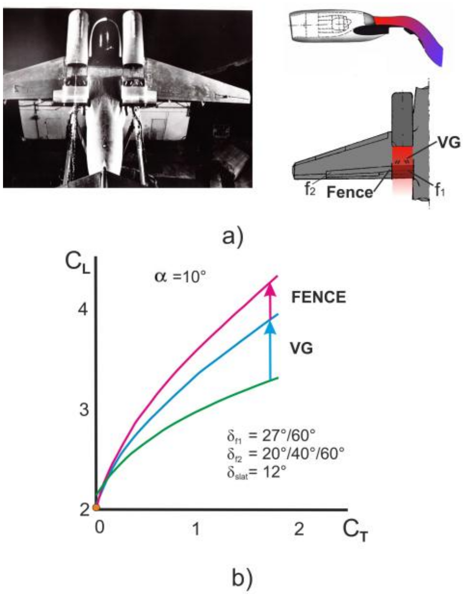
a) b)

Fig. 3. Influence of engines jets blowing on the wing lift coefficient

3.1 Aircraft with Over Wing Upper Surfaces Blowing by Turbofan Efflux

The basic feature of an over wing upper surface blowing (USB) system using turbofan efflux (see Fig. 3a) is the employment of so-called Coanda effect. In such a concept, thick propulsive jets, produced by turbofans flow over the wing, remaining attached to large radius flaps and deflecting downward behind the trailing edge of the wing.

The effective angle of jet downturn at high flap angle settings can be increased by the use of the D-shaped nozzles, installation of vortex generators on the wing behind the nozzles and fences along the jet lateral edges. Tests of the "Antonov-72" large-scale model with operating engines in the large T-101 WT (Fig. 4a) have shown that these means allow one to raise significantly the effectiveness of USB system (Fig. 4b).



a)

b)

Fig. 4. Tests of the "Antonov-72" large-scale model in the TsAGI T-101 WT

3.2 Aircraft with Externally Blown Flaps

The externally blown flap (EBF) concept (see Fig. 3a) in which the turbofan exhaust flow is directed at the undersurface of the multi-slot extended flap deflected downward, spreads spanwise and increases lift due to vertical jet reaction, suppression of flow separation on the flaps and a supercirculation effect.

The lift increment depends on engine thrust coefficient, an effective angle of jet deflection and some geometric parameters of the system: relative diameter of the nozzle, type of the flap, its deflection and sweepback, number of flap slots and their relative sizes, and also on the relative position of the engines and wing.

Typical aerodynamic characteristics of the transport aircraft model with a two-element slotted flaps blown by jets of four ejector simulators of turbofans with super-high bypass ratios of 16-18 (Fig. 5a) are shown in Fig. 5b. Tests have been performed in the TsAGI's subsonic T-102 WT at a flow speed of 40m/s, corresponding to Reynolds number of $Re \approx 0.9 \cdot 10^6$. Application of the EBF system allows the aircraft to use steep descent on approach.

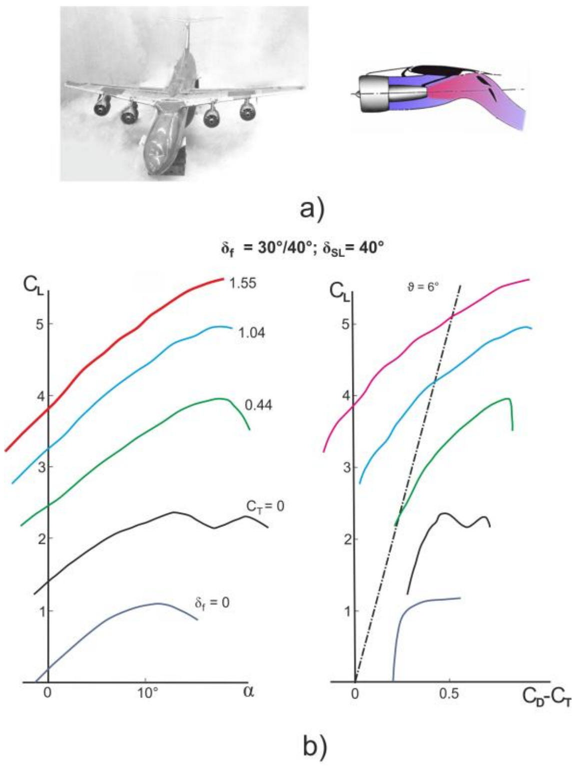


Fig.5. Aerodynamic characteristics of four-engine aircraft model with external slotted flap blowing

For improvement of takeoff and landing characteristics of modern twin-engine aircraft, the combined high-lift system, including the blown wing and BLC flap system, can be used (Fig.6). Extention and deflection of plain blown flaps provides an effective deflection and spanwise spreading of engines jets over the wing with corresponding lift increase .

