CONTROL OF STRONG SEPARATION OF FLOW VIA SIMULTANEOUS-BLOWING-SUCTION TECHNIQUE

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Abstract

An innovative solution dedicated for an effective control of strong separation of air flow has been proposed. The solution is based on a system of coupled pairs of nozzles located on the surface, where the strong flow separation is forecasted. When such phenomenon appears, in each pair of coupled nozzles a flow is activated, in such a way, that one of the nozzles starts blowing, while the other starts sucking the air from the main flow region. A matrix of such fluidic devices is able to significantly alleviate and even completely eliminate the strong separation of the flow on a given surface. The discussed solution has been investigated and partially optimized based on a computational-simulation approach. Additionally, an innovative idea of a fluidic actuator, feeding the nozzles with both the overpressure and underpressure has been presented.

Nomenclature

C_D	=	drag coefficient
C_F	=	friction coefficient
C_L	=	lift coefficient
C_P	=	pressure coefficient
C_μ	=	blowing momentum coefficient
M	=	Mach number
p_∞	=	reference static pressure
q_∞	=	reference dynamic pressure
Re	=	Reynolds number
S	=	reference area
t	=	time
V	=	flow velocity
V_J	=	jet velocity
V_∞	=	free stream velocity
α	=	angle of attack

1 Introduction

An aerodynamic deep stall is defined as a strongly unsteady phenomenon consisting in significant loss of lift generated by any lifting surface, e.g. an aircraft wing. This phenomenon is very dangerous from the point of view of flight safety, especially since it is accompanied by strong fluctuations of aerodynamic forces and moments. Typically the stall occurs when the wing exceeds its critical angle of attack. In a case of large transport aircraft equipped with Ultra-High-Bypass-Ratio engines, such phenomenon is likely to occur during a landing, in the slat cutout zones of a wing, directly behind a wing-pylon-nacelle junction [11].

The presented studies have aimed at a development of a completely new solution, being able to fight successfully against the deep stall on an aircraft wing, regardless of the reason for this phenomenon.

The solution presented in the paper belongs to a wide family of fluidic devices. It consists of a system of mini-nozzles, blowing the air jets. However, the proposed device is distinguished from others by the fact that the direction of the jets is controlled by a system of nozzles sucking the air from the main flow on the upper surface of the wing. In this case, a successful fight against the deep stall is mainly conditioned by proper shaping of the nozzles and by proper establishing of levels of overpressure and underpressure feeding the blowing and sucking nozzles respectively.

Application of fluidic devices to fight against flow separation is widely documented in scientific literature. One class of such solutions is based on an assumption that deep-stall characteristics of aircraft wing can be substantially improved by resizing separation vortices. To achieve this effect, attempts are made to apply synthetic-jet actuators [2],[3],[4],[6],[7],[10],[11].

Alternative approaches are utilizing a steady or pulse blowing in a tangential or nearly tangential direction to a wing surface [8],[9],[10],[13],[14]. In several solutions, the flow control based on blowing jets is enhanced by the application of a system of slots sucking the air flowing near the wing surface [5],[12].

The presented study has been focused on the following main topics:

- Development of an innovative concept of a fluidic device, being able to alleviate or even eliminate a strong separation of flow on an aircraft wing,
- Computational investigations and partial optimization of the developed system,
- Conceptual studies on the actuator that would be able to feed successfully the developed fluidic device.

2 Research Methodology

The studies have been conducted based on CFD simulations, using the software ANSYS FLUENT. The subject of these simulations has been a rectangular wing of infinite span with truly modelled three-dimensional shapes of blowing and sucking nozzles.

The assumed flow model has been based on 3D URANS (Unsteady Reynolds-Averaged Navier-Stokes) approach, with turbulence model: k-ω SST. The air has been assumed as viscous ideal gas.

The computational mesh has been of high quality, including fine modelling of boundary layer mesh (y+ ~ 1).

The following boundary conditions have been established:

- far away from the wing: "pressure farfield" and "pressure outlet",
- at side boundaries of the flow region: "spanwise periodicity" conditions,
- at inlets of blowing nozzles: "mass flow inlet",
- at outlets of sucking nozzles: "pressure outlet".

3 Concept of the Blowing-Sucking Device

The proposed solution is based on a system of coupled pairs of specially shaped nozzles, located in several rows on the wing surface, which is shown in Fig. 1. When the strong flow separation appears or is forecasted, in each pair of nozzles an air flow is stimulated, in such a way, that front nozzle (marked in red) blows the air, while the rear (marked in blue) sucks the air in an appropriate mass flow rates. The developed system was marked with SBS acronym (Simultaneous Blowing Suction).

