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APPLICATION OF TANGENTIAL JET BLOWING FOR SUPPRESSION OF SHOCK-INDUCED FLOW SEPARATION AT TRANSONIC SPEEDS

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Abstract

The results of calculation and experimental investigations of efficiency of application of compressed air jet tangential blowing through a slot nozzle over upper surface of a supercritical swept wing for suppression of shock-induced boundary layer separation at high transonic speeds are presented.

On the basis of numerical solution of the Navier-Stokes equations the effect of tangential jet blowing is examined on aerodynamics of a high-aspect ratio (AR=16) and low-sweep ($\Lambda_{1/4}$=20.5 deg.) wing in the range of transonic Mach numbers of M=0.7-0.8 and Reynolds number of $Re \approx 25 \cdot 10^6$, corresponding to real cruise flight conditions

The experimental data are obtained in the TsAGI T-106 transonic wind tunnel tests of the wing-fuselage model with jet blowing over the supercritical wing with aspect ratio AR=10.8, sweep $\Lambda_{1/4}$=20.5 deg. and relative thickness $\bar{t} = 15.4 \div 12.85$. The tests were carried out in ranges of Mach number M=0.4-0.8, Reynolds number of $Re=(1.4\text{-}2.2)\cdot 10^6$, angles-of-attack α= -2-15 deg. and jet momentum coefficient of $C\mu=0 \div 0.06$.

It is experimentally shown that at high transonic Mach numbers ($M \geq 0.75$) jet blowing with low intensity ($C\mu \leq 0.005$) eliminates the shock-induced flow separation and increases the maximum lift-to-drag ratio of the model by $\Delta(L/D)_{max} \approx 1.1$, what makes it about 9% at M=0.78.

On the basis of the obtained experimental and calculation data the estimations of possible flight performance improvements of a typical twin-engine subsonic transport aircraft equipped with the system of over-the-wing tangential blowing are given.

1. Introduction

One of the most important and complicated problem of modern aerodynamics is the problem of increasing flight cruise speeds of subsonic civil transport aircrafts. The main obstacle on this way is an abrupt rise of the wave drag and intensification of shock-induced flow separation, i.e. wave separation [1]. Moreover, non-stationary interference of shock-wave with the separated flow leads to the aircraft buffeting.

The possibilities of traditional, so-called ‘passive’ methods of solving these problems, for example, through decreasing relative thickness of supercritical wings, increasing of its sweep angle and optimization of wing’s configuration, are connected with many restrictions and are practically exhausted by now.

One of the ways to overcome the problem is the concept of active flow control at high subsonic Mach numbers by means of jet blowing over the wing. To suppress shock-induced flow separation the jet of compressed air is blown from a slot nozzle tangentially to the wing upper surface in the area of the shock-wave position in front of the expected flow separation. The possibilities of using this method for eliminating flow separation on the wing at high angles-of-attack and over flaps at low velocities (M=0.15-0.3) are well known[2,3]. Semi-empirical methods of calculating the jet momentum coefficient required for elimination of flow separation over an airfoils and wings at low velocities have been developed [4].

Preliminary numerical studies [5] based on the zonal approach [6], have shown that jet blowing over supercritical thick airfoils ($\bar{t} = 10 \div 14\%$) allows to eliminate boundary layer separation in the rear part of airfoils at high Mach numbers of M=0.7-0.88 and Reynolds number $Re=40 \cdot 10^6$, corresponding to natural cruise flight conditions. According to calculations performed, a decrease in drag of the supercritical airfoil with relative thickness of 10-14 percents is about 20-35 percent at wide range of transonic velocities.

A positive jet blowing effect on the flow over the supercritical high-aspect-ratio (AR=16) and low-sweep (20.5 deg.) wing was revealed by numerical solving of the 3 - dimensional Reynolds equations (3D RANS)[7]. The experimental studies of the wing-fuselage model in TsAGI T-106 wind tunnel confirmed the effectiveness of the tangential jet blowing for improvement of aerodynamics of swept wing.

