HELICOPTER RETREATING BLADE STALL CONTROL USING SELF-SUPPLYING AIR JET VORTEX

Andrzej Krzysiak
Institute of Aviation, Warsaw, Poland
andkrzys@ilot.edu.pl

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Abstract

The dynamic stall which may appear on retreating helicopter blade due to attain high angles of attack is an relevant limitation of its performance. Various methods to avoid or delay retreating blade stall, including flow control technology, are being explored. The work presents the results of experimental wind tunnel tests of using self-supplying air jet vortex generators to delay dynamic stall. In comparison with the conventional air-jet vortex generators, which are supplied with the air from an external compressor, the proposed self-supplying generators got the air from the overpressure region situated in the nose part of the airfoil lower surface. The paper presents a comparison of the effectiveness of both types of generators based on tests performed in low speed wind tunnel T-1 in the Institute of Aviation (IoA) in the range of Mach numbers M =0.05÷0.1.

The experimental tests modeling oscillating changes of flow around helicopter blade airfoil equipped with proposed self-supplying air jet vortex generators were performed in tri-sonic wind tunnel N-3 (with 0.6 x 0.6 m test section) in the IoA for Mach numbers M = 0.2 and 0.3. The NACA 0012 airfoil model of 0.18 m chord length used in wind tunnel test was oscillating in pitch ($\alpha = \pm 5^0$ with frequency 5 Hz) about an axis located at 35% chord length from the airfoil leading edge.

Nomenclature

a	=	length of the nozzle cross section
b	=	width of the nozzle cross section
c	=	airfoil chord
C_D	=	drag coefficient
C_L	=	lift coefficient
C_{Lmax}	=	maximum of lift coefficient
Cm	=	moment coefficient
Cn	=	normal force coefficient
Cx	=	drag coefficient
c	=	chord
f	=	frequency of the airfoil oscillations
k	=	reduced frequency
M	=	Mach number
$\dot{m}$	=	mass flow rate
t	=	time
Vj	=	jet velocity at AJVG exit
$V\infty$	=	freestream velocity
VR	=	ratio of mean jet velocity to mean freestream velocity
x	=	distance along the chord from the leading edge
α	=	airfoil angle of attack
α_{cr}	=	critical airfoil angle of attack
α_0	=	mean airfoil angle of attack for harmonic motion
$\Delta\alpha$	=	amplitude of the airfoil angle of attack oscillations
Φ	=	pitch angle
ω	=	angular frequency
Ψ	=	skew angle

1 Introduction

The dynamic stall which may appear on retreating helicopter blade due to attain high angles of attack is an relevant limitation of its performance. During the helicopter flight the flow around the rotor blade results from the superposition of the rotational movement of the rotor and forward helicopter movement. For this reason, velocity of flow around the rotor blade is changing periodically during its rotation (it increases on the advancing blade and decreases on the retreating blade). In this case, the balance of helicopter is provided by cyclic changes of the blades pitch implemented by swashplate. The increase in helicopter forward speed can lead to a situation where the retreating blade comes to conditions close to dynamic stall (Fig.1). Dynamic stall, which is considered as a most sever type of stall, is characterized by a strong vortex that forms on the blade's upper surface and moves across the airfoil chord towards trailing edge with increase of the airfoil angle of attack. The vortex formation and its movement contributes to relevant lift and moment increase and next to their rapid fall. Adverse effects associated with dynamic stall (e.g. blade vibration) limits the helicopter performance.

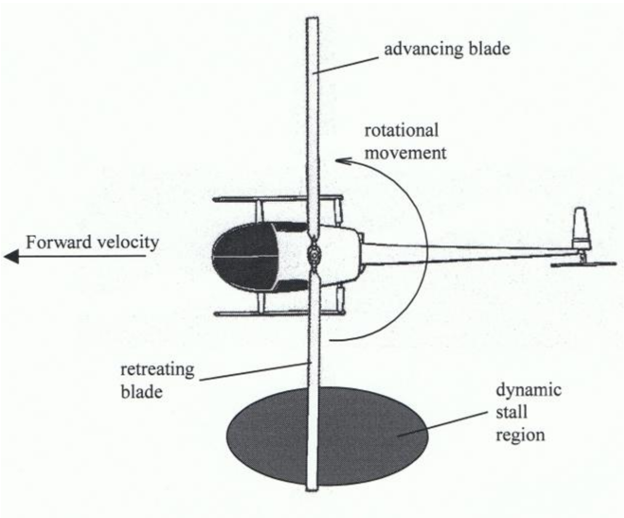

Fig. 1. The dynamic stall region in helicopter forward flight.

Various methods to avoid or delay retreating blade dynamic stall including flow control technology [1,2] are being explored. The possibility of using the flow control in various fields of technology is one of the areas of fluid mechanics that is investigated extensively in many research centers. The interest in this technique results both from the enormous potential for reducing operating costs of flying object equipped with modern control systems and the possibility of significant improvement of their performance. In the last time a particularly strong emphasis has been placed on the development of active control methods. One of those methods, is based on using air-jet vortex generators (AJVGs). In this method the interaction between the air-jets and the freestream flow changes the structure of flow creating well-organized vortical structures. As a results of this interaction we can obtain the alleviation of boundary-layer separation. This beneficial effect can be used to improve the aerodynamics of aircrafts (e.g. to improve efficiency of high lift system), engine turbine blades or helicopter rotors.

