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IMPROVEMENT OF HELICOPTER PERFORMANCE THROUGH PULSE AIR JETS BLOWN FROM THE TRAILING EDGE OF MAIN ROTOR BLADES

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Abstract

The new concept of improvement of helicopter performance has been developed and investigated based on a computational approach. The proposed solution utilises a system of micro nozzles located at the main-rotor-blade trailing edge. The momentary blowing from the nozzles is activated to momentary increase the lift generated by the blade, which is necessary at retreating-blade azimuths. The effect of significant growth of the lift has been obtained by special shaping of the micro nozzles that causes that the air-jest are blown perpendicularly to the blade chord. The presented solution has been investigated and partially optimised based on a computational simulation approach. At this stage, the investigations have been focused on an oscillating segment of the blade, which significantly reduced computational effort and let to conduct simplified optimisation of the developed device.

Keywords: main-rotor aerodynamics, active flow control, helicopter performance, fluidic devices, pulse jets

1. Introduction

In the field of helicopter main rotor aerodynamics, the term "active flow control" generally refers to the dynamic interference with the airflow around the rotor blades and is typically implemented by a so-called active-rotor technology. This field has been intensively developed recently, among others because modern helicopters have reached technological barriers that are very difficult to break, in particular those related to the further increase in cruising speed or the reduction of the level of generated noise.

A good example of the active flow control on main-rotor blades are so-called "servo-flaps" invented and successfully applied in practice by the American engineer Charles Kaman. Servo flaps are small, additional bearing surfaces located behind the trailing edge of the blade over about 75% of its span. Using a mechanical system located inside the blade, the servo-flaps can be deflected just like the control surfaces (ailerons, rudders) of aeroplanes. The flap deflection angle change cycles are consistent with the rotor rotation cycles. Depending on the azimuth, the appropriate deflection of the flap changes the aerodynamic torsional loads of the flexible blade, leading to its torsional deformation. In this way, an effect similar to the change of the pitch angle of the blade depending on its azimuth position is obtained.

The use of dynamically tilting mini-tabs on the main rotor blades has been the subject of many research studies, some of which have focused on the use of such solutions to control blade vibration. Within this theme, in the European project ADASYS, the BK117 helicopter adapted for experimental research was the world's first flying helicopter with an active rotor system based on deflection flaps powered by piezoelectric actuators [1]. The deflections of the tabs were realized with frequencies up to 5 cycles per one rotation of the rotor and their main purpose was to reduce nuisance vibrations. As a result of the measurements taken in flight, a significant reduction in the vibration of the entire helicopter was found in the scope of the vibration fourth harmonic.

The same ADASYS project also investigated the possibilities of controlling the phenomenon of dynamic stall on the retreating blade through a cyclic tilting of the leading edge of the blade [3]. The computational and experimental studies concerned a quarter-chord oscillating blade segment, in which the nasal flap tilting device was adapted to include the front 10% of the blade chord. The gaps between the fixed part of the segment and the swivelling nose flap were covered with an elastic coating. The deflections of the nasal flap, up to 6 °, were forced by a piezoelectric actuator. The frequency of these deflections was consistent with the segment oscillation frequency. According to the authors of the work [3], a very large influence on the effectiveness of the discussed solution in mitigating the negative effects of the dynamic stall was the phase shift between the maximum angle of attack achieved by the entire segment and the maximum deflection of the flap nose down. Thanks to the optimization of this displacement, it was possible to achieve the assumed goals of dynamic stall control: reduction of the characteristic peaks of the drag force and the tilting moment without a significant decrease in the lift force. The conducted tests, especially the experimental ones, confirmed the feasibility of the described solution and its reliability, also under the conditions of centrifugal force.

