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Control of Flow Separation Using Self-Supplying Air-Jet Vortex Generators

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Wind-tunnel experimental investigations were conducted to investigate the use of conventional outsupplying and proposed self-supplying air-jet vortex generators to delay flow separation over an NACA 0012 airfoil. The conventional air-jet vortex generators were supplied with the air from an external compressor, and proposed self-supplying generators got the air from the overpressure region situated in the nose part of the airfoil lower surface. The lift, drag, and pitching moment for the smooth airfoil equipped with air-jet vortex generators were determined based on the pressure distribution measurements. The experimental tests were carried out in both the low-speed wind tunnel ($M = 0.05$–0.1) with the airfoil model of 0.5-m chord length and the high-speed wind tunnel ($M = 0.1$–0.85) with the airfoil model of 0.18-m chord length. In the high-speed wind tunnel, the influence of using only the self-supplying air-jet vortex generators was tested. It was found that using both types of air vortex generators can delay the flow separation on the airfoil, which leads to the increase of both the lift coefficient and the critical angle of attack.

Nomenclature

a	=	length of the nozzle outlet sectional
b	=	width of the nozzle outlet sectional
C_D	=	drag coefficient
C_L	=	lift coefficient
$C_{L\max}$	=	maximum-lift coefficient
C_m	=	moment coefficient
C_p	=	pressure coefficient
Cx	=	drag coefficient
c	=	airfoil chord
M	=	Mach number
$\dot{m}$	=	mass-flow rate
Vj	=	jet velocity at the air-jet vortex generator exit
VR	=	ratio of mean jet velocity to mean freestream velocity
$V\infty$	=	freestream velocity
x	=	distance along the chord from the leading edge
α	=	airfoil angle of attack
α_{cr}	=	critical airfoil angle of attack
Φ	=	pitch angle
Ψ	=	skew angle

I. Introduction

THE control of flow is one of the future areas of interest in fluid mechanics that is investigated extensively in many research centers. During the last few years, a lot of emphasis has been placed on the development of active control methods. One such method is based on the use of air-jet vortex generators (AJVGs). In this flow control method, the interaction between the air jets and the freestream flow changes the structure of the flow, creating well-organized vortical structures that may be used to alleviate boundary-layer separation.

The concept of using AJVGs for boundary-layer control on an airfoil has been known for a long time. This idea was originally proposed in the beginning of the 1960s by Wallis [1] and Wallis and Stuart [2]. It was found that in many cases, the conventional vane vortex generators could be successfully replaced by the air-jet vortex generators for boundary-layer control because of the ease of control accompanied by a minimal drag penalty. However, the complexity of the installation of AJVGs in comparison with the simplicity of the vane vortex generators has limited the practical usage of AJVGs. Furthermore, experimental tests performed by several researchers [3–7] showed that identification of the optimum air-jet configuration was not simple and needed careful study, because the effectiveness of air-jet vortex generators depended on a number of parameters, such as 1) the pitch and skew angles, 2) the jet mass-flow rate, 3) the ratio of boundary-layer thickness to the jet diameter, 4) the jet Reynolds number, and 5) the ratio of mean jet velocity to mean freestream velocity.

The most important conclusions resulting from previous works were aimed at identifying the optimum jet parameters (see [8,9]); furthermore, the results of experimental works aimed at explaining the physical process of vortex formation were presented in [7]. For optimal results, a strong and persistent vortex should be created at the jet pitch angle Φ of about 30 deg and a jet skew angle Ψ of about 60 deg. Also, the peak vorticity (the value at the center of the core) rises linearly with an increase of the jet nozzle diameter and the velocity ratio (VR).

The main aim of this paper is, based on the results of previous works, to suggest a novel simpler solution to AJVGs (namely, self-supplying air-jet vortex generators) and to prove their usefulness experimentally. In the first part of the paper, the influence of some chosen AJVG parameters on the aerodynamic characteristics of a NACA 0012 airfoil equipped with conventional air-jet vortex generators is presented. The methodology and the equipment used in the experimental measurements and sample results are described next. The results of experimental tests of aerodynamic characteristics of the NACA 0012 airfoil equipped with the proposed self-supplying air-jet vortex generators are presented in detail.