Although the concept of using the air-jet vortex generators for boundary layer control has been known for a long time (the idea was originally proposed in the beginning of 1950s by Wallis [3,4]) and has been extensively investigated in later years (Pearcey [5-7], Selby [8,9], Zhang [10], Barberopoulos [11,12], Johnston [13]) it is still not in common use. That is because the usage of these vortex generators type is based on supplying them with the air from engine compressor or from any additional compressors. The complexity of such installation has limited the practical usage of AJVGs. In particular, this complexity of the design would exist in the case of usage of the conventional outsupplying air-jet vortex generators on the rotating helicopter rotor blades. For these reasons the application of self-supplying air-jet vortex generators on helicopter blades instead of conventional ones is proposed. This type of vortex generators are supplied with air from overpressure regions which exist on the lower surface of rotor blade at the higher angles of attack. The effectiveness of proposed self-supplying air-jet vortex generators has been previously tested on NACA 0012 airfoil in IoA low speed wind tunnel T-1. Furthermore, the comparison of the basic aerodynamic characteristics of this airfoil equipped with conventional air-jet vortex generators and self-supplying ones was performed.

The main aim of this paper is to show the possibility of using proposed self-supplying air-jet vortex generators for improving aerodynamic characteristics of helicopter rotor blades in conditions close to dynamic stall. It was assumed that this type of generators which was pre-tested earlier in static conditions and proved their usefulness, will also operate effectively in dynamic conditions. Described in this paper measurements of aerodynamic characteristics of oscillating NACA 0012 airfoil equipped with self-supplying air-jet vortex generators were performed in tri-sonic wind tunnel N-3 (IoA).

2 Experimental Setup and Instrumentation

2.1 Wind Tunnels

The experimental tests of aerodynamic characteristics of NACA 0012 airfoil equipped with proposed self-supplying air-jet vortex generators and comparison of their effectiveness with conventional ones were performed in low speed wind tunnel T-1 in the Institute of Aviation, Warsaw, PL.

The low speed wind tunnel T-1 is closed-circuit, continuous-flow wind tunnel with 1.5 meter diameter open test section. The test section length is 2.01 m. The range of freestream velocity is 15÷40 m/s. The support of the model (situated in vertical position in the test section) allows to change the airfoil incidence angle in the range of $\alpha = \pm 45^0$ (Fig.2). The static and total pressure of the undisturbed flow are measured by "Druck" transducers, having the range of measurement 14.85 in. H_2O, and accuracy of 0.1% F.S.

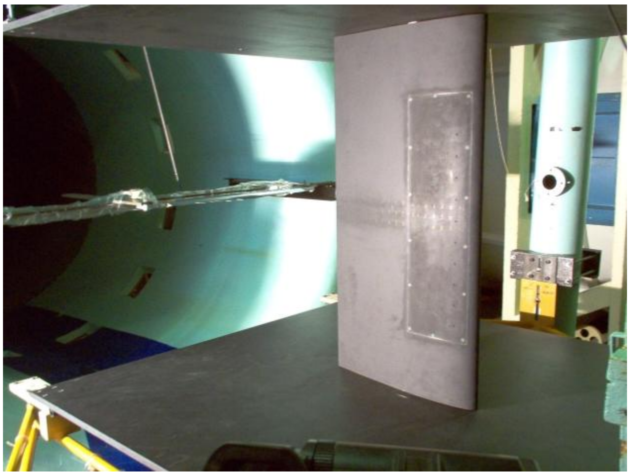

Fig. 2. The model of the airfoil NACA 0012 in the low speed wind tunnel T-1.

The dynamic wind tunnel tests of oscillating NACA 0012 airfoil equipped with self-supplying air-jet vortex generators were performed in tri-sonic wind tunnel N-3 (IoA).

The N-3 wind tunnel is a blow-down type with partial re-circulation of the flow. It can operate in subsonic, transonic and supersonic flow regimes at Mach numbers M = 0.2÷1.2, 1.5 and 2.3. The closed test section (cross section 0.6m x 0.6m, length 1.58 m) may have perforated top and bottom walls for tests at subsonic and transonic flow velocities and solid walls - at supersonic. The time duration of the tests depends on wind-tunnel operating regime and is up to 15 minutes at subsonic speeds, up to 5 minutes at transonic speeds and up to 3 minutes at supersonic speeds. Each side wall of the test section is equipped with two double windows of 0.25m diameter. During the airfoil tests, two of these windows are replaced by the support of the model (situated in horizontal position in the test section, Fig.3).