The results of calculation and experimental investigations of tangential jet blowing over the upper surface of swept wing are presented in this article.

2. Calculation studies of the tangential jet blowing effect on aerodynamics of swept wing

2.1 Statement of the problem. Method of analysis

The viscous compressible flow around the swept wing (Fig. 1,a) in the presence of developed local supersonic area, closed by shock-wave is considered. Near the line of flow separation (X_{sep}), caused by the shock-wave, the tangential blowing of compressed air jet from a slot nozzle, located at X_{SN} chordwise position, with an intensity sufficient for the displacement of the separation zone to the wing trailing edge is realized (see Fig. 1, b).

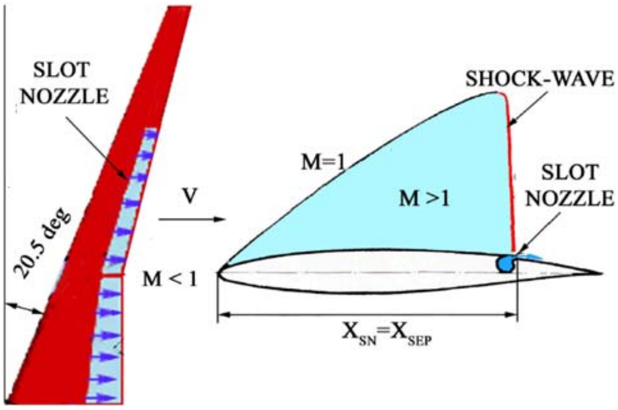

Fig.1. Scheme of the flow over the swept wing with tangential jet blowing

For the computation of viscous transonic separated flow around the isolated swept wing the numerical solving of Reynolds equations (3D RANS) with two-parameter *k-ε* SST turbulence model was used. The flow around the wing with the slot nozzle was calculated using multiblock structured grid, which included 2.1 million nodes. Its fragment is represented at Fig. 2.

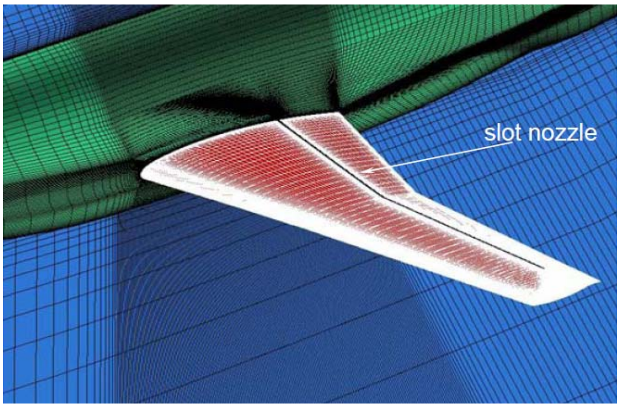

Fig.2. Fragment of structured computational grid

Transonic flow around the supercritical swept wing (with $\Lambda_{1/4}$=20.5 deg. and AR=16) at angles-of-attack of $\alpha=-4 \div 4$ deg. and Reynolds number $Re=24.6 \cdot 10^6$ was calculated for cases with and without tangential jet blowing. The jet at the slot exit section features the following assumed parameters: total pressure P_0=100 kPa, static pressure P_{ST}=26 kPa (so that P_0/P_{ST}=3.85), T=300 K, which corresponds to the jet Mach number of Mj=1.53.

2.2 Results of calculations

In Fig.3 the example of the effect of jet blowing on the flow over the swept wing at angle-of-attack of α=4 deg. and Mach and Reynolds number M=0.78 and $Re \approx 25\cdot10^6$ respectively is given. The computations results have shown that for case without blowing at the above indicated conditions the flow separation in the middle area of the wing takes place (Fig. 3,a). Jet blowing from a full-span slot nozzle, located along the 70 percent of wing chord line mostly eliminates the flow separation. It could be seen from the comparison of the local Mach number distribution in the middle wing cross-section with (see Fig.3,b) and without (see Fig.3, a) jet blowing.