II. Experimental Setup and Instrumentation

A. Wind Tunnels

The experimental tests were performed both in a low-speed wind tunnel T-1 and a trisonic wind tunnel N-3 at the Institute of Aviation in Warsaw, Poland. In the high-speed wind tunnel N-3, the influence of using only the self-supplying air-jet vortex generators was investigated. The low-speed wind tunnel T-1 is a closed-circuit continuous-flow wind tunnel with a 1.5-m-diam open test section. The controlled range of freestream velocity is 15–40 m/s.

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The N-3 wind tunnel is a blowdown type, with partial recirculation of the flow, equipped with the closed test section (0.6 × 0.6 m). It can operate in subsonic, transonic, and supersonic flow regimes at Mach numbers $M = 0.2 \div 1.2$, 1.5, and 2.3.

B. Airfoil Models

The model of the NACA 0012 airfoil used in the experimental tests in the low-speed wind tunnel T-1 had a chord of 0.5 m and a span of 1 m. It was made of composite materials. The model was mounted vertically in the working section between two stationary end plates (Fig. 1).

The steel model of the NACA 0012 airfoil used in the investigation in the high-speed wind tunnel N-3 had a chord of 0.18 m and a span of 0.6 m. The model was mounted horizontally between walls of the wind-tunnel test section (Fig. 2).

Both models were equipped with removable skin panels fastened to the model's upper airfoil surface. On the surface of the each skin panel, 10 air-jet vortex generator nozzles were glued. In accordance with the recommendations presented in [6,7], the nozzles were located at the same distance from the leading edge, $x/c = 0.12$, and spaced at the intervals of $0.11c$ along the airfoil span (see Fig. 3). The nozzles' outlet had a rectangular geometric shape with rounded corners. The conventional air-jet vortex generators were supplied with the air from two compressors of a total flow rate of 800 liter/ min.

Both models were equipped with measuring orifices situated along the chord (in the middle of theirs span) to measure the pressure distributions. The wake rakes made possible the measurement of the pressure distributions in the wake of the airfoil models.

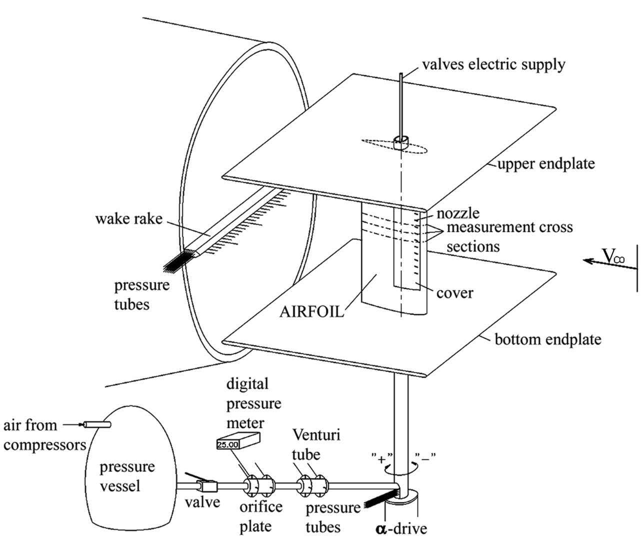

Fig. 1 Schematic drawing of the low-speed wind-tunnel test stand.

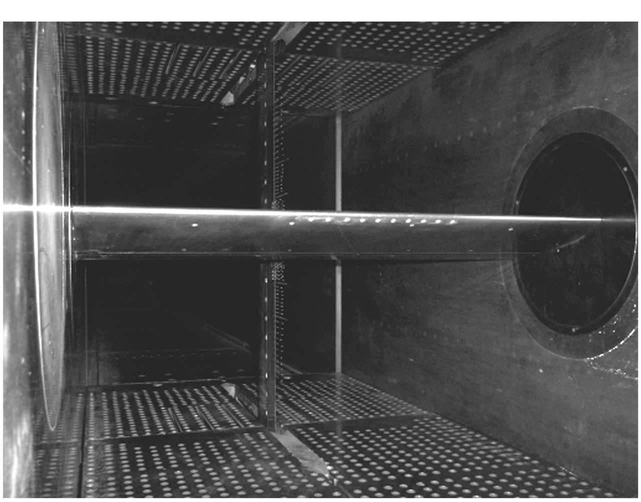

Fig. 2 Model of the airfoil in the high-speed wind tunnel N-3.