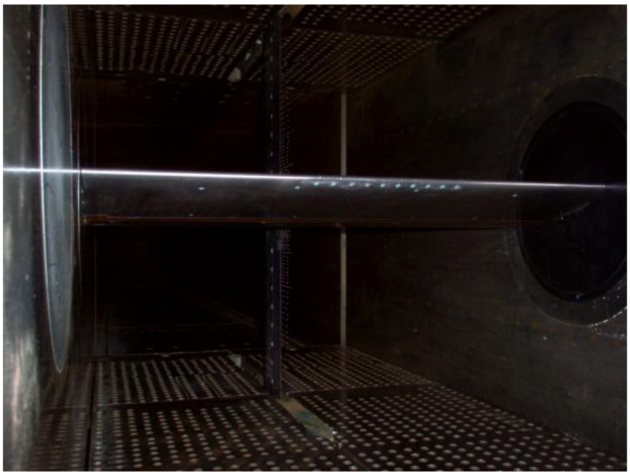

Fig. 3. The model of the airfoil NACA 0012 in the tri-sonic wind tunnel N-3.

The support of the model is controlled by computer, which allows changes of airfoil incidence angle within the range of 20^0 with 0.01^0 step. During the dynamic wind tunnel tests the support of the airfoil model is associated with driving system, which excites oscillations of the model (Fig.4, 5). Driving system consists of the crank-shaft assembly, driven by DC motor (with the range of rotations from 0 up to 6000 rpm.) connected by reduction gears (1:10). The frequencies of oscillations of the airfoil are changed by changing the motor rpm. The driving system allows to obtain the frequency of the airfoil oscillations in continuous way from 0 to 10 Hz (so, for M=0.3 the reduced frequency k can vary from k=0 to k=0.056). The amplitudes of the airfoil oscillations might be changed by changing the place on the flywheels, where the cranks are fixed. Instantaneous values of the airfoil angle of attack are measured by rotation sensor ROC 412 (Heidenhain) with max instrumental error $\pm 0.10^0$.

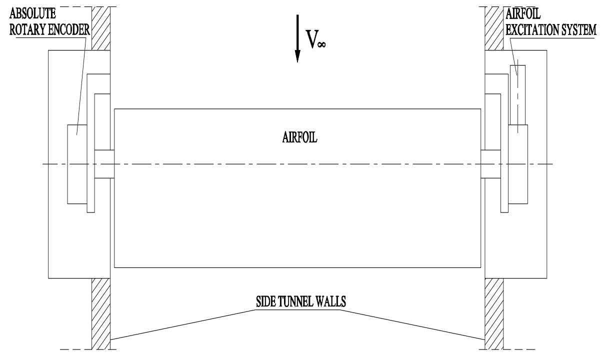

Fig. 4. Test setup in the tri-sonic wind tunnel N-3 (IoA).

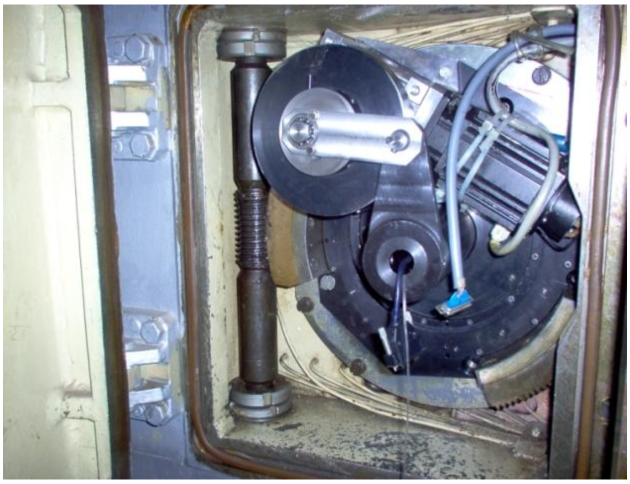

Fig. 5. Driving system of airfoil.

Static and total pressure of the undisturbed flow are measured by two independent sets of Solatron and Sonix transducers, having the range of measurement 1.3 and 2.6 bars, and accuracy of 0.02% Full Scale.

2.1 The Airfoil Models

The model of NACA 0012 airfoil, used in experimental static tests in the low speed wind tunnel T-1 had chord of 0.5 m and a span of 1m. It was made of composite materials except for the ends fixing sleeves (made of steel). The model was mounted vertically in working section between two immobile endplates (Fig. 2) and was able to rotate in bearings fixed to the endplates. The model axis of rotation was in 40% of the airfoil chord and the driving system was situated under the lower endplates.

The removable cover, fixed to the rest of model with the screws, was the part of upper model airfoil surface. On the outside surface of the cover, ten nozzles of the air-jet vortex generators were glued. The same nozzles were used for both conventional and air-jet vortex generators. The location and geometry of these nozzles were chosen mainly in accordance with the recommendation presented in literature [6,7]. They were located in the same distance from the leading edge x/c = 0.12 and spaced at intervals of 0.11c along the airfoil span, see Fig. 6. The nozzle cross section had rectangular geometric shape (a = 7.2 mm and b = 1.2 mm) with rounded corners.

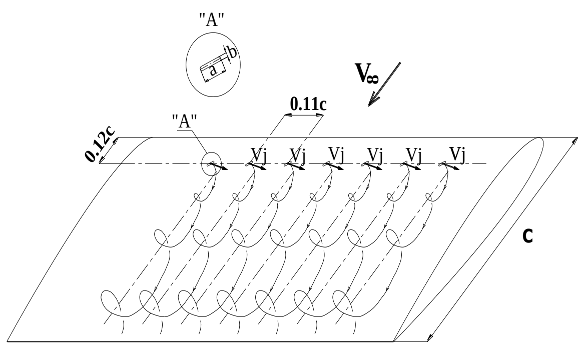

Fig. 6 The location of air-jet vortex generator nozzles on the airfoil upper surface .