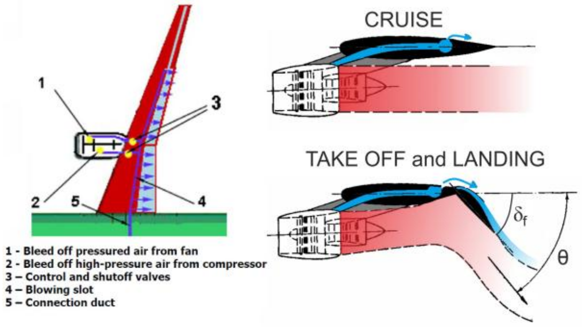


Fig. 6. Twin-engine aircraft with the combined high-lift system

In case of failure of one of the engines, application of BLC to flaps and ailerons allows one to effectively counteract the rolling moment due to differential jet blowing over the wing panels and ailerons (Fig.7). Compressed air for BLC system is bled from the compressor or the fan of the operating engine or from an auxiliary power unit.

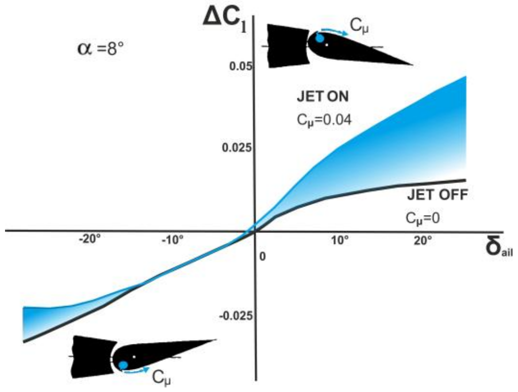


Fig. 7. Effectiveness of blown ailerons

BLC system can be used not only during takeoff and landing operations, but also at cruise high subsonic speeds. Calculations have shown that tangential jet blowing is an effective means of suppression of a shock-induced flow separation on the wing [6], Fig. 8. Reliability of computational results is confirmed by tests of a wing-fuselage model in the TsAGI T-106 large transonic wind tunnel. It was shown that tangential blowing of a supersonic jet of low intensity (jet momentum coefficient $C\mu_R$=0.005-0.007) eliminates boundary layer separation on the swept wing at transonic speeds and raises the maximum value of the model lift-to-drag ratio approximately by 10 % at a Mach number M=0.78 (Fig. 9).

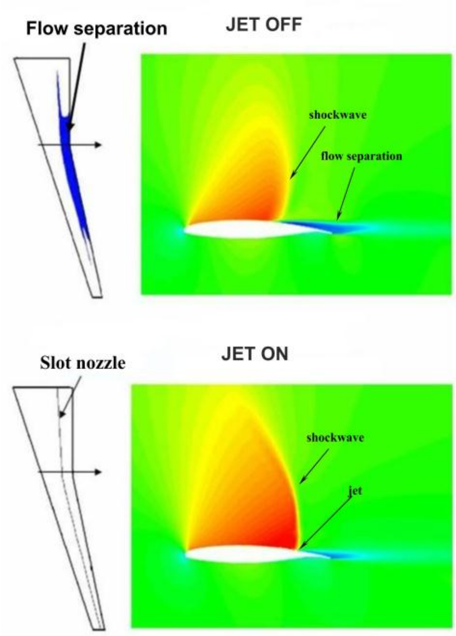


Fig. 8. Influence tangential jet blowing on a flow over swept wing , M=0.78 , Re=$25 \cdot 10^6$

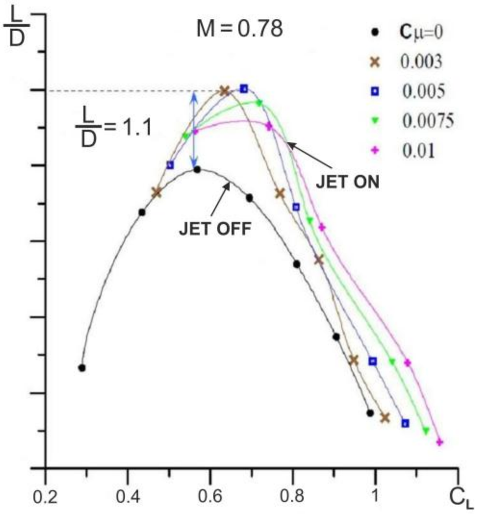


Fig. 9. Influence of tangential jet blowing on the lift-to-drag ratio of the wing-fuselage model

According to the estimations based on experimental data, application of tangential jet blowing over the wing of the twin-engine aircraft with 1,5-2% of compressed air bled from engines allows one to increase the cruise Mach number by 0.05-0.08, the flight range by 8-10% or to reduce the fuel consumption by 6-8% in comparison with aircraft with no blowing system.