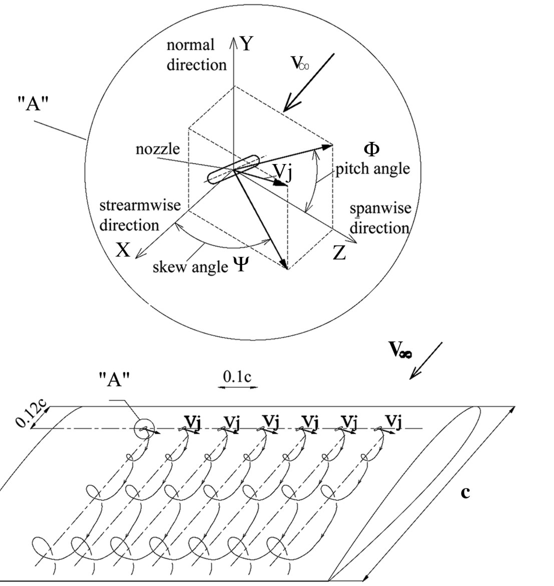

Fig. 3 Location of air-jet vortex generator nozzles on the airfoil upper surface.

III. Idea of Self-Supplying Air-Jet Vortex Generators

The idea of using conventional air-jet vortex generators for boundary-layer control on airfoil is usually based on the principle of supplying air from the turbine engine compressor or from any auxiliary compressors. The complexity of such installation has limited the practical usage of AJVGs. In this paper, it is proposed to use the airfoil overpressure regions as a source of the air for the AJVGs. The rest of the air-jet vortex generator system (i.e., the shape and location of the nozzles on the upper airfoil surface) remain unchanged, as in the conventional one. This idea has been called *self-supplying air-jet vortex generators* and is presented in Fig. 4.

The self-supplying air-jet vortex generators consist of a number of nozzles with outlets situated on the upper surface of the airfoil and the pneumatic pipes supply the nozzles with air. The inlets of these pneumatic pipes are situated in the nose part of the lower airfoil surface. The inlet axes cross the outline of the lower airfoil surface as close as possible to the flow stagnation points for circumcritical angles of attack and are positioned parallel to the airstream's direction in these points. At the higher angles of attack in the nose part of the lower airfoil surface, the overpressure region is formed. The difference of the pressure between the lower and upper airfoil surfaces forces the airflow through the pneumatic pipe connecting the inlet to the nozzle (in the presented investigation, the pipes had constant diameter). The location of the inlet axis close to the flow stagnation points makes the self-supplying air-jet vortex generators more effective. The air jets flowing out from a number of nozzles with certain velocity Vj, similar to the conventional air-jet vortex generators, interact with the freestream flow, forming vortices on the upper airfoil surface. The self-supplying air-jet vortex generators are characterized by the fact that they remain inactive at low angles of attack and only become active at the higher angles of attack, close to

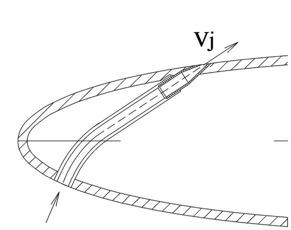

Fig. 4 Concept of self-supplying air-jet vortex generators.

Table 1 Test conditions for conventional air-jet vortex generators in the low-speed wind tunnel T-1

Parameter	Value	Measurement uncertainty
Mach number M	0.05, 0.075, 0.1	0.003
Reynolds number Re	$0.6\,10^6$ ($M = 0.05$) $1.1\,10^6$ ($M = 0.1$)	——
Nozzle dimensions	5.6×1.1 mm	0.05 mm
Airfoil angle of attack α[a]	-2.7 deg |21.7 deg	0.1 deg
Jet pitch angle Φ	20, 30 deg	1 deg
Jet skew angle Ψ	30, 60, 75 deg	1 deg
VR	$1.2 \div 4.6$	0.2
Jet mass-flow rate	$10^{-4} \div 10^{-3}$ kg/s	$1 \div 5\,10^{-5}$ kg/s

[a]With wind-tunnel corrections.

