

## IMPROVEMENT OF HELICOPTER PERFORMANCE USING SELF-SUPPLYING AIR JET VORTEX GENERATORS

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### **Abstract**

*The work presents the results of experimental wind tunnel tests of using self-supplying air jet vortex generators to delay dynamic stall on helicopter blade due to attain high angles of attack. The dynamic stall which may appear on retreating helicopter blade is considered as the most severe type of stall, characterized by a strong vortex that forms on the blade's upper surface. Its appearance is a significant limitation of helicopter performance. To improve helicopter aerodynamic characteristics the using of self-supplying air jet vortex generators was proposed. In comparison with the conventional air-jet vortex generators, which are supplied with the air from an external compressor, the self-supplying generators receive air from the overpressure region situated in the nose part of the blade lower surface at the higher angles of attack. 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 periodic 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 ( $\alpha = \pm 5^\circ$  with frequency 5 Hz) about an axis located at 35% chord length from the airfoil leading edge.*

**Keywords:** *air vehicle, helicopter, applied aerodynamics, vortex generation*

### **1. Introduction**

The dynamic stall which may appear on retreating helicopter blade due to attain high angles of attack is a significant limitation of its performance. During the helicopter flight, the flow around the rotor blade is a 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 a 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 the most severe 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 contribute to relevant lift and moment increase followed by their rapid fall. Adverse effects associated with dynamic stall (e.g. blade vibration) limits the helicopter performance.

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. Currently 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 vertical structures. As a result of this interaction we can obtain the alleviation of boundary-layer separation. This beneficial effect can be used to improve aerodynamics of aircrafts (e.g. to improve efficiency of high lift system) or engine turbine blades.

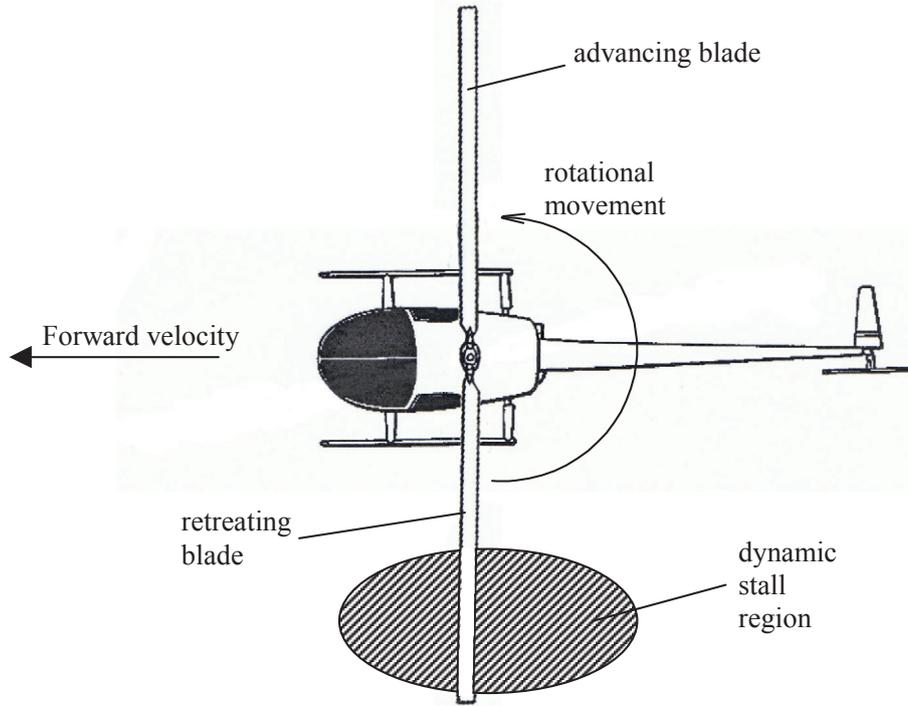


Fig. 1. Dynamic stall region in helicopter forward flight

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]) it is still not in common use. That is because the usage of this type of vortex generators 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 out supplying air-jet vortex generators on the rotating helicopter rotor blades. For these reasons the application of self-supplying air-jet vortex generators [7] on helicopter blades instead of conventional ones is proposed. This type of vortex generators is 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 Institute of Aviation 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 to improve 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

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, Poland.