In the presented solution three rows of SBS nozzles have been used (see Fig. 1), which was partially resulted from limitations of planned similar experimental investigations. However, the optimal number of rows of SBS nozzles is an open matter and it is planned to be a subject of future investigations.

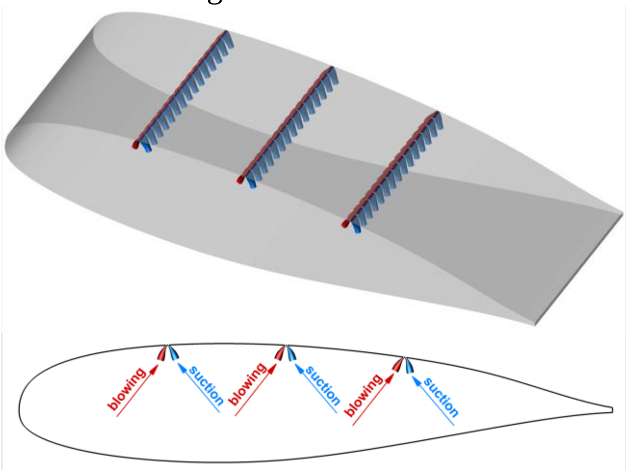

Fig. 1. The general concept of the system of SBS-nozzles.

Effects of activation of the described above SBS system are presented in Fig. 2, where the red-marked part of the wing surface corresponds to the region of flow separation, characterized by the upwind direction of wall-shear-stress vector. In the presented simulation, the deep stall was observed until the time t=2s. At this moment the SBS system was activated. After next 2 seconds, the flow separation completely disappeared.

During the simulation, significant changes of velocity profiles, within the boundary layer, were observed, which is presented in Fig. 3.

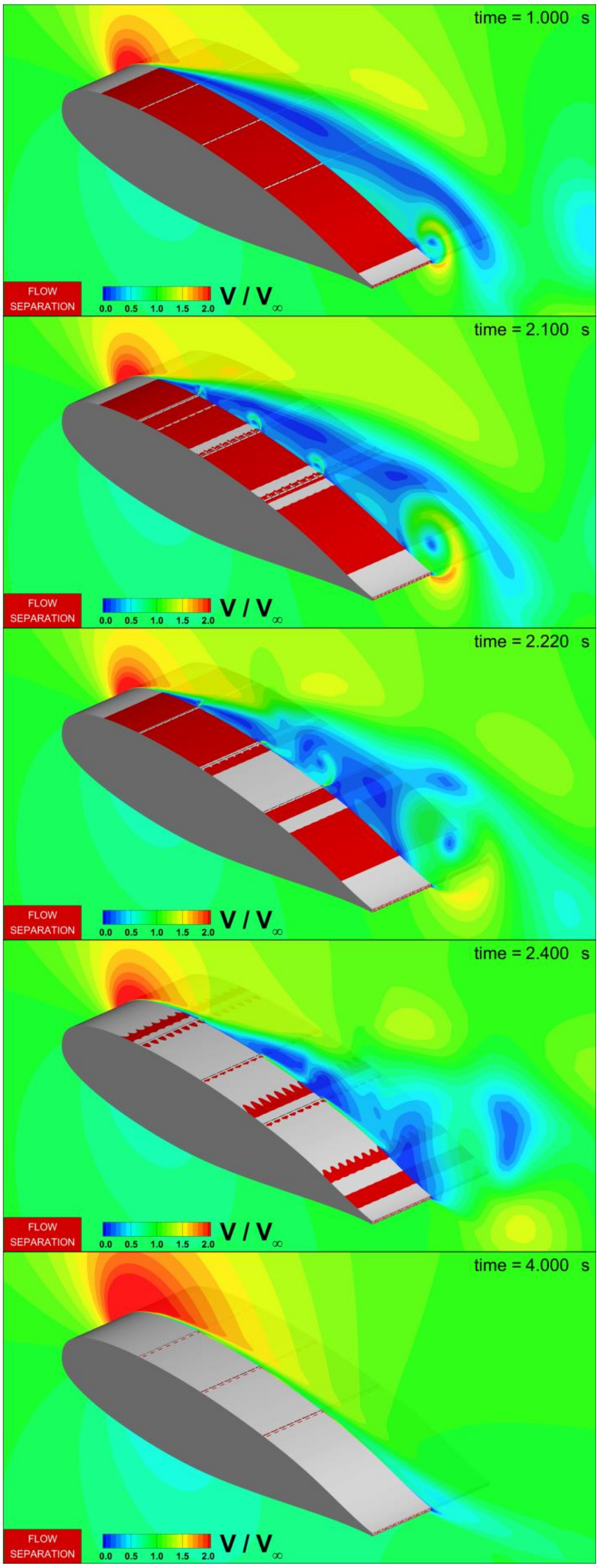

Fig. 2. Sequential stages of an activation of the SBS system. Velocity-magnitude contours in the plane of symmetry of the wing. The flow-separation region on the wing surface marked in red.