Table 2 Test conditions for self-supplying air-jet vortex generators in the low and high-speed wind tunnels

Parameter	Value	Measurement uncertainty
Mach number M	$0.05 \div 0.85$	0.003
Reynolds number Re	$0.6\,10^6$ ($M = 0.05$) $2.6\,10^6$ ($M = 0.85$)	
Nozzles dimensions: low-speed wind tunnel	7.2×1.2 mm	0.05 mm
Nozzles dimensions: high-speed wind tunnel	3×0.6 mm	0.03 mm
Airfoil angle of attack α[a]	-2.7 deg |21.7 deg	0.1 deg
Jet pitch angle Φ	20, 30 deg	1 deg
Jet skew angle Ψ	30, 60, 75 deg	1 deg
VR[b]	1.6	0.1
Jet mass-flow rate[b]	$2.1\,10^{-4}$ kg/s	10^{-5} kg/s

[a]With the wind-tunnel corrections.
[b]Numerical calculations at $M = 0.05$ and $\alpha = 14$ deg.

critical values, as a result of the greater pressure difference between the upper and the lower airfoil surfaces in the nose region.

IV. Experimental Uncertainties

The following are estimates of the experimental uncertainties. The angle of attack of the airfoil model is determined to within ± 0.1 deg in low-speed wind tunnel T-1 and ± 0.02 deg in high-speed wind tunnel N-3. The pressure is accurate to within ± 0.01 kPa in the range of Mach numbers $M = 0.05 \div 0.1$ and ± 0.1 kPa in the range of Mach numbers $M \geq 0.2$. The experimental uncertainties of aerodynamic coefficients are the following: lift ± 0.01, drag ± 0.002, and pitching moment ± 0.001.

V. Results and Discussion

A. Conditions of the Tests

In Tables 1 and 2 the test conditions for the experimental investigation of control of flow separation on the airfoil with conventional and self-supplying air-jet vortex generators are given.

B. Sample Test Results of Conventional Air-Jet Vortex Generators

The tests of the NACA 0012 airfoil with a conventional air-jet vortex generator were performed in the low-speed wind tunnel T-1 in the range of Mach numbers $M = 0.05 \div 0.1$ (which correspond to $V\infty = 18.3 \div 34.4$ m/s). The lift C_L and the moment C_m coefficients were calculated by integrating pressure distributions along the airfoil chord, and the C_D coefficient was calculated by integrating pressure distribution along the wake rake. For pressure integration, the trapezoidal rule was used. The sample result of the pressure distribution along the airfoil chord is presented in Fig. 5.

To estimate the influence of the air-jet velocity Vj on the lift coefficient C_L, the measurements of the NACA 0012 airfoil characteristics for various mass-flow rates through the nozzles were carried out. During these tests, the mass-flow rate was controlled by a valve in the range $\dot{m} = 4.6 \times 10^{-4}$–$11.7 \times 10^{-4}$ kg/s for each nozzle (corresponding to $Vj = 57$–112 m/s). To achieve a mass-flow rate $\dot{m} > 8 \times 10^{-4}$, it was necessary to stop the flow through two external nozzles (eight nozzles were used), and for mass-flow rate $\dot{m} > 11 \times 10^{-4}$, it was necessary to stop the flow through two additional nozzles (only six nozzles were used). Stopping the flow through the nozzles was realized by electromagnetic valves. In Fig. 6, the lift coefficient versus angle of attack for different jet velocities Vj and Mach numbers $M = 0.05$ ($V\infty = 18,3$ m/s), 0.075 ($V\infty = 25.8$ m/s), and 0.1 ($V\infty = 34.4$ m/s) are shown.

From the analysis of these results, it can be concluded that use of the air-jet vortex generators on the NACA 0012 airfoil causes an increase of the maximum-lift coefficient and an increase of the value of critical angle of attack. For the preceding test conditions (i.e., $M = 0.05 \div 0.1$, $\Psi = 60$ deg, and $\Phi = 30$ deg) the highest increase of these values was achieved for the range of velocity ratio $\mathrm{VR} = 2.7 \div 3.9$. Among the Mach numbers tested in the low-speed wind tunnel T-1, the highest rise of the lift coefficient ($\Delta C_{L\,\max} \approx 0.2$), due to use of the air-jet vortex generators, occurred at $M = 0.05$ (VR = 2.7). Simultaneously, the increase of critical angle of attack at about $\Delta\alpha_{\mathrm{cr}} = 2$ deg was achieved.