The jet exits of vortex generators were pitched at $\Phi = 30^0$ and skewed at $\Psi = 60^0$. The definition of jet pitch and skew angles is presented in Fig. 7. Air was supplied to the conventional air-jet vortex generators from two external compressors of total flow rate 800 l/min. The air from the two compressors was pumped to the pressure vessel and next, through the throttle valve, orifice plate and Venturi tube flowed in pressure pipe to the model of the airfoil. The orifice plate and Venturi tube were designed for the flow rate measurements. The throttle valve has been used for keeping the constant pressure in the pressure system. The presented test results of the conventional air-jet vortex generators were conducted with mass flow rate $\dot{m} \approx 6.5 \times 10^{-4}$ kg/s.

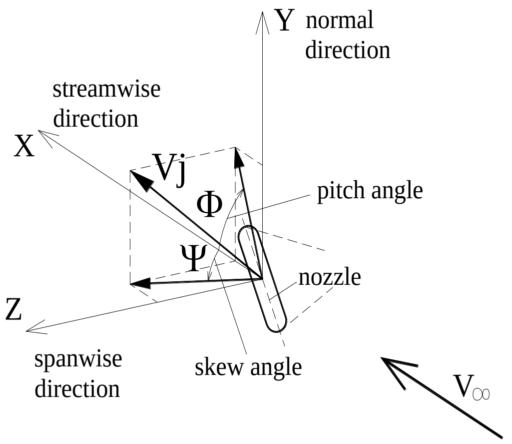

Fig. 7 Air-jet geometry.

The proposed self-supplying air-jet vortex generators used the same nozzles as conventional ones (pitched at $\Phi = 30^0$ and skewed at $\Psi = 60^0$), but in contrast with them, were supplied with the air from the overpressure region situated in the nose part of the airfoil lower surface, Fig.8. The axes of the inlets cross the outline of the lower airfoil surface as close as possible to the flow stagnation points for circum-critical angles of attack and are positioned parallel to the air streams direction in these points.

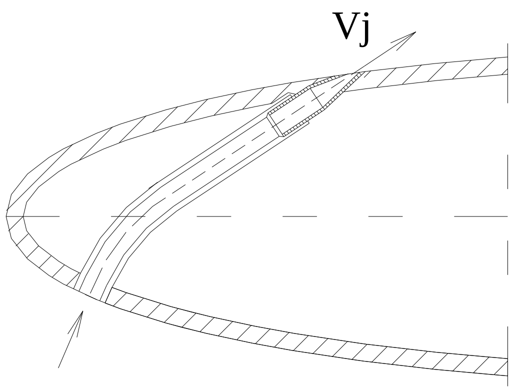

Fig. 8 The concept of self-supplying air-jet vortex generators.

The pressure difference between the lower and upper airfoil surface forces the air flow through the pneumatic pipe, connecting the inlet to the nozzle. The air jets flowing out from number of nozzles with certain velocity Vj, like it is in 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 at the higher angles of attack, close to critical values, they become active because of the increase of the difference of pressure between the upper and the lower airfoil surfaces in the nose region. According to the numerical calculation performed at M = 0.05 and $\alpha = 14^0$ the mass flow rate through the proposed self-supplying air-jet vortex generators was $\dot{m} \approx 2.7 \times 10^{-4}$ kg/s. So it was significantly lower than in case of conventional ones.

The one hundred thirty eight measurement orifices of 0.5 mm diameter were distributed on the upper and lower surfaces of the airfoil along its chord in three cross sections. The central measurement cross section was situated in the middle of the model span and crossed the axis one of the nozzles. The adjacent measurements cross section were situated at the distance of 27.5 mm from central cross section i.e. in the middle between AJVGS nozzles. All the measurement orifices were connected to the mechanical pressure scanner “Scanivalve” by elastic pipes. The pressure scanner was equipped with four “Druck” transducers having the range of measurement 14.85 in. H_2O, and accuracy of 0.1% F.S.

To calculate the total drag coefficient of the airfoil, the wake rake measurements were performed. The wake rake, which consists of 122 total pressure probes (only 44 were used), was situated behind the model at the distance of 525 mm. The pressure probes, like measurement orifices from the model, were connected to the mechanical pressure scanner “Scanivalve”.

The model of NACA 0012 airfoil, used in the study in the high speed wind tunnel N-3 had a chord of 0.18 m and a span of 0.6 m. It was made of steel. It was equipped with removable cover fixed to upper model surface. On the outside surface of the cover ten air-jet vortex generator nozzles were glued. They were located in the same place and position as it was on the model tested in low speed wind tunnel i.e. at the distance from leading edge x/c = 0.12, spaced at intervals of 0.11c along the airfoil span, pitched at $\Phi = 30^0$ and skewed at $\Psi = 60^0$. The nozzles cross section had rectangular geometric shape (a = 3 mm and b = 0.6 mm) with rounded corners.