An alternative method of controlling dynamic stall using active flow control devices is presented in [4]. In this case, the flow-control system is based on a classic "synthetic jet", in which alternating cycles of blowing a stream of air and sucking in the same volume of air are forced by a membrane vibrating with high frequency (usually electrostatically, electromagnetically or piezoelectrically excited). In the described paper, a device of this type was located near the leading edge of the tested blade segment built based on the VR-7 profile. The performed numerical simulations were aimed at demonstrating the potential benefits of using the "synthetic jet" technology to improve the aerodynamic properties of helicopter profiles under dynamic stall conditions.

The Active Gurney Flap (AGF) [2],[8],[9] is a small, flat plate that is mounted on the underside of the blade, near its trailing blade. A plate is deployed from inside the blade, perpendicular to the blade chord, and retracts inside it cyclically - usually in line with the rotation of the rotor. When fully deployed, the plate temporarily increases the lift of the blade by deflecting the airflow behind the trailing edge. This is particularly useful in deflecting blade conditions where, especially at high airspeed, there is usually insufficient bearing capacity to balance the helicopter laterally. Under advancing blade conditions, the plate is retracted inside the blade in order not to generate unnecessarily additional rotor thrust. Due to the limitations of the mechanisms implementing the tilting of the plate, the entire device is usually located some distance (a few per cent of the blade chord) from the trailing edge of the blade. Additionally, the same design constraints mean that in the blade span where the AGF is mounted, it is usually necessary to thicken the trailing edge of the blade. In terms of helicopter performance improvement, the AGF deflection and retraction frequencies are assumed to be consistent with the rotor rotation frequencies. The use of AGF to reduce the effects of helicopter or rotor vibration is also contemplated. In this case, higher AGF oscillation frequencies are assumed, on the order of several cycles per one complete revolution of the rotor.

The paper focuses on the active-flow-control device, functionally similar to the AGF, described above. This means, that this device has been designed to significantly deflect the airflow at a trailing edge of the helicopter blades (preferably by 90 degrees), to force a momentary increase of the lift generated by the main-rotor blade when it is needed, usually on retreating-blade azimuths, in a fast flight of a helicopter. Contrary to the AGF, the device discussed in the paper is not mechanical but fluidic, i.e. it uses high-intensity pulse jets to control an airflow on main-rotor blades.

2. The Concept of Dual Trailing-Edge Nozzle

The practical use of AGF for effective flow control on the main rotor blades of a helicopter may be significantly limited in the application sense due to the technical limitations of mounting this type of mechanical devices on the rotating blades of the rotor. The effectiveness of the AGF decreases as its position is moved away from the trailing edge. This makes that the main limitation becomes the need to fit the retracted flap inside the trailing edge of the blade. This is difficult to reconcile with the restriction on the thickness of the trailing edge of the blade, which must not exceed a certain limit, above which there is a significant increase in drag (so-called "drag penalty"). A very big challenge in the field of structural mechanics is also to ensure the required frequency and amplitude of AGF deployment, in extremely heavy and variable helicopter flight conditions. For these reasons, the author of this paper undertook independent studies on alternative solutions for active flow control on the main rotor blades, characterised by the fact that they generate flow effects similar to those originating from AGF, but on the other hand, they are devoid of the major disadvantages of this mechanical device.

As a result of the in-depth investigations in the field of flow physics, the author finally focused on innovative fluidic devices, that in this case would be used to actively control the flow on the main rotor blades of a helicopter. In this regard, the author developed his invented "Dual Trailing-Edge Nozzle" (DTEN) System, which is the subject of pending patent proceedings.

The system of mini-nozzles of type DTEN was originally invented, designed and implemented by the Author as a study system for active wing load control [11],[12]. This work was carried out as part of the European Project STARLET (Clean Sky Project). The high efficiency of this system, designed solely based on computational techniques, has been confirmed in experimental studies carried out within the same project. Based on the experience gained during the STARLET project, the author has developed a version of the DTEN mini-nozzle system designed specifically for the helicopter main rotor blades. This innovative fluidic system, shown in Figure 1, consists of a row of mini-nozzles located within a certain range of the blade span along its trailing edge. It is assumed that the nozzles are fed by some source of compressed air. This potential source is neither the subject of the invention nor of this article, however, when analysing various possibilities, the most promising solution seems to be electromagnetically or piezoelectrically driven mini-pumps housed in the blade structure.