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 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  $2.3$ . During the dynamic wind tunnel tests the support of the airfoil model was associated with driving system, which excites oscillations of the model, Fig. 2,. Driving system consists of the crank-shaft assembly, driven by DC motor connected by reduction gears. 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  $\pm 0.1^\circ$ .

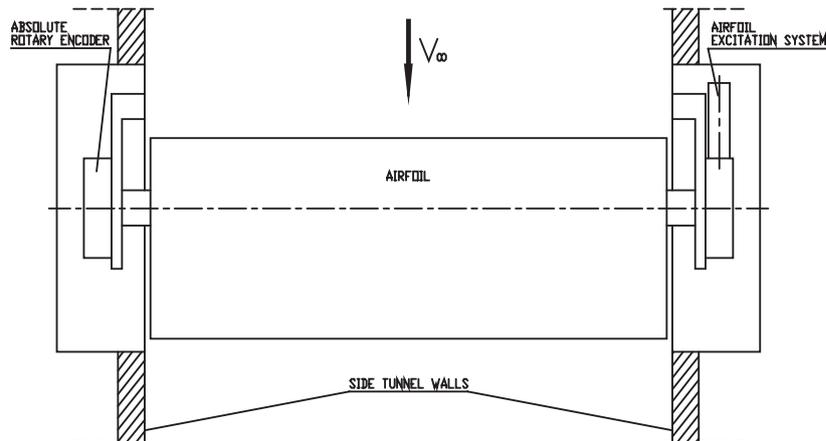


Fig. 2. Test setup in the tri-sonic wind tunnel N-3 (IoA)

## 3. 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 1 m. It was made of composite materials except for the ends fixing sleeves. 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]. 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. 3. The nozzle cross section had rectangular geometric shape with rounded corners. The jet exits of vortex generators were pitched at  $\Phi = 30^\circ$  and skewed at  $\Psi = 60^\circ$ . Air was supplied to the conventional air-jet vortex generators from two external compressors of total flow rate 800 l/min. The tests results of the conventional air-jet vortex generators presented in this paper were conducted with mass flow rate of  $\dot{m} \approx 6.5 \times 10^{-4}$  kg/s.

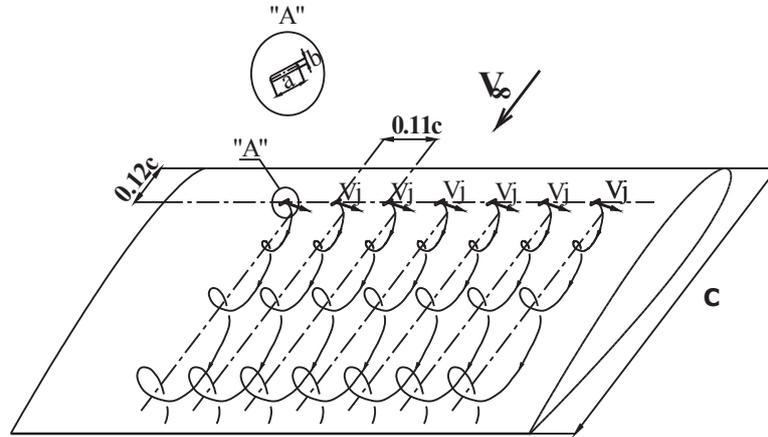


Fig. 3. Location of air-jet vortex generator nozzles on the airfoil upper surface

The proposed self-supplying air-jet vortex generators used the same nozzles as conventional ones (pitched at  $\Phi = 30^\circ$  and skewed at  $\Psi = 60^\circ$ ), 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. 4. 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.

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  $V_j$ , like it is in the conventional air-jet vortex generators, interact with the freestream flow, forming vortices on the upper airfoil surface.