$M = 0.78, Re = 24.6\cdot10^6, \alpha = 4\,deg.$

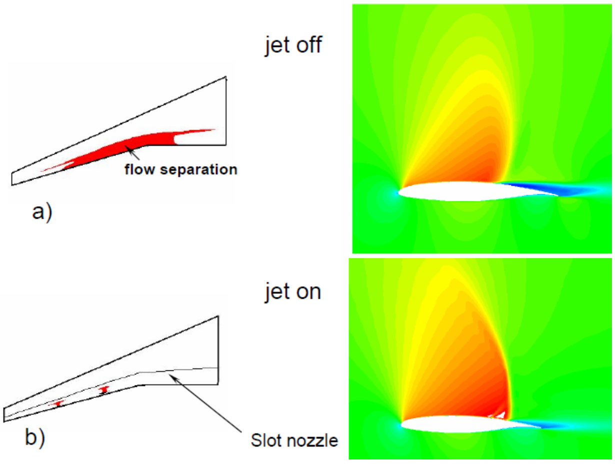

Fig.3.Jet effect on the flow over the swept wing

The pressure distribution in the same wing cross-section confirms the jet effect on flow improvement over the wing (Fig.4).

$M = 0.78, Re = 24.6\cdot10^6, \alpha = 4\,deg.$

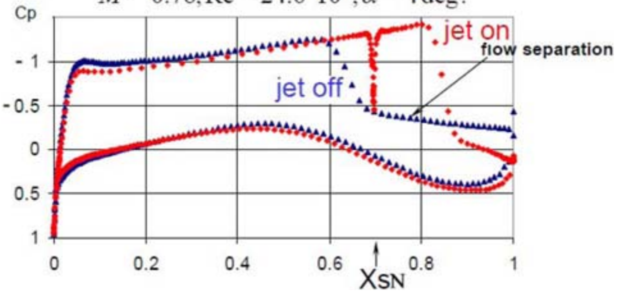

Fig.4.Jet effect on pressure distribution at the swept wing middle cross-section

At the slot nozzle location (X_{SN}) one can see an abrupt change in the pressure on wing upper surface as a result of influence of the supersonic jet at Mach number Mj=1.53. A comparison of pressure distributions in the wing cross section with and without blowing shows that, the jet blowing leads to pressure recovery at the wing trailing edge, extension of local supersonic flow area and the shift of shock-wave towards the trailing edge.

As a result of a positive jet effect on the flow over the wing, its lift significantly increases. It should be noted, that linear parts of lift and pitching moment dependencies on the angle-of –attack become longer (Fig.5).

$M = 0.78, Re = 24.6\cdot10^6, \alpha = 4\,deg.$

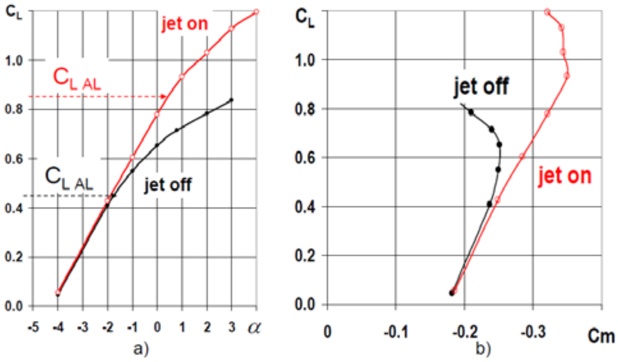

Fig.5.Jet effect on wing lift and pitching moment

This effect significantly increases the allowable operating angle-of-attack range. For example, the value of maximal allowable lift coefficient at Mach number M=0.78 increases from $C_{L\,AL}$=0.45 (without blowing) up to $C_{L\,AL}$=0.85, that is greater than by 80 percents.

Owing to improvement of the flow over the wing due to jet blowing, the wing drag decreases while the lift-to-drag ratio increases. According to computations, jet blowing leads to increase of the maximal lift-to-drag ratio of the wing at Mach numbers M=0.78 and Reynolds number $Re=24.6\cdot10^6$ from $L/D_{max}=22$ to $L/D_{max}=24$, that is approximately 10 percents

3. Experimental studies

3.1 The wing-fuselage model. Test conditions.

To validate the computational results, the experimental studies were performed in TsAGI T-106 transonic wind tunnel on the wing-fuselage model equipped with the system of wing upper surface jet blowing (Fig.6).