In general, the compressed air delivered to the nozzles has a flow direction "nearly" parallel to the local chords of the blade. The main task of the DTEN nozzles is to change the direction of this high-energy air jet by 90 degrees downwards, as shown in Figure 2 and Figure 3. It was a huge challenge to fit nozzles working in this way into the thin trailing edge of the blade. To achieve this goal, thorough optimisation studies on possible the best shape, dimensions of the nozzle, as well as the spacing between neighbouring nozzles, have been conducted. The main problem that had to be solved when designing the nozzle shape was the very small space in which the effect of a strong deflection of the airstream had to be realized. This space was limited by the thickness of the blade trailing edge. Ultimately, the desired flow effect was obtained through the special design of the two-channel outlet from the nozzle and also using the Coanda effect [6] - a physical phenomenon consisting in the adhesion of a high-energy fluid stream to the nearest solid surface. As shown in Figure 2 and Figure 3, the strongly deflected compressed air jet exiting the DTEN nozzle strongly deflects the airflow near the trailing edge, causing a local increase in the flow-velocity circulation, and finally leading to a momentary increase in lift acting on the blade.

In a fast forward flight of a helicopter, the greatest deficit of the lift force is observed at blade azimuths in the proximity of the retreating blade. Therefore, the blowing from DTEN nozzles should be activated and the most intense at such azimuths. At other azimuths, there is no need to sustain the blowing, so it should be stopped. Therefore, separate studies have been devoted to the optimal determination of a duty cycle (DC) of pulse blowing from the nozzles, which an important part of the optimisation of pulse-jet systems [5]. Some results concerning this problem are presented in the paper.