The forty eight measurement orifices of 0.4 mm diameter were distributed in the middle of the model span, along the chord on the upper and lower surfaces of the airfoil. The orifices were connected (by the elastic pipes of the same length 100 mm) to the three miniature pressure scanners ESP 16HD (Pressure System), Fig.9. Two of them had the range of measurement 10 psid and one 5 psid. The ESP 16HD pressure scanner contains an array of 16 silicon piezoresistive pressure sensors, which may be multiplexed at rates up to 20.000 Hz. Their accuracy is 0.1% F.S.

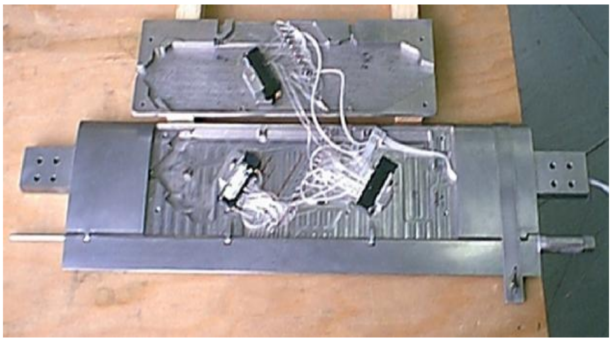

Fig. 9 Model of NACA 0012 airfoil with pressure sensors scanners.

3 Results and Discussion

3.1 The Conditions of the Static and Unsteady Tests of NACA 0012 Airfoil

In Tables 1 and 2 the test conditions for the experimental investigation of control of flow separation for the airfoil NACA 0012 with air-jet vortex generators in the static and dynamic conditions are given.

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

Parameter	Value
Mach number M	0.05, 0.075, 0.1
Reynolds number Re	0.6×10^6 (M=0.05) 1.1×10^6 (M=0.1)
Airfoil angle of attack *	$-2.7^0 \div 21.7^0$
Jet pitch angle Φ	30^0
Jet skew angle Ψ	60^0
Mass flow rate $\dot{m}$ (conventional AJVGs)	6.5×10^{-4} kg/s
Mass flow rate $\dot{m}$ ** (self-supplying AJVGs)	2.7×10^{-4} kg/s

* with wind tunnel corrections

** numerical calculation at M = 0.05 and $\alpha = 14^0$

Table 2. Test conditions for unsteady measurements performed in the tri-sonic wind tunnel N-3

Parameter	Value
Mach number M	0.2, 0.3
Reynolds number Re	0.87×10^6 (M=0.2) 1.27×10^6 (M=0.3)
Mean airfoil angle of attack α_0	$0^0 \div 15^0$
Nominal amplitude of the airfoil oscillations	$\pm 5^0$
Frequency of the airfoil oscillations f	5 Hz
Reduced frequency k	0.042 (M = 0.2) 0.028 (M = 0.3)
Jet pitch angle Φ	30^0
Jet skew angle Ψ	60^0

* due to torsional deflections of the model during oscillations, the real amplitudes of the airfoil oscillations were a little greater than nominal and equal $\Delta\alpha \approx \pm 6^0$

3.2 Comparison of the Effectiveness of the Self-Supplying and Conventional Air Jet Vortex Generators

The comparison of the effectiveness between the self-supplying and conventional air jet vortex generators mounted on NACA 0012 airfoil were performed in the low speed wind tunnel T-1 in the range of Mach numbers M = 0.05÷0.1 (which correspond to $V\infty$ = 18.3÷34.4 m/s). This effectiveness of the generators used to the stall control can be measured as a lift coefficient increase and a critical angle of attack increase, but also the impact of these generators on the other airfoil aerodynamic coefficients like drag and moment is important. In the Fig. 10 the comparison of the NACA 0012 airfoil lift coefficient versus angle of attack obtained for the conventional and self-supplying air jet vortex generators at Mach numbers M = 0.05, 0.075 and 0.1 is presented.

From analysis of these results it can be concluded that usage of both types of air-jet vortex generators on NACA 0012 airfoil causes increase of the maximum lift coefficient and increase of the critical angle of attack. Among the freestream velocities tested in the low speed wind tunnel T-1 the highest rise of the lift coefficient occurred at M = 0.05 for conventional air-jet vortex generators ($\Delta C_{Lmax} \approx 0.15$). Simultaneously the increase of critical angle of attack at about $\Delta\alpha_{cr} \approx 2.1^0$ was achieved. For this Mach number the effectiveness of the self-supplying air-jet vortex generators (measured as a increase of C_{Lmax} and α_{cr}) is less than conventional ones. That is because the following values, i.e.$\Delta C_{Lmax} \approx 0.08$ and $\Delta\alpha_{cr} \approx 1.6^0$ have been achieved. The primary cause of the lower performance of these generators in comparison with conventional ones is significantly smaller mass flow rate (see table 1).