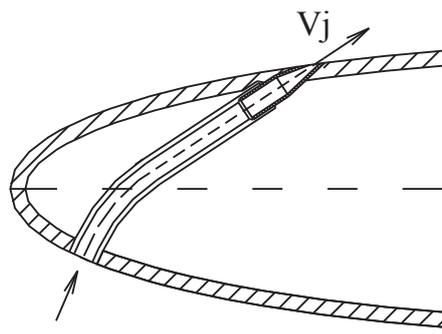


Fig. 4. Concept of self-supplying air-jet vortex generators

The self-supplying air-jet vortex generators are characterized by the fact that they remain inactive at low angles of attack and they become active only at the higher angles of attack, close to critical values, 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  $\alpha = 14$  deg 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.

#### 4. Results and Discussion

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. However impact of the generators on the other airfoil aerodynamic coefficients like drag and moment is also important. In the Fig. 5 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  $M = 0.05$  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  $\Delta\alpha_{cr} \approx 2.1^\circ$  was achieved. For this Mach number the effectiveness of the self-supplying air-jet vortex generators (measured as a increase of  $C_{Lmax}$  and  $\alpha_{cr}$ ) is less than conventional ones. The following values,  $\Delta C_{Lmax} \approx 0.08$  and  $\Delta\alpha_{cr} \approx 1.6^\circ$  have been achieved. The primary cause of the lower performance of these generators in comparison with conventional ones is significantly smaller mass flow rate.

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  $\Delta\alpha_{cr} \approx 0.9^\circ$ ), 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.

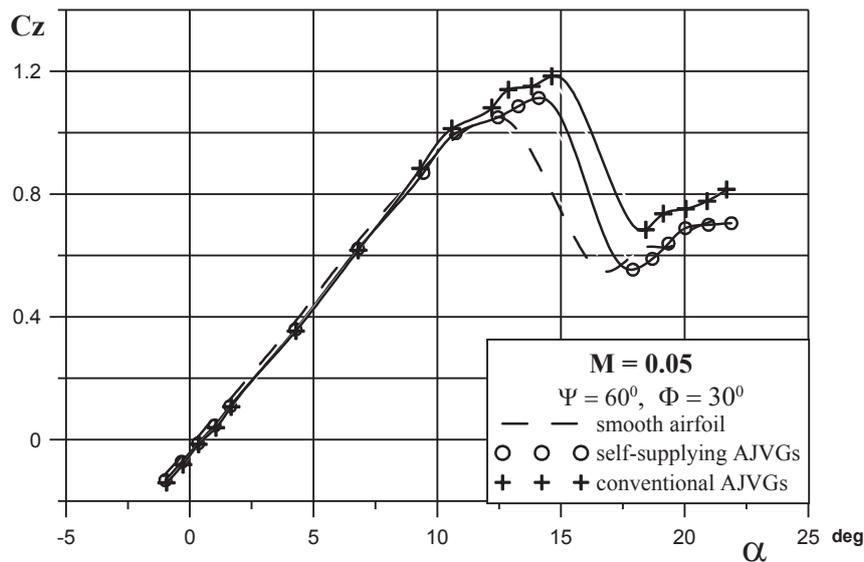


Fig. 5. Comparison of the lift coefficient vs. angle of attack for the conventional and self-supplying AJVGs

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  $M = 0.2$  and  $0.3$  for 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 [7]. The airfoil reduced oscillation frequencies, at which the tests were performed, were a little less than on a typical full-scale rotor (e.g. for PZL W-3 ‘‘Sokol’’,  $k \approx 0.081$ ) 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 [8-9] 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 change 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. 6 the influence of the self-supplying air-jet vortex generators (mounted on the oscillating airfoil  $\alpha = \alpha_0 + 5^0 \sin \omega t$ ) on normal force coefficient as functions of angle of attack at  $M = 0.3$  and  $\alpha_0 = 13.15^0$  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  $\Delta C_n \approx 0.05$ ) in the range of highest tested angles of attack up to their critical value. Moreover, blowing the air from generator’s nozzles eliminates nonlinear increase of 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 significantly changes pressure distribution on the upper airfoil surface resulting in a negative divergence of the quarter-chord pitching moment. In Fig. 7 the influence of the self-supplying air-jet vortex generators (mounted on the oscillating airfoil  $\alpha = \alpha_0 + 5^0 \sin \omega t$ ) on moment coefficient as function of angle of attack at  $M = 0.3$  is presented for three different angles of attack,  $\alpha_0 = 13$  and  $15^0$ . The blowing through self-supplying AJVGs delays the pitching moment break 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 delay the flow separation delaying also formation and migration of the dynamic stall vortex.