In Figs. 7 and 8 the influence of skew angle and pitch angle on the lift coefficient at Mach number $M = 0.075$ ($V\infty = 25.8$ m/s) is presented. The measurements were performed at the mass-flow rate $\dot{m} = 6 \times 10^{-4}$ kg/s (corresponding to $Vj \approx 71$ m/s) ,at skew angles $\Psi = 30$, 60, and 75 deg, and at pitch angles $\Phi = 20$ and 30 deg.

Test results suggest that a strong and persistent vortex is created at the jet pitch angle Φ of about 30 deg and the jet skew angle Ψ of about 60 deg, which has an effect on the increase of the lift coefficient and the increase of the critical angle of attack.

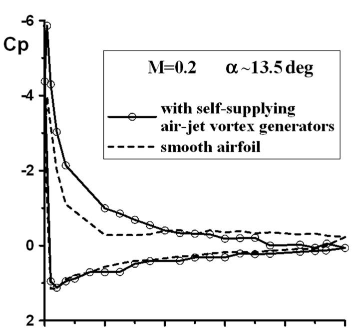

Fig. 5 Influence of the self-supplying air-jet vortex generators on pressure distribution along the airfoil chord.

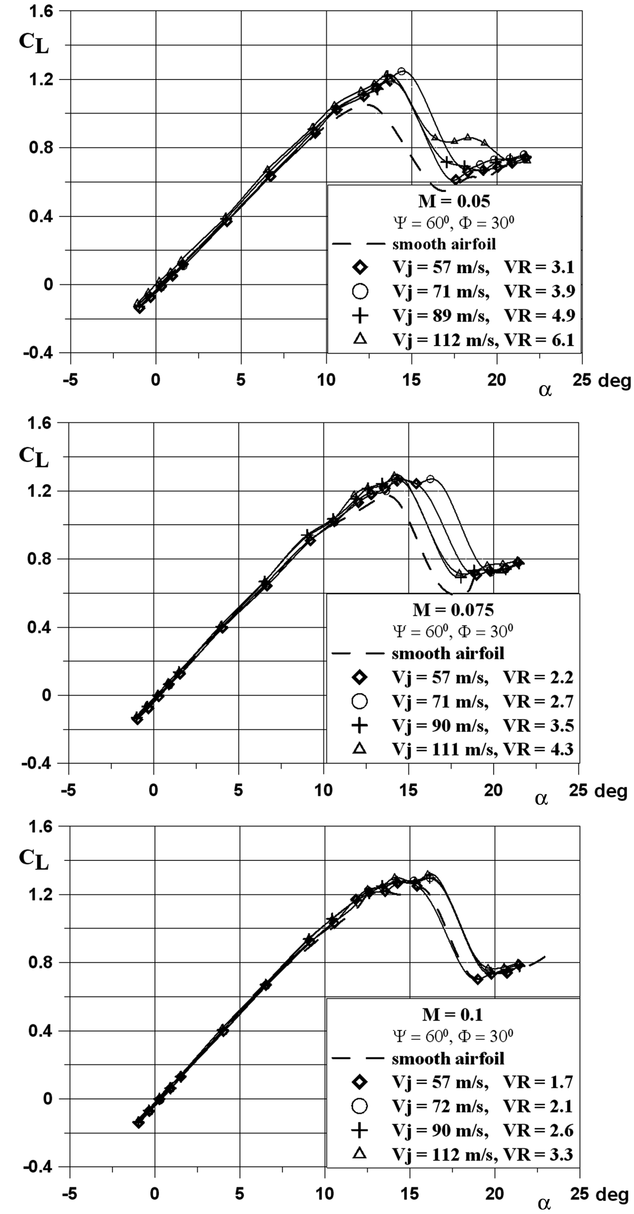

Fig. 6 Lift vs angle of attack for different jet velocities at $M = 0.05$ ($V\infty = 18.3$ m/s), $M = 0.075$ ($V\infty = 25.8$ m/s) and $M = 0.1$ ($V\infty = 34.4$ m/s).