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The model consists of the wing of a moderate sweep angle ($\Lambda_{1/4}$=20.5 deg.) and aspect ratio of AR=10.8. Model wing span equals 1.9 m. The fuselage midship area makes it up 18 percents of the wing area. The wing is formed by thickened supercritical airfoils with the relative thickness of 15.4 percent in the wing root and about 13 percents in the middle and tip sections.

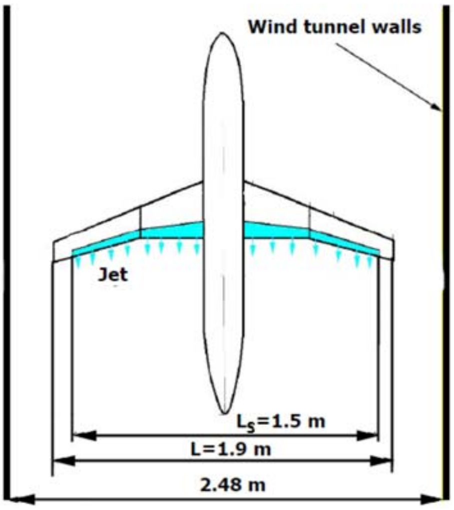

Fig.6.The wing-fuselage model equipped with jet blowing system

Near the wing trailing edge kink a pressure tapped sections are implemented for wing static pressure measurement. The jet was blown on the wing upper surface through a shaped clotted nozzle. The nozzle has height of 0.2 mm and length of 1.5 m, and is located along the 70 percent of the local chord line from the wing leading edge.

The tests were performed in TsAGI T-106 transonic wind tunnel which has the test section of diameter of 2.48 m. The model was mounted in the wind tunnel on a standard belt support system. Aerodynamic loads, acting on the model were measured by the external electro-mechanical AV-106 balance. High-pressure compressed air was fed into the model through the shaped hollow strut with maximal operating pressure of 7 atm.

Using the measurements of the pressured air parameters, the jet momentum coefficient was calculated by the formula:

$$C\mu = J_j / (q_\infty \cdot S) \qquad (1)$$

where J_j is the jet momentum, q_∞ is the flow dynamic head and S is the model wing area.

The tests were conducted at Mach number range from M=0.4 to M=0.8, corresponding to Reynolds number range of Re =(1.4-2.2)·10^6, and angles-of-attack of α=-2÷15 deg. and jet momentum coefficient range $C\mu$=0÷0.06.

3.2 Test results

In Fig.7 an example of the jet effect on pressure distribution at a wing middle cross-section is presented at Mach number M=0.75 and different values of jet momentum coefficient at angle-of-attack α=4 deg. For the case without jet blowing (Cμ=0) the intensive shock induced boundary layer separation is observed. In this case, the value of pressure coefficient near the wing trailing edge is about Cp=-0.3. Jet blowing results in pressure recovery at the wing trailing edge vicinity, expansion of the supersonic flow region and displacement of the pressure shock towards the wing trailing edge.

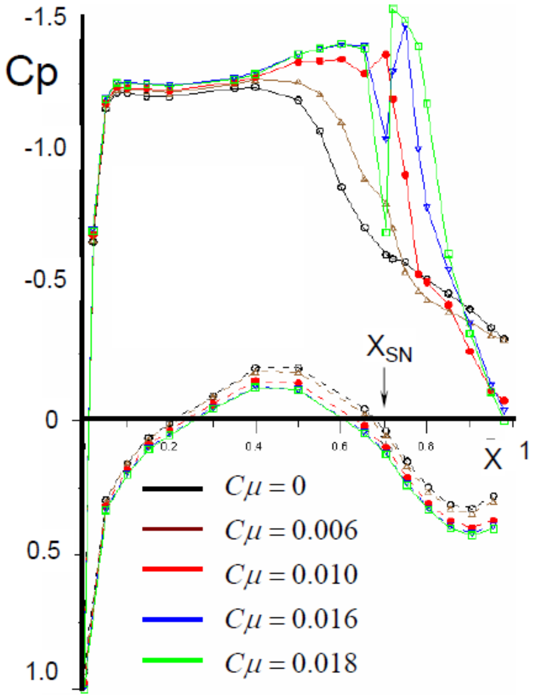

Fig.7.Jet effect on pressure distribution.