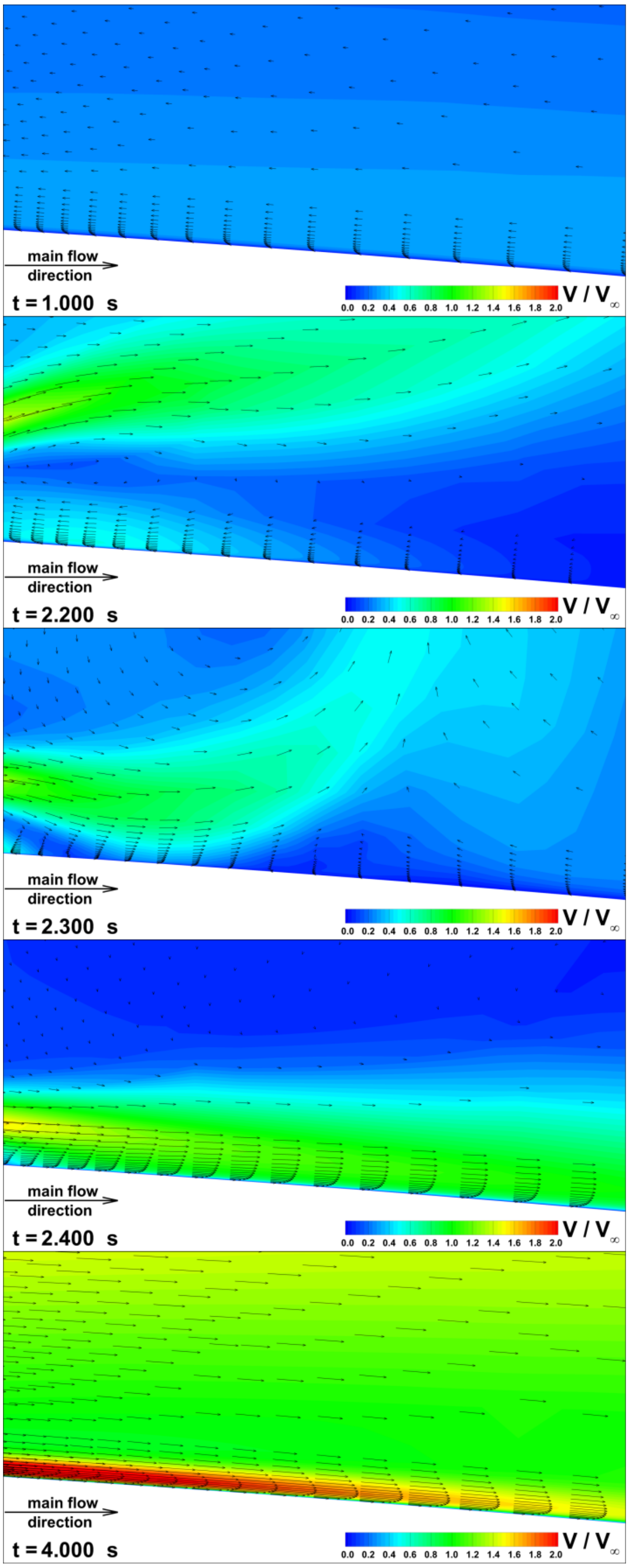

Fig. 3. Sequential stages of an activation of the SBS system. The flow-velocity profiles within the boundary layer, directly behind the SBS nozzles.

Initially, the flow inside the boundary layer had inverse direction in respect to the main flow, which was a symptom of strong separation. After activation of SBS system (at time t=2s), the velocity profiles quickly changed their direction and they became typical for a fully attached flow. Moreover, at time t=4s, significant amplification of boundary-layer momentum by the jets blown from nozzles was observed. This effect was achieved due to directing the jets tangentially to the wing surface, which were the results of appropriate decreasing of pressure in the sucking nozzles.

Fig. 4 shows significant changes in pressure distribution of the wing surface, as an effect of the activation of the SBS system. As an effect of these changes of pressure, a significant growth of lift coefficient was observed which is discussed in details in the next section.