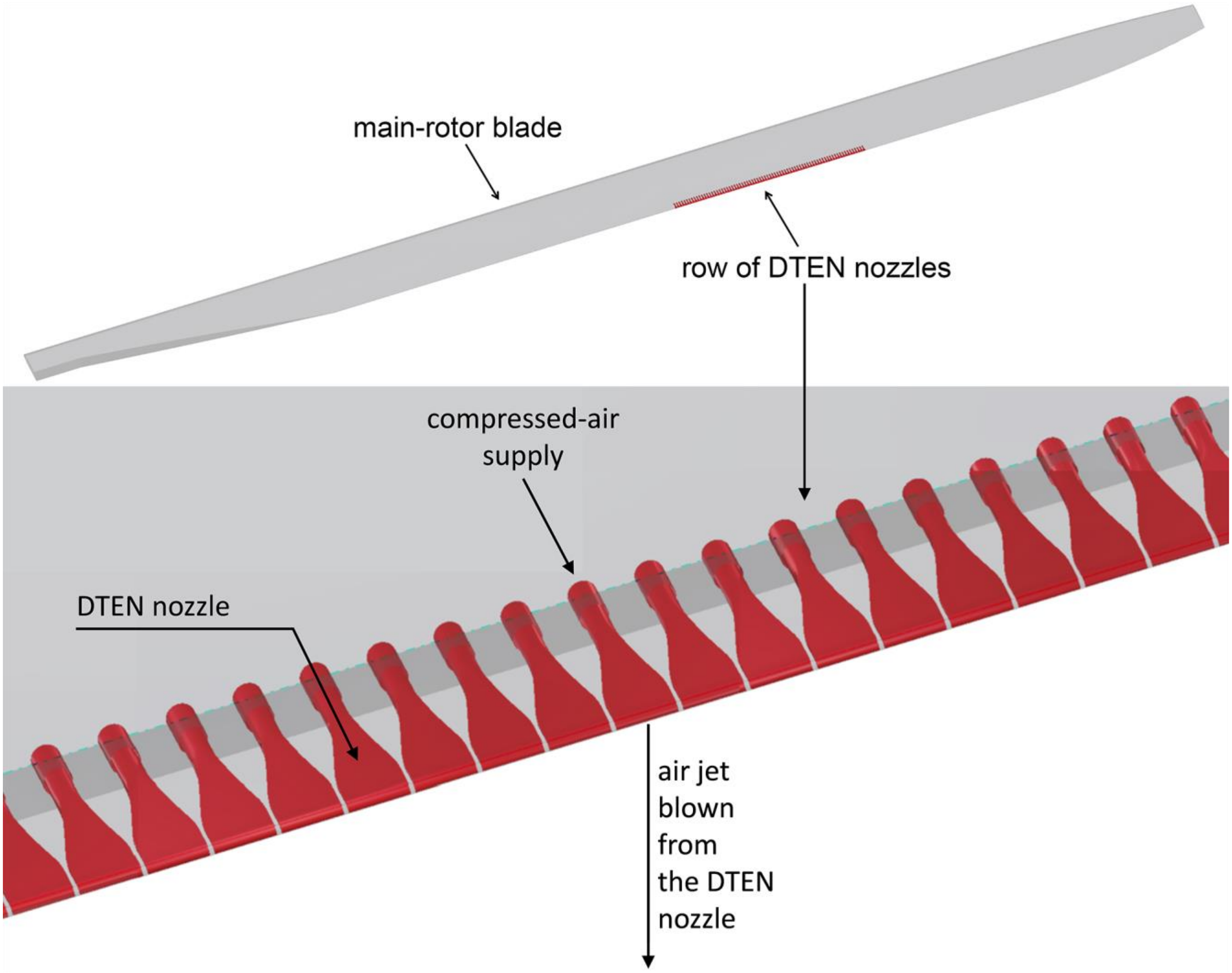

Figure 1 - The system of the DTEN mini-nozzles system designed and optimised for active flow control on the helicopter-main-rotor blades.