The jet momentum coefficient, corresponding to the maximum positive value of pressure coefficient near wing trailing edge, denoted $C\mu_R$, is taken to be the jet momentum coefficient, recovering an attached flow at a given wing section.

Presented in Fig.8, as an example, are the experimental dependencies of increments in lift coefficient ΔC_L and longitudinal force coefficient ΔC_D due to jet blowing at Mach number M=0.75 and angle-of-attack α=0. The lift coefficient increment grows intensively as the jet coefficient increases (see Fig.8,a). The longitudinal force coefficient increments ΔC_D are negative due to impact of jet reaction (see Fig.8,b).

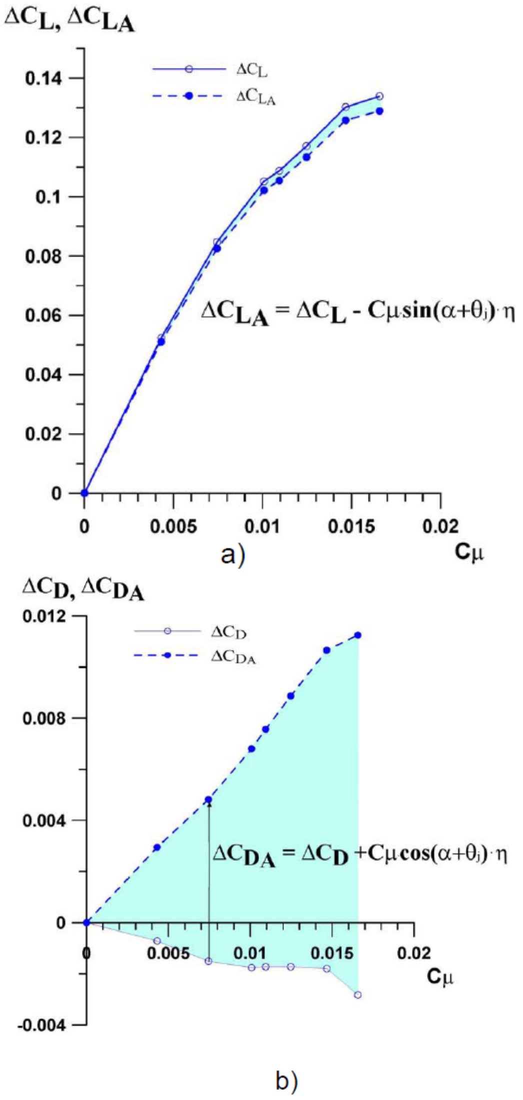

Fig.8. Lift and drag increments due to jet blowing (M=0.75, α=4 deg)

The aerodynamic components of the lift coefficient increments $\Delta C_{L\,A}$ and aerodynamic drag coefficient $\Delta C_{D\,A}$ are defined as differences of total lift and longitudinal force coefficients and coefficients of jet reaction force components:

$$\begin{aligned} \Delta C_{LA} &= \Delta C_L - C\mu \cdot \eta \cdot \sin(\alpha + \theta_j) \\ \Delta C_{DA} &= \Delta C_D + C\mu \cdot \eta \cdot \cos(\alpha + \theta_j) \end{aligned} \tag{2}$$

where θj is an effective angle of jet deflection, η – coefficient of a jet momentum losses (these values are determined by separate tests)

One could see, that the contribution of jet reaction force in lift is not large at zero angle-of-attack (see Fig.8,a), but drag increment $\Delta C_{D\,A}$ increases along with increase of blowing momentum coefficient (see Fig.8,b).