With the increase of Mach number and unchanged mass flow rate of jets, the effectiveness of the conventional air-jet vortex generators decreases significantly (at M = 0.1 $\Delta C_{Lmax} \approx 0.03$ and $\Delta\alpha_{cr} \approx 0.9^0$), because the ratio of mean jet velocity to mean freestream velocity is reduced (from VR = 2.8 at M = 0.05 up to VR = 1.5 at M = 0.1). Simultaneously, with increase of Mach number the mass flow rate of the self-supplying jets increases due to the higher pressure difference between the lower and upper airfoil surfaces. As a result, at M = 0.1 the efficiency of the conventional and self-supplying air-jet vortex generators is similar. To keep the high performance of the conventional air-jet vortex generators with the rise of freestream velocity, the increase of mass flow rate would be needed.

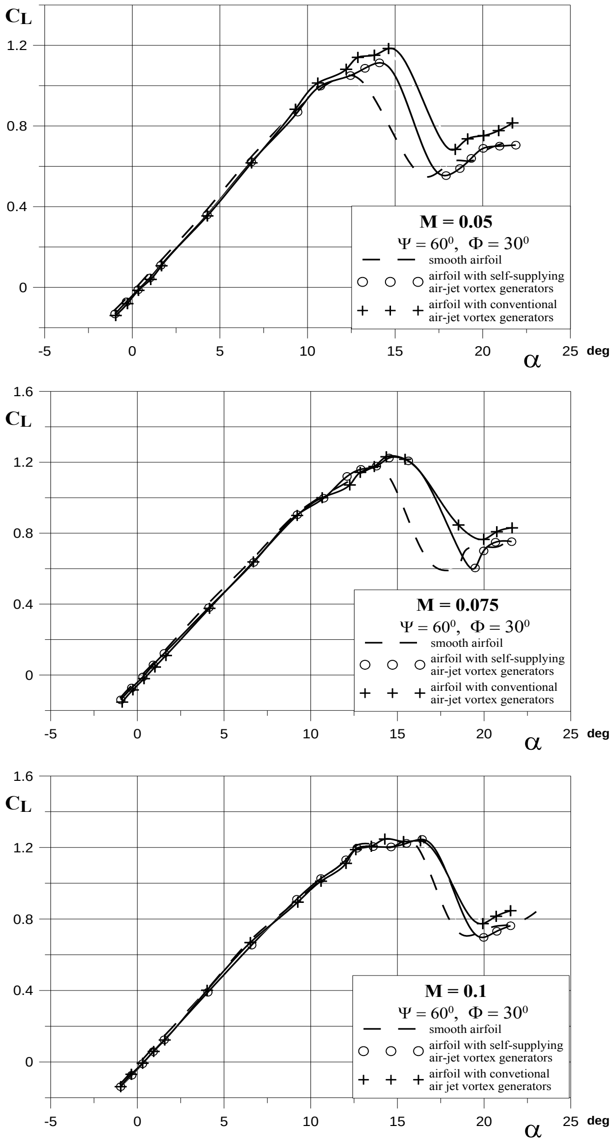

Fig. 10 Comparison of the lift coefficient vs angle of attack for the conventional and self-supplying AJVGs.

The forming of the vortices on the upper airfoil surface due to use of the conventional and self-supplying air-jet vortex generators, generally do not change the value of the drag coefficient in the range of low angles of attack, Fig. 11. The delay of the flow separation (which occurs in the case of usage both types of generators) and connected with this phenomenon an increase of the critical angle of attack causes a decrease of the drag coefficient in region of critical angles of attack in comparison with the smooth airfoil.

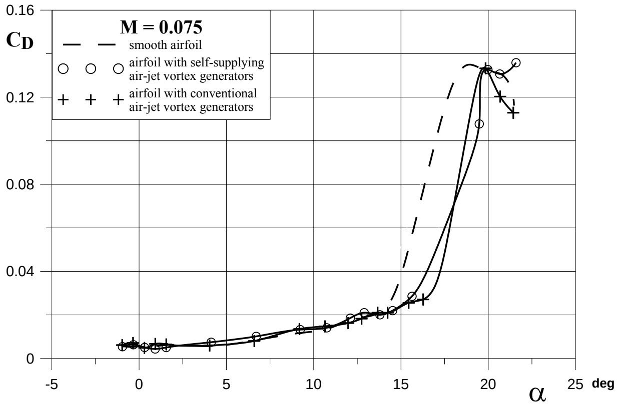

Fig. 11 Comparison of the drag coefficient vs angle of attack for the conventional and self-supplying AJVGs.

3.3 Unsteady Wind Tunnel Tests of NACA 0012 Airfoil Equipped with Self-Supplying AJVGs

The dynamic wind tunnel tests of oscillating NACA 0012 airfoil equipped with self-supplying air-jet vortex generators were performed in tri-sonic wind tunnel N-3 (IoA) at Mach numbers M = 0.2, 0.3 and for an airfoil reduced oscillation frequencies of k = 0.042 (M = 0.2) and k = 0.028 (M = 0.3). The range of tested Mach numbers resulted on one hand from the tri-sonic wind tunnel operational ability (M_{min} = 0.2), on the other hand from the limits of the self-supplying air-jet vortex generators effectiveness at the higher Mach numbers. Previous studies have shown that for Mach numbers M > 0.3 the influence of the self-supplying air-jet vortex generators (of presented parameters) on the aerodynamic characteristics of NACA 0012 airfoil deteriorates significantly [14]. The airfoil reduced oscillation frequencies, at which the tests were performed, was a little less than on a typical full-scale rotor (e.g. for PZL W-3 “Sokol”, k ≈ 0.081) because of the wind tunnel restriction on the model size and limits of the airfoil driving system.