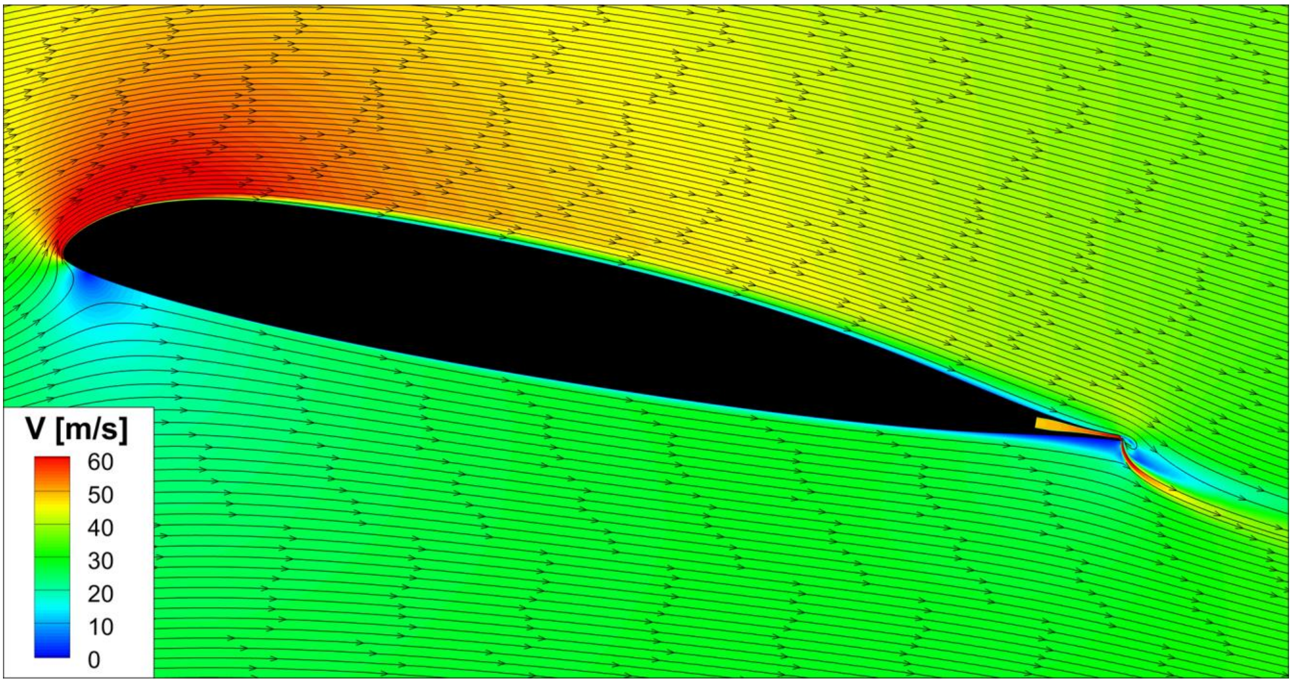

Figure 2 - Air-flow visualisation around the main-rotor blade equipped with a row of DTEN nozzles localised at its trailing edge.

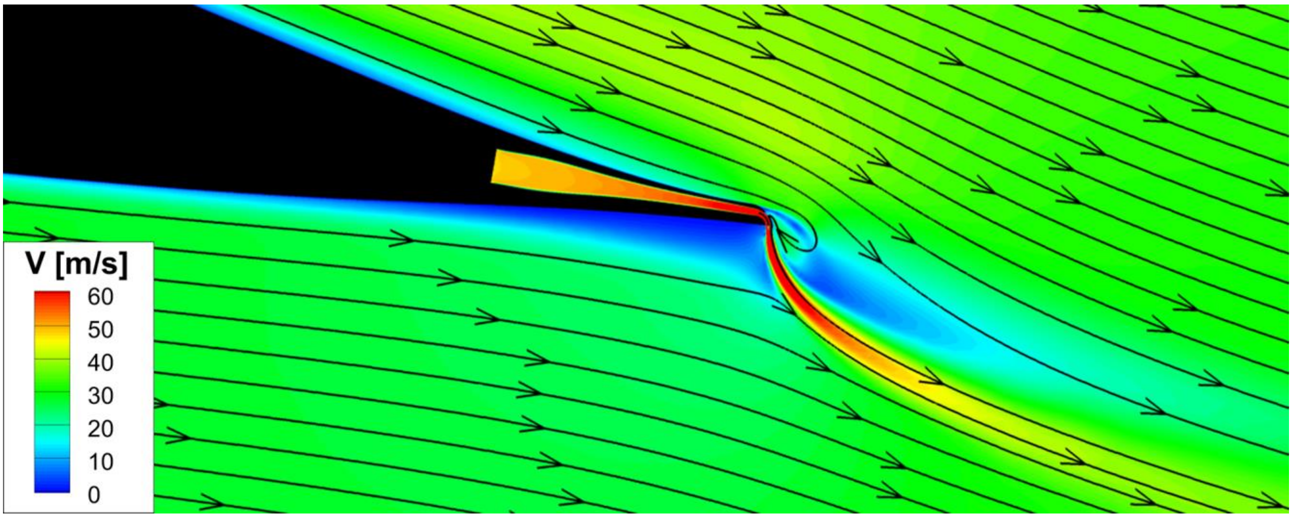

Figure 3 - Air-flow visualisation around the main-rotor blade equipped with a row of DTEN nozzles localised at its trailing edge. Zoomed view.

3. Research Methodology

Computational investigations of discussed DTEN system mounted on helicopter blades were conducted based on a 2.5D approach. The assumed simplification of the problem consisted in a replacement of fully three-dimensional main-rotor-blade geometry and kinematics, by three-dimensional analysis of flow around the section of the blade changing harmonically its angle of attack (α) in this case corresponding to the blade pitch angle in a real flight of the helicopter.