Experiments have shown, that the jet blowing increases the lift coefficient of the wing-fuselage model in the wide range of angles-of-attack (Fig.9,a) and shifts the drag polars left both due to the jet reaction force and improvement of flow over the wing (Fig.9,b).

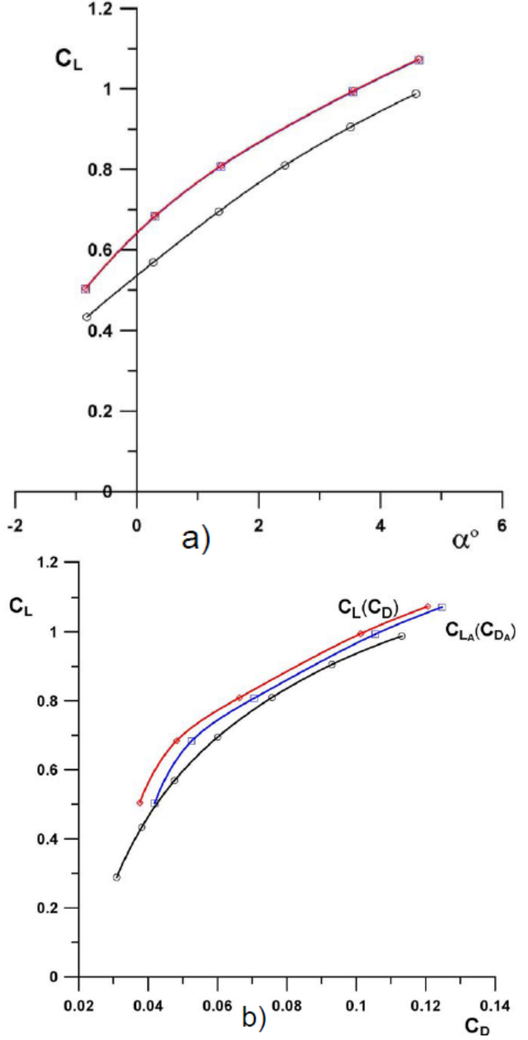

Fig.9. Jet blowing effect on wing fuselage aerodynamic characteristics (M=0.78)

Generally, the improvement of the flow around the wing increases the lift-to-drag ratio of the wing-body model. So, for example, at Mach number M=0.78 the jet blowing of very low intensity (Cμ=0.003÷0.005) increases the maximum lift-to-drag ratio of the wing-body model by $\Delta(L/D)_{max} \approx 1.1$, that is about 9 percent (Fig.10).

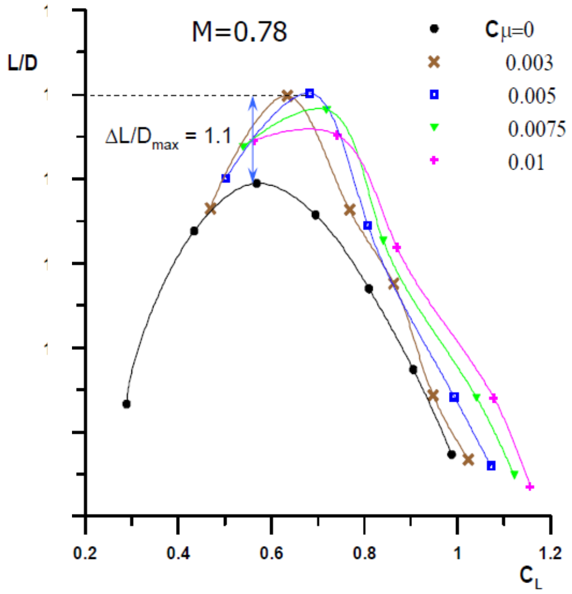

Fig.10.Jet blowing effect on wing-fuselage model lift-to-drag ratio.

So, the experimental data confirms the conclusion about a high effectiveness of tangential jet blowing for suppressing of shock-induced flow separation on the wing at high subsonic flow velocities. A satisfactory agreement of experimental and calculation data confirms that tangential jet blowing is an effective mean of essential improvement of high-speed wings aerodynamics.