The prior studies of the dynamic stall phenomenon [15,16] have shown that oscillating airfoil can produce significantly greater lift than that achieved in steady conditions. This higher lift value is obtained at angles of attack greater than static critical angle of attack. The changes in the value of maximum lift is connected with a strong vortex that forms on the upper airfoil surface and migrates towards the trailing edge during the airfoil motion.

In Fig. 12 the influence of the self-supplying air-jet vortex generators (mounted on the oscillating airfoil with $\alpha = \alpha_0 + 5^0 \sin\omega t$) on normal force coefficient as functions of angle of attack at M = 0.3 and $\alpha_0 = 11^0, 13^0, 15^0$ is presented. From analysis of these results it can be concluded that use of the air-jet vortex generators on NACA 0012 airfoil causes a little increase of the normal force coefficient (up to $\Delta Cn \approx 0.05$) in the range of highest tested angles of attack (up to theirs critical value). Moreover, the blowing air from generators nozzles eliminates nonlinear increase of a normal force coefficient, which is characteristic for the dynamic stall due to formation of the dynamic stall vortex. For the highest tested mean airfoil angle of attack $\alpha_0 = 15^0$ a little increase in critical angle of attack of the lift stall was achieved ($\Delta\alpha_{cr} \approx 0.3^0$).

On an oscillating airfoil the movement of dynamic stall vortex toward the trailing edge changes significantly a pressure distribution on the upper airfoil surface, which results in a negative divergence of the quarter-chord pitching moment. In Fig. 13 the influence of the self-supplying air-jet vortex generators on moment coefficient as function of angle of attack at M = 0.3 is presented for mean angles of attack $\alpha_0 = 11^0, 13^0$ and 15^0. The blowing through self-supplying AJVGs delays the pitching moment break by about 0.5^0 for $\alpha_0 = 11^0$ and by about 1^0 for $\alpha_0 = 13^0$ and $\alpha_0 = 15^0$.

An elimination of the nonlinear increase in normal force coefficient and delay of the pitching moment break due to usage of the self-supplying air-jet vortex generators suggests, that vortices created on the upper airfoil surface delays the flow separation delaying also formation and migration of the dynamic stall vortex.

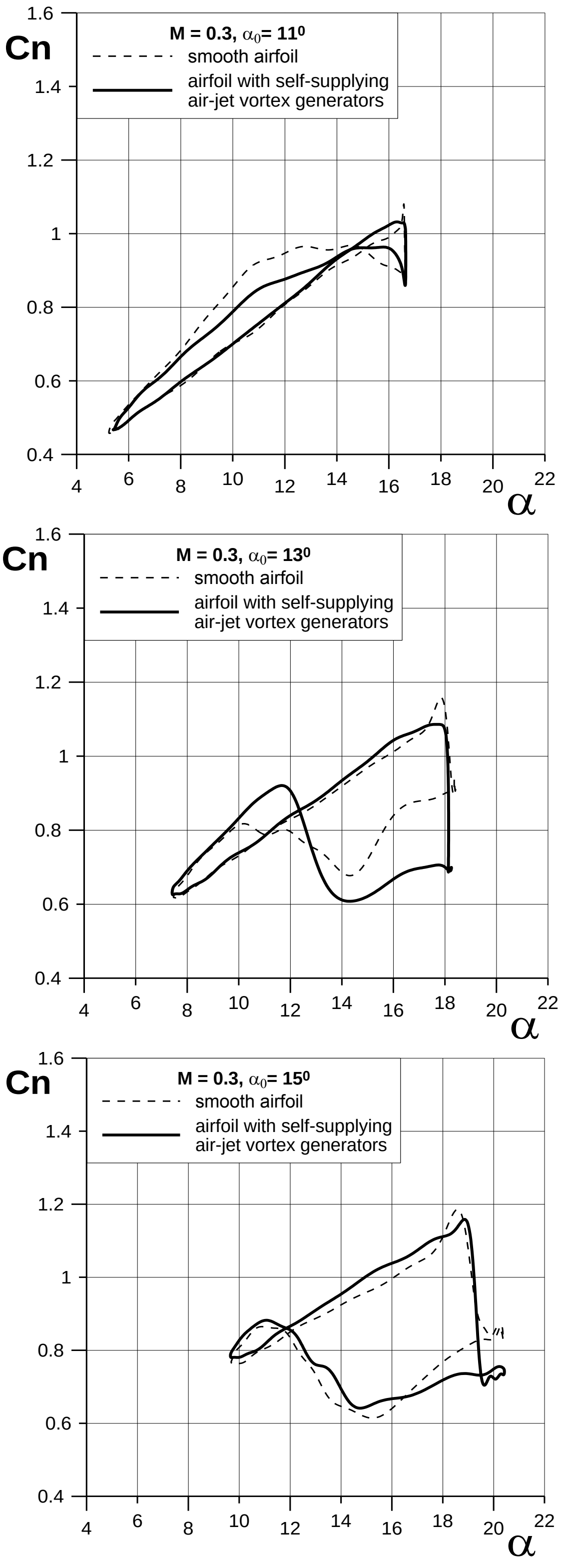

Fig. 12 Influence of the self-supplying air-jet vortex generators on normal force coefficient vs. of angle of attack at M = 0.3 and $\alpha_0 = 11,13,15^0$.