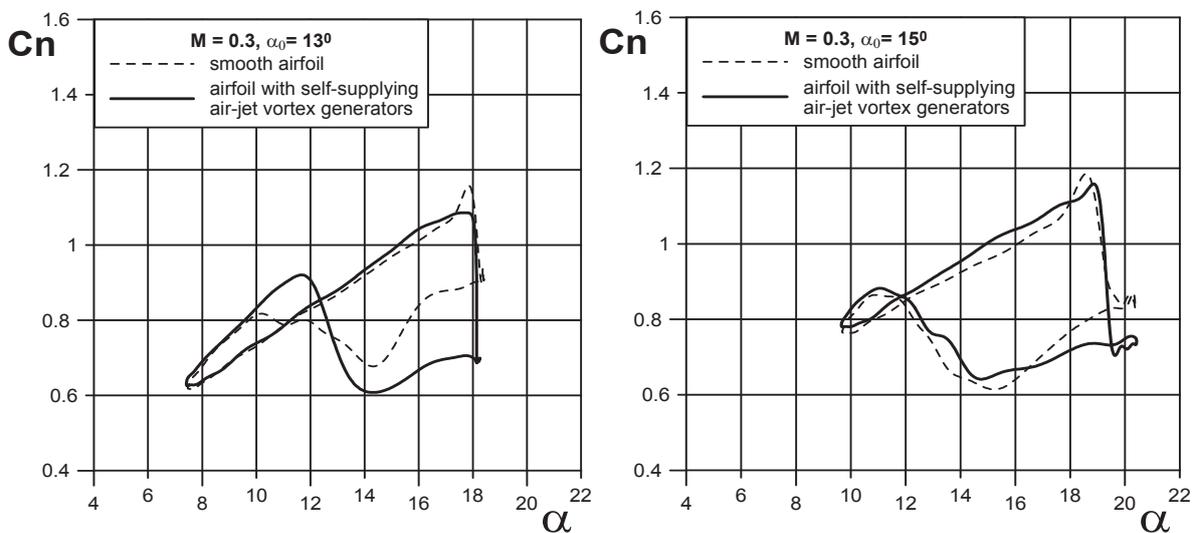


Fig. 6. Influence of the self-supplying AJVGs on normal force coefficient at  $M = 0.3$  and  $\alpha_0 = 13.15^0$

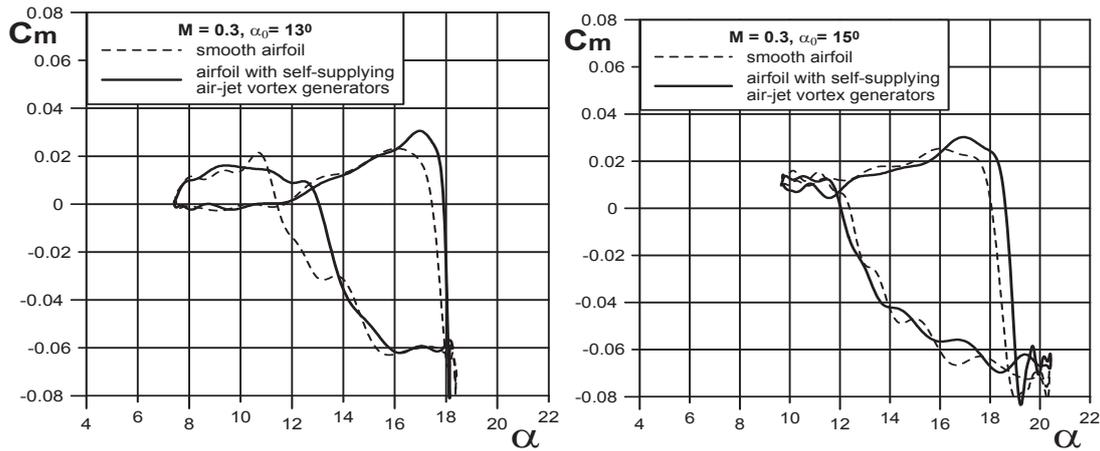


Fig. 7. Influence of the self-supplying AJVGs on moment coefficient at  $M = 0.3$  and  $\alpha_0 = 13.15^\circ$