4. Estimation of tangential jet blowing effectiveness for improvement of aircraft performance

An aerodynamic layout of a typical subsonic twin engine aircraft equipped with the jet blowing system is shown at Fig.11. Compressed air for jet blowing is tapped from the bypass duct or from the compressor of two turbofan engines. The slot nozzle is located at chordwise distance of 70-75% from the wing leading edge. The selected location of the nozzle can be used both for suppression of shock-induced flow separation and for flow improvement over the plain deflected flaps during the takeoff and landing operations.

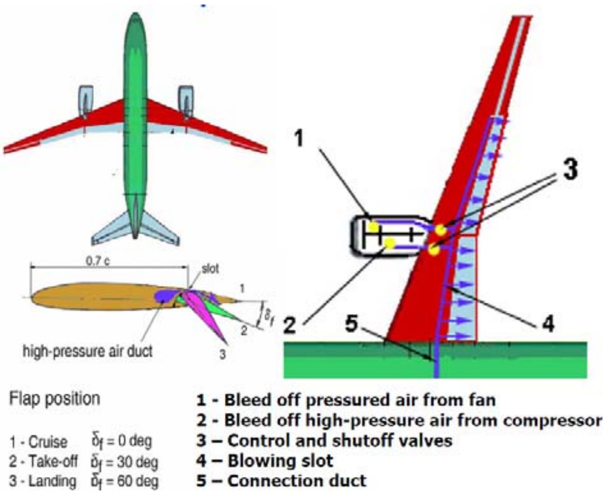

Fig.11. Aircraft with jet blown wing

One of the key problems of incorporation of jet blowing system into an aircraft is the minimization of powerplant thrust losses due to bleed of compressed air from the engines. The assessments of thrust losses of turbofan engine due to air bleed of 1% from behind the fan decreases the engine thrust by 1.5-2%, whereas the air bleed from the compressor increases the engine thrust losses by up to 3-4%. But, it should be noted, that about 70-80% of thrust losses are compensated by the jet blowing reaction. Thus, the total thrust losses of the powerplant in cruise flight may be about 1.2-1.5% with air bleed from behind the fan and 2.5-3.5% with air bleed from the compressor. Estimations performed have shown that the relative weight of blowing system can be about 0.4-0.5% of takeoff weight. However, the replacement of slotted flaps by plain flaps may result in increasing the total aircraft weight only by 0.2-0.3%.

The jet blowing effectiveness at cruise flight was estimated as applied to the aircraft at M=0.78 at different values of relative weight of blowing system and engines thrust losses due to blowing. The use of jet blowing on the plain flaps may decrease the takeoff velocity by 5% and takeoff run by 13% as compared with the traditional aircraft, having slotted flaps. The jet blowing allows decreasing also of the landing speed by 10-15% and landing run by 20-25%, which significantly improves flight safety at these critical regimes.

Summary

A complex of calculation and experimental investigations of the tangential jet blowing over a supercritical high-aspect-ratio low swept wing have shown:

1. The tangential blowing is an effective mean of suppression of shock-induced separation on a swept supercritical wing at high transonic speeds ($M \geq 0.75$). As a result of positive jet effect the lift and lift-to-drag ratio increase significantly. For example, at Mach number of $M=0.78$ the jet blowing with low intensity ($C\mu=0.003$-0.005) increases the maximum lift-to-drag ratio by about 9percents.

2. According to estimations, the jet blowing over a supercritical high aspect ratio ($AR=16$) low swept wing ($\Lambda_{1/4}=20.5$ deg) wing of typical twin engine subsonic aircraft leads to following improvements of characteristics:

- Increase of the maximum lift-to-drag ratio approximately by 8 percents at cruise Mach number $M=0.78$

- Increase of the aircraft flight range by 6-8 % and the fuel savings up to 6-7% (relative tothat for the aircraft without blowing)

- improvement of takeoff/landing performance by blowing over plain non-slotted flaps (decreasing the takeoff run by 10-15 % and landing run by 20-25%)

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