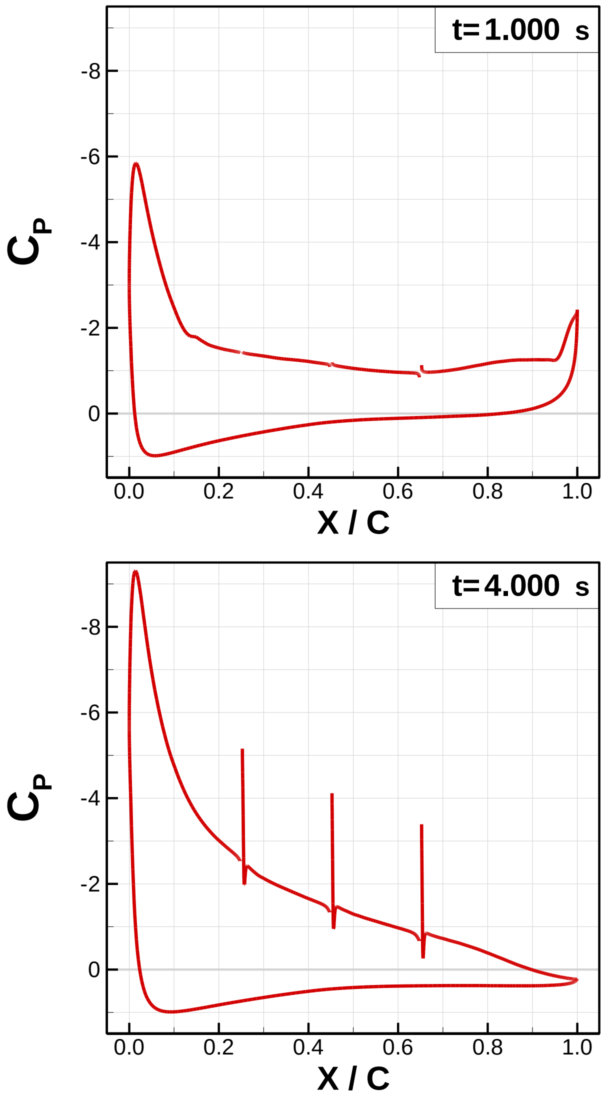

Fig. 4. Chordwise distribution of pressure coefficient (C_P) in a wing cross-section. Upper graph: before activation of SBS system. Lower graph: after activation of SBS system.

4 Results of Computational Simulations

The results presented below, concern the flow around the infinite-rectangular wing, equipped with three rows of pairs of blowing-and-sucking nozzles. The free-stream Mach and Reynolds numbers were: M=0.1 and $Re=1.165\cdot10^6$ respectively. The angle of attack has been set to α=20 deg, because for this angle, the computational results showed a deep-stall phenomenon on the upper surface of the clean wing.

In the conducted simulations, the intensities of the air jets blown from the nozzles have been measured by the blowing momentum coefficient (C_μ) [2] defined as follows:

$$C_\mu = \frac{\dot{m} \cdot V_J}{q_\infty \cdot S} \quad (1)$$

where: $\dot{m}$ - mass flow rate, VJ - jet velocity, q_∞- free-stream dynamic pressure, S - reference area of the wing.

The computational results presented below, concern two independent cases demonstrating the operation of the SBS system, where the maximum intensities of jets blown from the nozzles were: $C_{\mu(max)} \approx 0.0276$ and $C_{\mu(max)} \approx 0.0555$ respectively. During the simulations, a monitoring of flow parameters, started when the system SBS was inactive and the flow was strongly unstable and separated from the wing upper surface. After 2 seconds of monitoring of the strongly separated flow, the SBS system was activated, i.e. the intensities of jets blown from the nozzles were increased quickly to their maximum values, as shown in Fig. 5. Simultaneously, the sucking nozzles were fed by appropriate rates of underpressure. Simultaneously, the sucking nozzles were fed by appropriate levels of underpressure. Values of static pressure set at the sucking nozzle outlets, were presented and analyzed in the non-dimensional form of pressure coefficient (C_P), defined as follows::

$$C_P = \frac{p - p_\infty}{q_\infty} \quad (2)$$

where: p_∞ is a reference (atmospheric) static pressure. Fig. 6 presents exemplary time varying pressure coefficients corresponding to values of static pressure set at inlets and outlets of blowing and sucking nozzles. The presented graphs concern the simulation conducted for a higher maximum intensity of jets blown from the nozzles ($C_{\mu(max)} \approx 0.0555$).

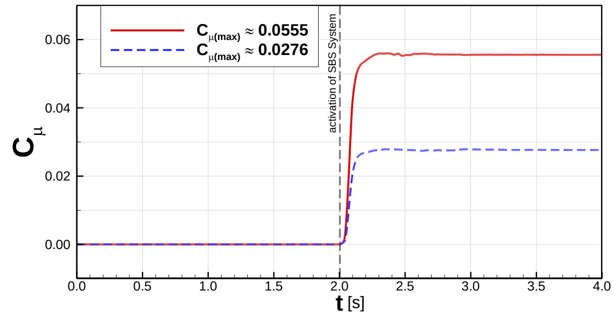

Fig. 5. Time-varying, blowing momentum coefficient (C_μ) describing intensities of jets blown from all blowing nozzles, during two computational simulations demonstrating the efficiency of the SBS system in preventing a strong separation of flow.