3.3 Aircraft with Over- the- Wing Blowing by Turboprop Slipstreams

The over-the-wing blowing (OWB) by slipstreams provides the lift increase due to higher aerodynamic loading not only on flap elements, but also on the basic part of the wing.

A rather effective way to increase lift is to use wing blowing by propeller slipstream in combination with blown flaps. Tests in the T-101 WT of the "Antonov-10" transport large-scale model (Fig.10a) have shown that application of the combined system allows one to raise the model maximum lift coefficient from $C_{Lmax} \approx 2.8$ to 5.4 at a flap angle of $\delta_f = 40^o$, jet momentum coefficient of $C\mu = 0.2$ and propeller loading factor B=3.14 (Fig. 10b).

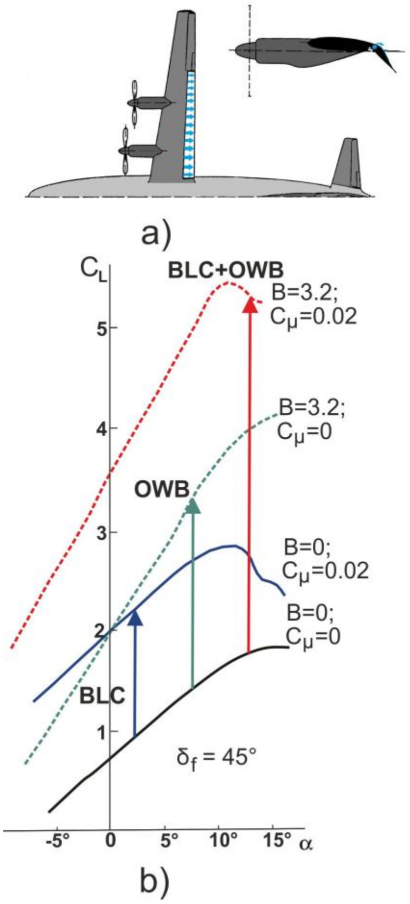
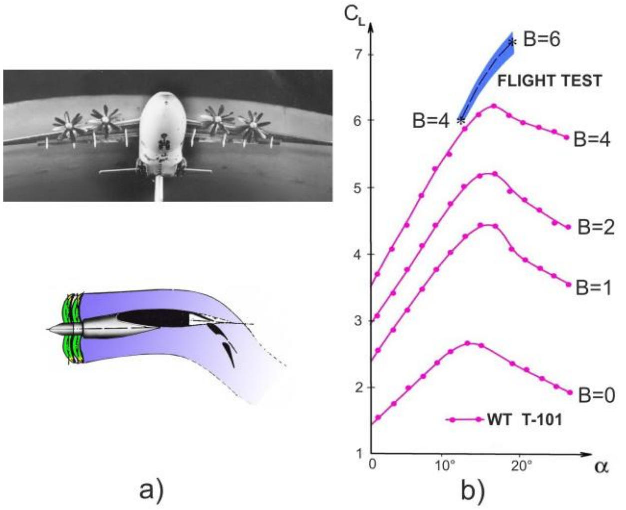


Fig. 10. Aerodynamic characteristics of the "Antonov-10" transport large-scale model with the combined high-lift system

An effective way of increasing lift and improvement of takeoff and landing characteristics of transport aircraft is intensive blowing of the high-lift wing by slipstream of highly fuel-efficient propfans. Tests of the "Antonov-70" STOL transport model with TPS engines simulators in the T-101WT (Fig. 11a) have shown the high effectiveness of the developed wing high-lift system under conditions of intensive blowing by four propfans (Fig.11b). Flight tests of the aircraft have confirmed the experiments in the T-101 WT and have shown possibility of achieving a very high values of lift coefficient ($C_L \geq 7$ at propfan loading coefficient B=6) when flying at high angles of attack and a speed of 120km/h.



a) b)

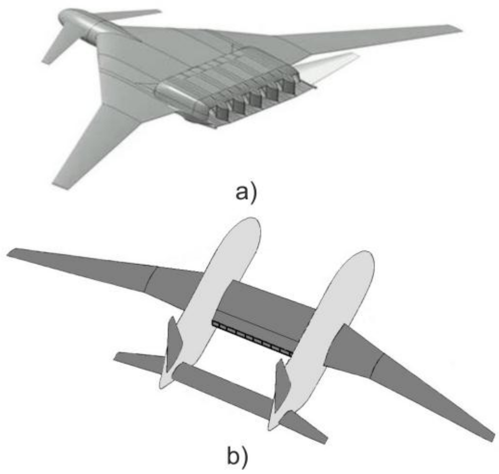
Fig. 11. Aerodynamic characteristics of the "Antonov-70" STOL transport aircraft

4 New Concepts of STOL Transport Aircraft

4.1 An Aircraft with Integrated Layout and the Distributed Power-Plant

Shown in Fig.12a is one of possible variants of the integrated layout aircraft with the distributed power plant located in the tail part of its flattened fuselage. Placing of engines over the fuselage allows one not only to reduce noise level from engines, but also provides protection of engines against damage due ingestion of foreign matter from the runway surface.