The forming of the vortices on the upper airfoil surface due to the use of the air-jet vortex generators does not generally change the value of the drag coefficient in the range of low angles of attack (Fig. 9). The delay of the flow separation connected with the

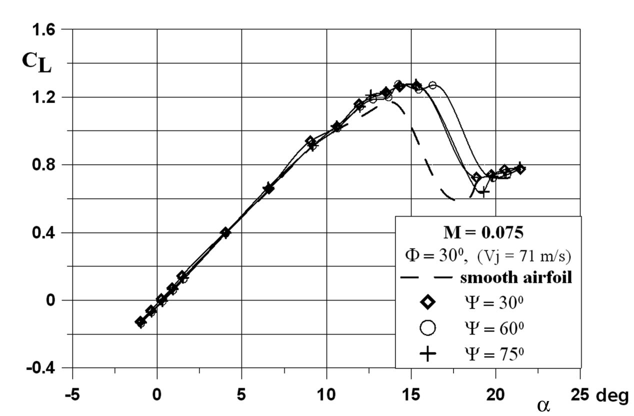

Fig. 7 Lift vs angle of attack for different skew angles at $M = 0.075$ ($V\infty = 25.8$ m/s).

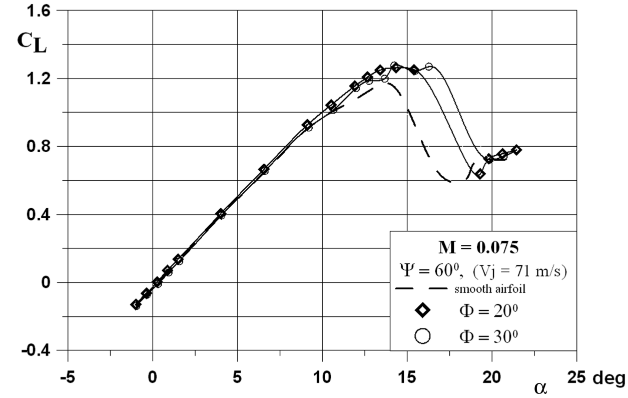

Fig. 8 Lift vs angle of attack for different pitch angles at $M = 0.075$ ($V\infty = 25.8$ m/s).

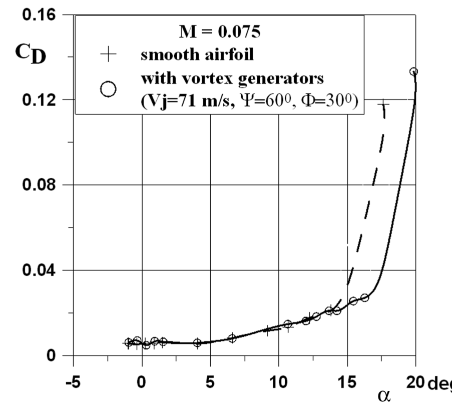

Fig. 9 Influence of the air-jet vortex generators on drag coefficient vs angle of attack at $M = 0.075$ ($V\infty = 25.8$ m/s).

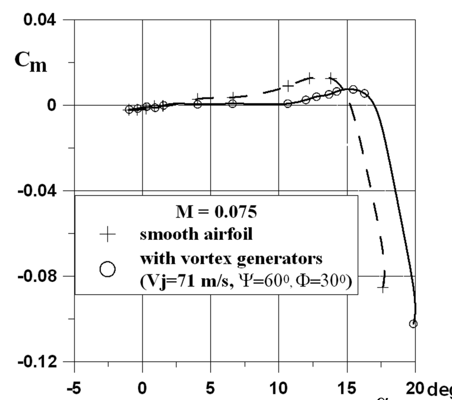

Fig. 10 The influence of the air-jet vortex generators on pitch moment coefficient vs angle of attack at $M = 0.075$ ($V\infty = 25.8$ m/s).

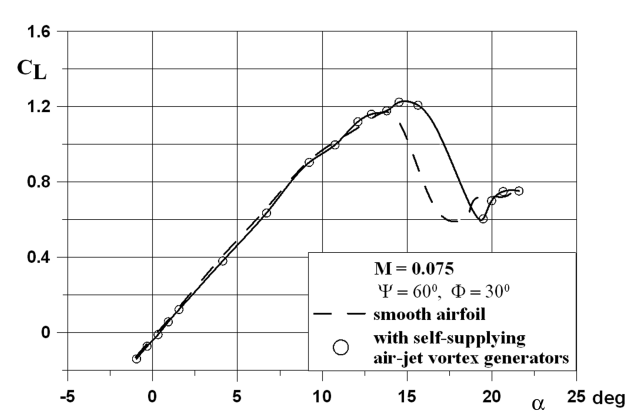

Fig. 11 Influence of the self-supplying air-jet vortex generators on lift coefficient vs angle of attack at $M = 0.075$ (low-speed wind tunnel).

phenomenon of the increase of the critical angle of attack causes the decrease in the drag coefficient in this region of the critical angles of attack in comparison with the smooth airfoil.