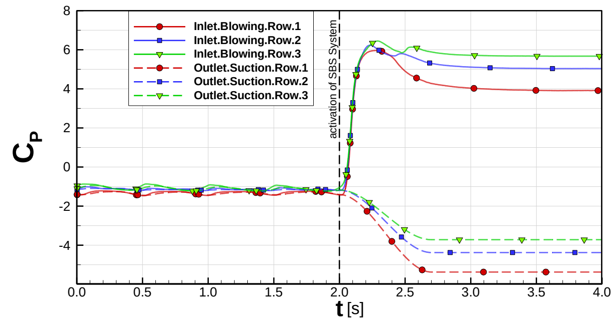

Fig. 6 Time-varying, pressure coefficients corresponding to values of static pressure set at inlets and outlets of blowing and sucking nozzles. Case: $C_{\mu(max)} \approx 0.0555$.

In general, the underpressure feeding the sucking nozzles should ensure a fast attachment to the wing surface of jets blown from the blowing nozzles. Such a process, in computational case $C_{\mu(max)} \approx 0.0555$, is visualized in Fig. 7. At the moment of initiation of the SBS system (t=2.0) the flow near the wing surface has an inverse direction with respect to the main flow. This causes the jets blown from the nozzles to be initially deflected upwind with respect to the main flow. However, the appropriate level of underpressure feeding the sucking nozzles, lead to fast redirection of the jets downwind and their attachment to the wing surface. This phenomenon finally leads to a thorough attachment of flow to the wing surface, which is visualized in the lowest picture in Fig. 7.

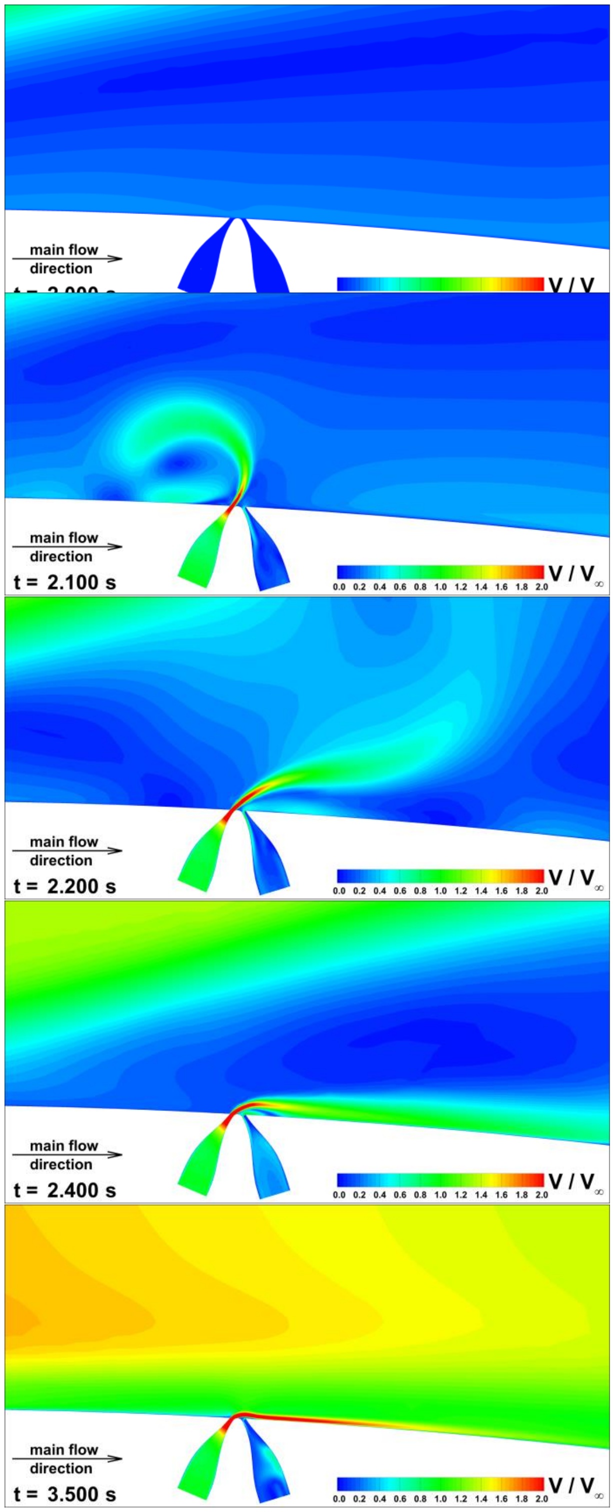

Fig. 7. Sequential stages of activation of the SBS system. Velocity-magnitude contours near the second row of SBS nozzles.