Use of this system can also enhance lifting properties of the aircraft on takeoff and landing due to thrust vector control by a two-dimensional nozzle. For counteracting the pitching moment due to nozzle deflection, it is expedient to use a high-lift canard with the BLC system.



a)

b)

Fig. 12. STOL aircraft of non-conventional aerodynamic configurations

4.2 Twin-Fuselage Aircraft

A twin-fuselage aircraft (Fig. 12b) allows one to place of passengers or cargoes in two fuselages that essentially increases number of passengers or volume of transported cargoes and significantly enhance the transportation capabilities and efficiency. For improvement of aircraft takeoff characteristics, an augmented propulsive system can be used consisting of a number small-sized turbojets (gasgenerators), located in the wing center section. Due to ambient air ejection the takeoff engine thrust can be increased by 15-20%. Due to the ejector system, the noise level can be reduced owing to reduction jet efflux speed. Thrust vectoring of two-dimensional nozzle located in a rear part of the wing increases the aircraft lifting properties on takeoff and landing. The pitch moment due to nozzle deflection is rather small because the nozzle is located close to the aircraft center of gravity, and lift trim losses will be minimal. Besides, the box-shaped arrangement of the power plant between the fuselages reduces structural weight of the aircraft and decreases noise level.

5 Flight Performances of STOL Aircraft

Obtaining high lift coefficients due to use of PLS allows one to reduce considerably takeoff and landing speeds and accordingly required runway lengths (Fig. 13) and also to raise the flight safety on these critical modes in comparison with conventional aircraft.

For achievement of a high requirement values of lift coefficient (at takeoff C_L=2.5-3.0, at landing approach C_L = 3.5- 4.0) various types of powered lift systems (PLS) can be used.

The boundary layer control systems (BLC) possessing high aerodynamic efficiency at rather small needed expenses of compressed air, are realized on a number of serial and experimental planes.

The external blowing of the slotted flaps (EBF) by turbofan jet efflux allows to receive necessary values of the C_L at landing, but create relatively small lift at takeoff mode as a result of lesser angles of jet deflection.

The upper wing surface blowing system (USB) by turbofan jet efflux possesses advantage on takeoff (high values of a lift and lift-to-drag ratio), but demands special means for realization of Coanda effect on landing modes.

The over the wing blowing (OWB) by propeller slipstreams possess advantages of systems EBF and USB. Unique runway characteristics the military-transport aircraft "Antonov-70" possesses due to intensive blowing the high-lift wing by slipstream of coaxial propfans (see Fig. 1, 11,13) .

Application of STOL aircraft with PLS makes it possible to considerably expand the number of airfields with short runways and to provide with more intensive aircraft movement, or to increase aircraft payload capacity when using regular airports.

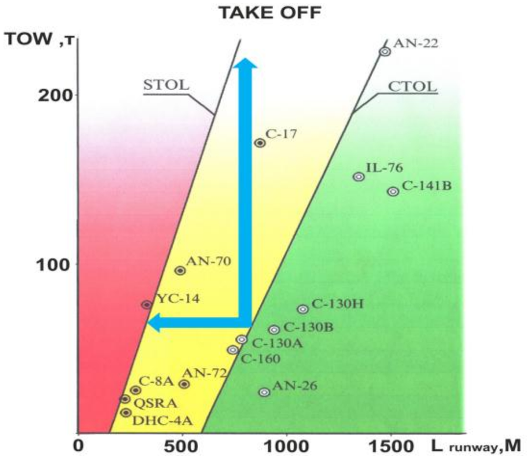


Fig. 13. Takeoff characteristics of aircraft

6 Conclusion

Results of the complex computational and experimental researches have shown that radical improvement of takeoff and landing characteristics of advanced aircraft can be provided due to application of various types of powered high-lift systems, based on "deep" integration of power plants with airframes.

The most effective powered high-lift systems are:

- boundary layer and circulation control by tangential jet blowing of the compressed air over the upper surfaces of the wing and deflected flaps,
- blowing over high-lift wings by turbofan or turboprop engine jets,
- the combined lift-augmentation systems, based on over-wing tangential compressed air blowing and engines jets blowing over the wing and flaps .

A promising direction in the advancement of the powered high-lift technologies may be the development of STOL transports with distributed power plant and thrust vector control.

It is shown that STOL technology can provide operational capability of transport aircraft with takeoff weights at up to 100-130t from short and unimproved natural-surfaced airfields 600-800m in length, which is 2-2,5 times less than RW lengths needed for conventional aircraft of the similar class.

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