In Fig. 10, the influence of air-jet vortex generators on the pitch moment coefficient of the NACA 0012 airfoil at $M = 0.75$ is presented.

Generally, it can be said that in the less-than-critical range of the airfoil angles of attack, the vortices formed on the upper airfoil surface move the pressure center toward airfoil trailing edge. It is a result of the certain pressure decrease in the middle of the upper airfoil surface. In consequence, it causes a slight diminishing of the $\delta C_m/\delta\alpha$ derivative (e.g., from $\delta C_m/\delta\alpha \approx 0.06$ to 0.025 for the NACA 0012 airfoil at $M = 0.075$).

C. Sample Test Results of Self-Supplying Air-Jet Vortex Generators

The tests of the NACA 0012 airfoil with the self-supplying air-jet vortex generator were performed in both the low-speed wind tunnel T-1, in the range of Mach numbers $M = 0.05 \div 0.1$ (which correspond to $V\infty = 18.3 \div 34.4$ m/s), and the high-speed wind tunnel N-3, in the range of Mach numbers $M = 0.2 \div 0.85$. In Figs. 11 and 12, the influence of the self-supplying air-jet vortex generators on the lift coefficient vs angle of attack at $M = 0.075$, 0.2, 0.3, and 0.4 is presented.

From the analysis of the preceding results, it can be concluded that the use of the proposed self-supplying air-jet vortex generators on the NACA 0012 airfoil may be as useful as the conventional air-jet vortex generators and is technically significantly simpler. The self-supplying air-jet vortex generators provide an increase of the maximum of lift coefficient and a increase of the critical angle of attack at the wide range of Mach numbers (up to $M = 0.4$ at the test condition presented in this work). For the higher Mach numbers (i.e., $M = 0.5 \div 0.85$), the influence of these vortex generators on the aerodynamic characteristics of the NACA 0012 airfoil deteriorates significantly. Although the effectiveness of the self-supplying air-jet vortex generators (measured as a increase of $C_{L\max}$ and α_{cr}) is less than conventional ones, the advantages of their use are clear.

At the lower Mach numbers (up to $M = 0.3$) and low angles of attack, the self-supplying air-jet vortex generators cause a minimal increase of drag coefficient ($\Delta Cd = 0.001 \div 0.0015$) (Fig. 13). At the higher Mach numbers, this drag coefficient increase is a little greater (e.g., $\Delta Cd = 0.003$ for $M = 0.7$).

In Fig. 14, the influence of self-supplying air-jet vortex generators on the pitch moment coefficient of the NACA 0012 airfoil at $M = 0.075$ is presented. The forming of the vortices on the upper airfoil surface causes the slight diminishing of the $\delta C_L/\delta\alpha$ derivative, similar to the case of the conventional air-jet vortex generators.