Fig. 8 and Fig. 9 show how the activation of the SBS system affects changes in the wing lift coefficient (C_L) and drag coefficient (C_D). Before the activation of the SBS system, both coefficients indicate strong oscillations, which is a result of a deep stall on the wing. After activation of the SBS system, the oscillations disappear quickly. Simultaneously, the significant growth of the lift coefficient, as well as the drop of the drag coefficient, is observed.

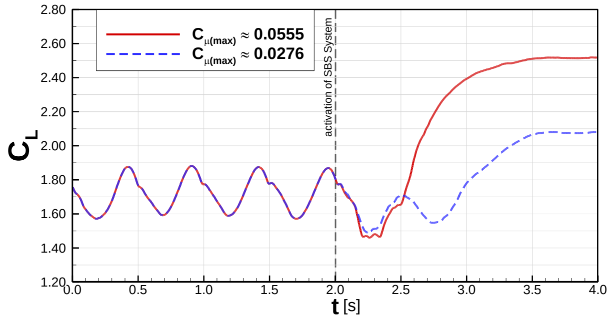

Fig. 8. Time varying lift coefficient (C_L) before and after activation of the SBS system.

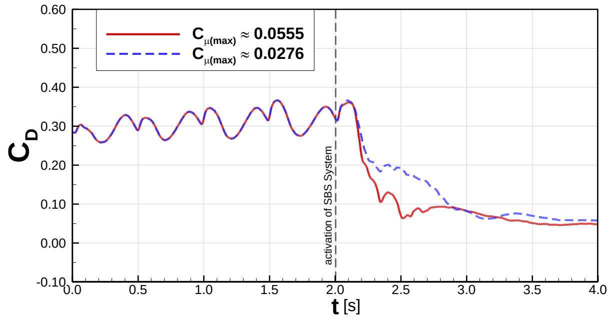

Fig. 9. Time-varying drag coefficient (C_D) before and after activation of the SBS system.

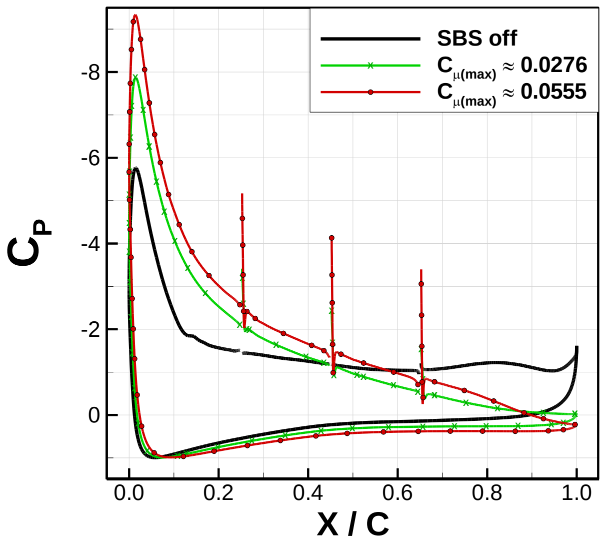

Fig. 10. Comparison of pressure coefficient (C_P) distribution in wing section, for the clean wing (SBS off) and for two cases of blowing-jet intensities: $C_{\mu(max)} \approx 0.0276$ and $C_{\mu(max)} \approx 0.0555$.

The growth of the lift coefficient after activation of the SBS system is especially impressive (approx. 0.8) in the case $C_{\mu(max)} \approx 0.0555$. This effect is partially explained in Fig. 10. The figure compares the pressure coefficient distributions in wing section, for the clean wing (SBS off) and for two cases of blowing-jet intensities: $C_{\mu(max)} \approx 0.0276$ and $C_{\mu(max)} \approx 0.0555$. The differences in pressure distributions on the wing suction side clearly explain the growth of the lift coefficient.

Based on the conducted simulations one can assess the efficiency (η) of the SBS system, defined as follows:

$$\eta = \frac{\Delta C_L}{C_{\mu(max)}} \tag{3}$$

where ΔC_L is the growth of lift coefficient being an effect of activation of SBS system, with an intensity of blowing jets described by the blowing momentum coefficient $C_{\mu(max)}$. This efficiency has been evaluated at:

$\eta \approx 14.1$ for $C_{\mu(max)} \approx 0.0276$
$\eta \approx 14.4$ for $C_{\mu(max)} \approx 0.0555$

Fig. 11 compares distributions of friction coefficient (C_F) in a wing cross-section, for the clean wing (SBS off) and for two cases of the SBS system active, with blowing momentum coefficient maximum values set at $C_{\mu(max)} \approx 0.0276$ and $C_{\mu(max)} \approx 0.0555$.