## 5. Conclusions

The experimentally obtained aerodynamic characteristics of oscillating NACA 0012 airfoil (at  $\alpha = \alpha_0 + 5^\circ \sin \omega t$ ) 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's lower surface. Test results (presented for  $M = 0.3$ ) show that the self-supplying air-jet vortex generators give a little increase in normal force coefficient (up to  $\Delta C_n \approx 0.05$ ) at higher angles of attack and cause small lift stall delay (up to  $\Delta \alpha_{CR} \approx 0.3^\circ$  at  $\alpha_0 = 15^\circ$ ) and moment stall delay (at about  $1^\circ$  for  $\alpha_0 = 13^\circ$  and  $\alpha_0 = 15^\circ$ ). It was also found that blowing the air from generator's 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 the formation of a dynamic stall vortex and its migration towards the trailing edge.

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 a relevant increase of the maximum lift coefficient and increase in critical angle of attack. The effectiveness of the self-supplying air-jet vortex generators is a little less than conventional ones. However, because of their simplicity, they may be consider as an alternative to conventional air-jet vortex generators.

## References

- [1] Post, M. L., Corke, T. C., *Separation Control Using Plasma Actuators: Dynamic Stall Vortex Control on Oscillating Airfoil*, AIAA Journal, Vol. 44, No. 12, pp. 3125-3135, 2006.
- [2] Coton, F., et al., *Control of Rotorcraft Retreating Blade Stall Using Air-Jet Vortex Generators*, Journal of Aircraft, Vol. 43, No. 4, Jul.-Aug., pp. 1169-1176, 2006.
- [3] Wallis, R. A., *A Preliminary Note on a Modified Type of Air Jet for Boundary Layer Control*, Report ARC CP 513, 1960.
- [4] Wallis, R. A., Stuart, C. M., *On the Control of Shock-Induced Boundary Layer Separation with Discrete Air Jets*, Report ARC CP 595, 1962.
- [5] Pearcey, H. H., Stuart, C., *Methods of Boundary-Layer Control for Postponing and Alleviating Buffeting and Other Effects of Shock-Induced Separation*, SMF Paper No. FF-22., Institute of the Aeronautical Sciences, New York 1959.
- [6] Pearcey, H. H., *Shock Induced Separation and Its Prevention by Design and Boundary Layer Control*, *Boundary Layer and Flow Control*, edited by Lachmann, G. V., pp. 1312-1314, Pergamon, Oxford 1961.

- [7] Krzysiak, A., *Control of Flow Using Self-Supplying Air Jet Vortex Generators*, AIAA Journal, Vol. 46, No. 9, Sept. 2008.
- [8] Mc Croskey, W. J., Carr, L. W., McAlister, K. W., *Dynamic Stall Experiments on Oscillating Airfoils*, AIAA Journal, Vol. 14, No. 1, pp. 57-63, January 1976.
- [9] Carr, L. W., *Progress in Analysis and Prediction of Dynamic Stall*, Journal of Aircraft, Vol. 25, No. 1, pp. 6-17, 1988.

## Nomenclature

$a$	= length of the nozzle cross section
$b$	= width of the nozzle cross section
$c$	= airfoil chord
$C_L$	= lift coefficient
$C_{L,max}$	= maximum of lift coefficient
$C_m$	= moment coefficient
$C_n$	= normal force coefficient
$f$	= frequency of the airfoil oscillations
$k$	= reduced frequency, $k = (\omega c / 2) / V_\infty = (\pi f c) / V_\infty$
$M$	= Mach number
$\dot{m}$	= mass flow rate
$V_j$	= 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.
$\alpha$	= airfoil angle of attack
$\alpha_{cr}$	= critical airfoil angle of attack
$\alpha_0$	= mean airfoil angle of attack for harmonic motion
$\Delta\alpha$	= amplitude of the airfoil angle of attack oscillations
$\Phi$	= pitch angle
$\omega$	= angular frequency
$\Psi$	= skew angle