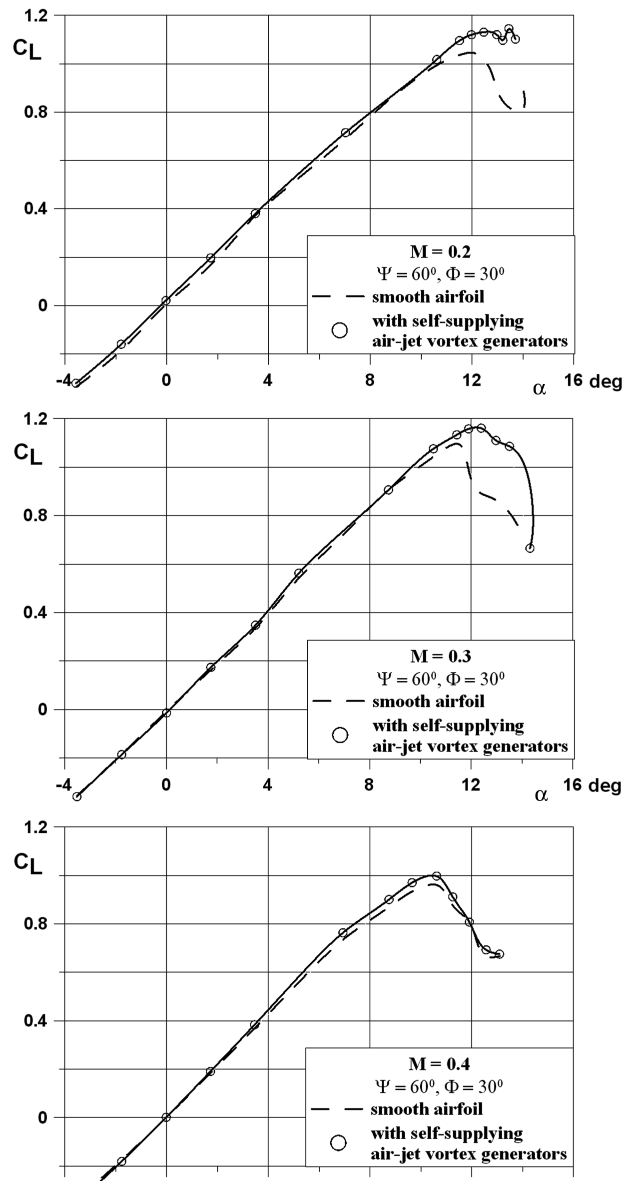

Fig. 12 Influence of the self-supplying air-jet vortex generators on lift coefficient vs angle of attack at $M = 0.2$, 0.3 and 0.4 (high-speed wind tunnel).

VI. Conclusions

The results of the experimental measurements of aerodynamic characteristics of the NACA 0012 airfoil with the conventional air-jet vortex generators and proposed idea of the self-supplying air-jet vortex generators are presented. These results show that air-jet vortex generators are able to delay the flow separation, which, in consequence, leads to the increase of the critical angle of attack and

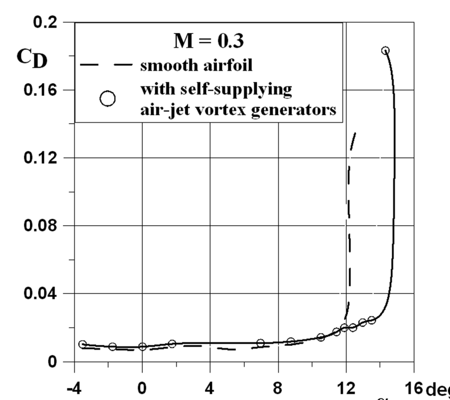

Fig. 13 Influence of the self-supplying air-jet vortex generators on drag coefficient vs angle of attack at $M = 0.3$.

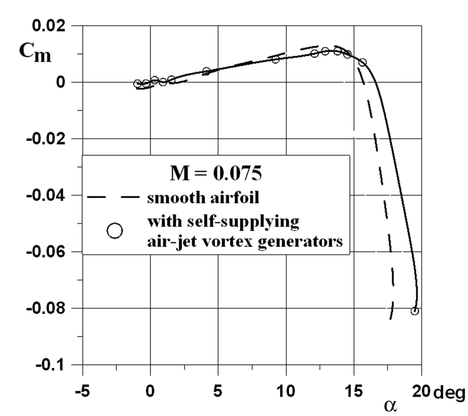

Fig. 14 Influence of the self-supplying air-jet vortex generators on pitch moment coefficient vs angle of attack at $M = 0.075$.

lift coefficient. Furthermore, experimental tests performed for the different values of the air-jet vortex generators parameters suggest that the highest effectiveness (i.e., increase of lift coefficient and increase of critical angle of attack) of air-jet vortex generators should be achieved at the jet skew angle Ψ of about 60 deg and the jet pitch angle Φ of about 30 deg, as per previous references.

The wind-tunnel investigation showed that the proposed self-supplying air-jet vortex generators may be a viable alternative to conventional ones, because they may also cause the delay of flow separation. In this concept, the air-jet vortex generators are supplied with air from the overpressure region situated in the nose part of the airfoil lower surface. Although the effectiveness of the self-supplying air-jet vortex generators is less than the conventional ones, the advantages of their use seems to be interesting, especially because of the simplicity of their manufacture.

Acknowledgment

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