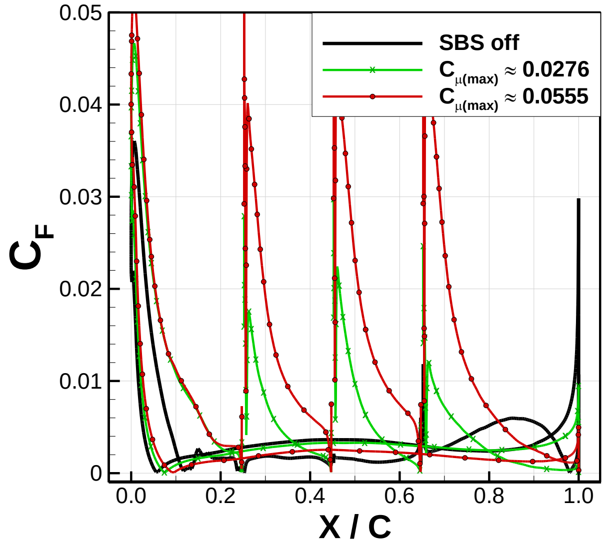

Fig. 11.Comparison of friction coefficient (C_F) distribution in wing section, for the clean wing (SBS off) and for two cases of blowing-jet intensities: $C_{\mu(max)} \approx 0.0276$ and $C_{\mu(max)} \approx 0.0555$.

The C_F distribution for the "SBS off" configuration indicates total flow separation on the upper surface of the wing. The C_F distributions corresponding to the SBS system active, show significant amplification of wall shear stress downstream behind the blowing nozzles. This is a symptom of significant growth of momentum of fluid flowing inside the boundary layer. As the result, this flow stays stable and fully attached to the wing upper surface.

5 Simultaneous-Blowing-Suction Actuator

To solve the problem of effective feeding of the SBS type nozzles described above, by appropriate levels of overpressure and underpressure, the general idea of a device simultaneously blowing and sucking air has been developed. The concept of developed device is presented in Fig. 12.

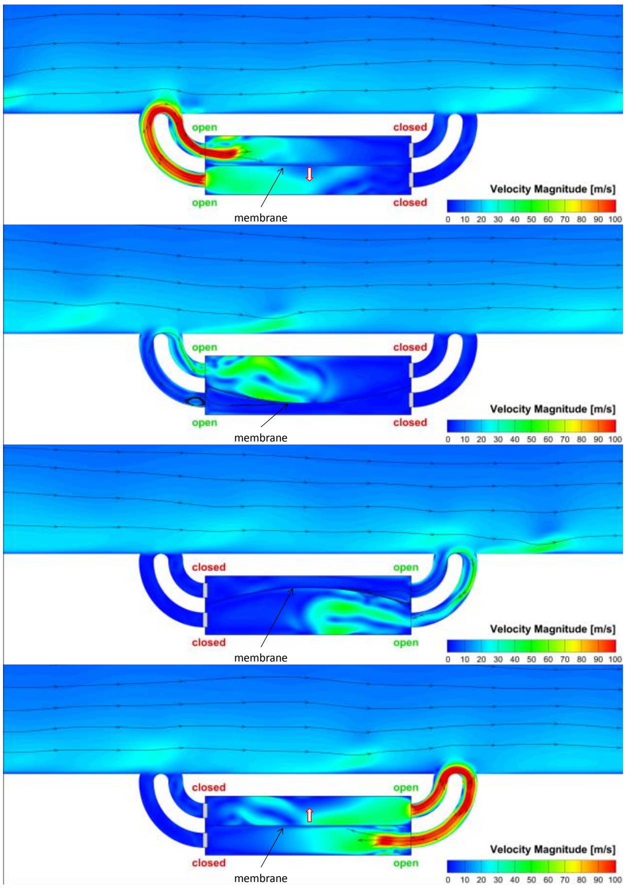

Fig. 12. Sequential stages of work of the proposed simultaneous-blowing-suction actuator.

The device is based on the flow excitation technology commonly used in "synthetic jet" type devices. The flow-inducing element is a membrane moving up and down hundreds of times per second, sucking the surrounding fluid into a chamber and then blowing it outside.

The device is equipped with a system of valves, directing the air stream outwards and inwards the chamber through different ducts, which differs this device from typical synthetic-jet actuators. The synchronization of the valves and the membrane leads to one-directional flow through four ducts connected to the chamber.