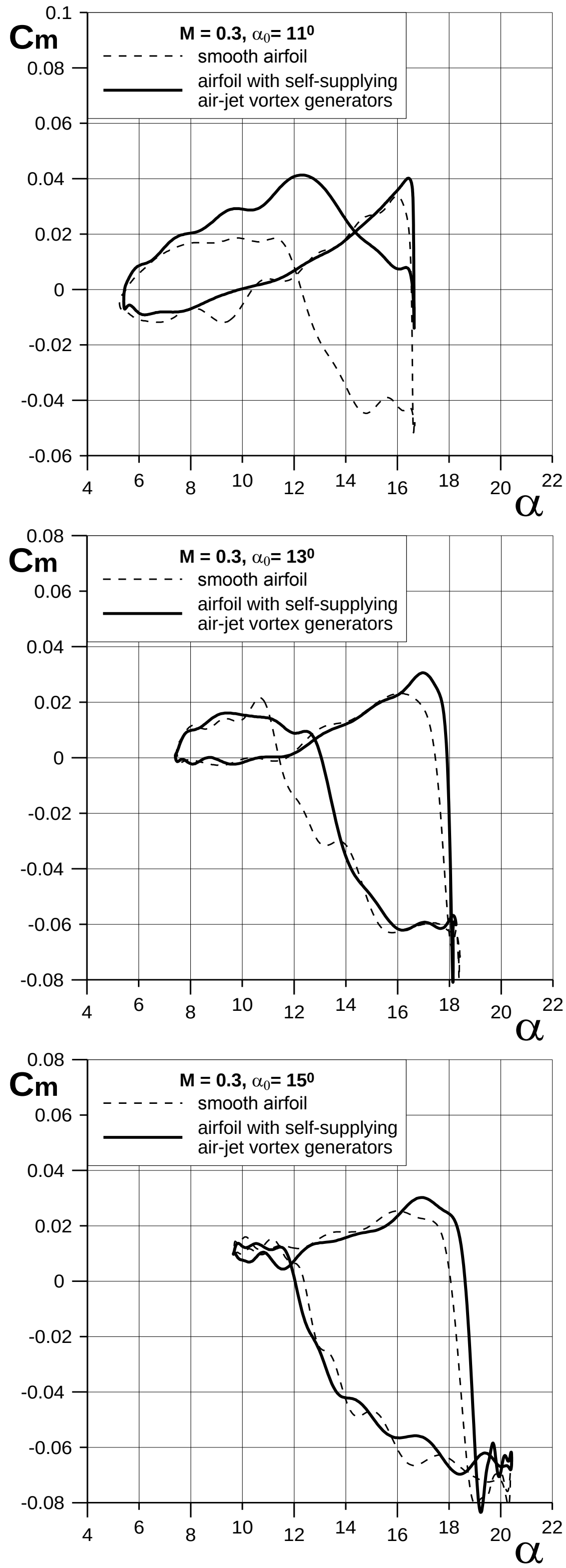

Fig. 13 Influence of the self-supplying air-jet vortex generators on moment coefficient vs. angle of attack at M = 0.3 and $\alpha_0 = 11,13,15^0$.

4 Conclusions

The static wind tunnel investigation of self-supplying air jet vortex generators and comparison of their effectiveness with conventional ones (i.e. supplied with the air from compressor) showed that the proposed generators also provide an relevant increase of the maximum lift coefficient and an increase in critical angle of attack. Although, the effectiveness of the self-supplying air-jet vortex generators is a little less than conventional ones, but because of their simplicity, they may be consider as an alternative to conventional air-jet vortex generators.

The experimentally obtained aerodynamic characteristics of oscillating NACA 0012 airfoil (at $\alpha = \alpha_0 + 5^0 \sin\omega t$) equipped with the proposed self-supplying air-jet vortex generators are presented. In this conception the air-jet vortex generators are supplied with air from the overpressure region situated in the nose part of the airfoil lower surface. Test results (presented for M = 0.3) show that the self-supplying air-jet vortex generators gives a little increase in normal force coefficient (up to $\Delta Cn \approx 0.05$) at higher angles of attack and causes small lift stall delay (up to $\Delta\alpha_{CR} \approx 0.3^0$ at $\alpha_0 = 15^0$) and moment stall delay (at about 0.5^0 for $\alpha_0 = 11^0$ and by about 1^0 for $\alpha_0 = 13^0$ and $\alpha_0 = 15^0$). It was also found that blowing the air from generators nozzles eliminates nonlinear increase of the normal force coefficient. Presented results suggest that usage of the self-supplying air-jet vortex generators on the oscillating airfoil delays the flow separation and delays formation of a dynamic stall vortex and its migration towards the trailing edge.

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