The proposed idea needs further research. From the point of view of feeding the SBS nozzles, it is necessary to vary the mass flow of the air blown and sucked from these nozzles. It is also important to optimize the efficiency of the device in question so that it is able to deliver the appropriate mass of compressed air to a single blow nozzle. Research on these issues is in a progress.

Based on conducted preliminary computational simulations, the developed device seems to be very promising and well matched to the described SBS system controlling a strong separation of flow on an aircraft wing.

6 Conclusions

The novel fluidic device, named SBS (Simultaneous Blowing and Suction) has been developed and investigated based on computational simulations.

The SBS system consists of a matrix of coupled pairs of mini nozzles, blowing and sucking an air, located on the suction side of an aircraft wing. The air suction is utilized to direct the air stream blown from the blowing nozzles tangentially to the wing surface, which effectively enhances the momentum of a fluid flowing inside the boundary layer and may lead to alleviation or even suppression of the flow separation.

The SBS system seems to be a very promising solution as a means to fight against unfavourable effects of deep-stall.

The SBS system has been developed so far at low Technology Readiness Level. Future research will focus on both the optimisation of geometric aspects of the SBS system (geometry of nozzles, their number and chordwise distribution on the wing surface) as well as optimisation of the strategy of feeding the nozzles by the overpressure and underpressure.

Separate development and optimisation studies are planned with respect to the presented in the paper unconventional and very promising actuator feeding the SBS system with an appropriate level of overpressure and underpressure.

References

[1] ANSYS FLUENT User's Guide. Release 15.0, ANSYS, Inc., November 2013. Available from: http://www.ansys.com

[2] Goodfellow, S.D., Yarusevych, S., Sullivan, P.E., "Momentum Coefficient as a Parameter for Aerodynamic Flow Control with Synthetic Jets", AIAA Journal, Vol. 51, 2013, pp. 623, 631.

[3] Greenblatt, D., Wygnanski I.J., "The control of flow separation by periodic excitation", Progress in Aerospace Sciences, Vol. 36, 2000, pp. 487, 545.

[4] Greenblatt, D., Nishri, B., Darabi, A., Wygnanski, I.J., "Dynamic stall control by periodic excitation, Part 2: Mechanisms", Journal of Aircraft, Vol. 38, 2001, pp. 439, 447.

[5] Hamdani, H., Sun, M., "Separation Control by Alternating Tangential Blowing/Suction at Multiple Slots", AIAA Journal Vol. 39, 2001, pp. 735, 737.

[6] Hassan, A.A., "Oscillatory and pulsed jets for improved airfoil aerodynamics – a numerical simulation", 42nd AIAA Aerospace Sciences Meeting and Exhibit, AIAA paper 2004-0227, Reno, NV; United States, January 2004.

[7] Huang, L., Huang, P.G., LeBeau, R.P., Hauser, Th., "Numerical Study of Blowing and Suction Control Mechanism on NACA 0012 Airfoil", Journal of Aircraft, Vol. 41, 2004, pp. 1005, 1013.

[8] Hue, D., François, C., Dandois, J., Gebhardt, A., "Simulations of an aircraft with constant and pulsed blowing flow control at the engine/wing junction", Aerospace Science and Technology, Vol. 69, 2017, pp. 659, 673.

[9] Khodayar, J., K., Hajipour, M., "Separation control using quasi-radial wall jets", Aerospace Science and Technology, Vol. 68, 2017, pp. 240, 251.

[10] Kim, S.H., Kim, C., "Separation Control on NACA23012 Using Synthetic Jet", Aerospace Science and Technology, Vol. 13, 2009, pp.172, 182.

[11] Schloesser P., Meyer M., Schueller M., Weigel P., Fluidic actuators for separation control at the engine/wing junction, Aircraft Engineering and Aerospace Technology, Volume 89, Issue 5, Emerald Publishing Limited 2017.

[12] Soudakov, V., Amiryants, G., Schloesser, P., Bauer, M., Weigel, P., Bardet, M., Ciobaca, V., Gebhardt, A., Wild, J., "Full-Scale Wind-Tunnel Test of Active Flow Control at the Wing/Pylon/Engine Junction", Aerospace Europe 6th CEAS Conference, Bucharest, Romania, October 2017.

[13] Sun, M., Sheikh, S. R., "Dynamic stall suppression on an oscillating airfoil by steady and unsteady tangential blowing", Aerospace Science and Technology, Vol. 3, 1999, pp.355, 366.

[14] Zhou P., Wang Y., Wang J., Sha Y., Blowing momentum and duty cycle effect on aerodynamic performance of flap by pulsed blowing, Journal of Physics Conference Series 822 (2017) 012052.

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