Computational simulations and aerodynamic analyses of the discussed fluid-dynamic phenomenon were carried out using the URANS (Unsteady Reynolds-Averaged Navier-Stokes) solver ANSYS FLUENT [1] and the in-house UDF (User Defined Function) code VIRTUAL-ROTOR-2.5D [9].

The simulations conducted concerning the "infinite" blade, shown in Figure 4. The blade segment, of a chord of 0.5 m was built based on the modified high-performance helicopter airfoil ILH312 [10]. The geometry of DTEN nozzles and the flow phenomena occurring inside them were modelled fully three-dimensionally.

The flow simulations using the ANSYS FLUENT solver were conducted assuming the flow model three-dimensional, unsteady, compressible, viscous, with Shear-Stress Transport k-ω turbulence model. The computational mesh was of high quality and density (Y+≈1). The effect of changing harmonically pitch of the blade (angle of attack α), was modelled by the Sliding Mesh and Non-Conformal Interface techniques, implemented in the ANSYS FLUENT solver.

In the computational simulations, discussed in the next section, the Mach (*M*) and Reynolds (*Re*) numbers of the external uniform flow around the segment were: *M=0.1* and *Re=1164800*, respectively. The blade-segment pitching amplitude was 5 degrees, the average pitch was 5 degrees and the pithing-oscillation frequency (*f*) was *f* = 5Hz, so the reduced frequency (k) of pitching oscillations was *k = 0.461*. For given: *C* - blade reference chord, *f* - frequency of blade oscillations and *V* - external flow velocity, the reduced frequency (k) is defined as follows:

$$k = \frac{2\pi \cdot f \cdot C}{V} \quad (1)$$

For all investigated configurations, presented in this paper, the same blade kinematics was assumed. Figure 5 and Figure 6 show assumed changes in time of a blade angle of attack (α). The same Figures show assumed changes in time of the Blowing Momentum Coefficient (C_μ), defined as follows:

$$C_\mu = \frac{\dot{m} \cdot V_j}{S \cdot q_{ref}} \quad (2)$$

where: $\dot{m}$ – total ma flow rate (through all nozzle active), V_j – average flow velocity at nozzle outlets, S – reference area, q_{ref} – reference dynamic pressure. In general, the coefficient C_μ corresponds to the momentum of air jets blown from all nozzles related to a reference force calculated based on free stream dynamic pressure.

As shown in Figure 4, an appropriate mass flow rate was set at the nozzle inlets to obtain the required momentum of air streams blown from the nozzles. To do this, the "mass flow inlet" boundary conditions were established at nozzle inlets. At planes limiting the blade segment in a spanwise direction, the "periodicity" boundary conditions were applied.

In conditions of helicopter fast horizontal flight, the pulse blowing from the DTEN nozzles was investigated for several different values of the duty cycle (DC), which is often characterized by a square waveform and is the ratio of the on-time of the blowing actuation to the total actuation period [5]. In simulations presented in this paper, two alternative scenarios of setting the mass flow rate at nozzle inlets as a function of time were investigated. In the first scenario, "sinusoidal", the mass flow rate vs. time was w harmonic function, reaching a minimum at the advancing blade azimuth, while maximum at the retreating blade azimuth. Within the "ramp" scenario the dependency: mass flow rate vs. time had trapezoidal form but only in the proximity of the retreating blade azimuths. In the case of helicopter hover simulations, a constant, non-zero value of mass flow rate at nozzle inlets was set for all blade azimuths.

The simulations discussed in the next section were carried out for a fast flight of a helicopter, for three configurations: the reference configuration "Clean Blade", corresponding to the classic case without any flow-control system active, and for two configurations with the blowing active, i.e. the "DTEN (Sinusoidal)" with the coefficient C_μ changing quasi-harmonically as a function of time (t), as shown in Figure 5 and the "DTEN (Ramp) "with the quasi-trapezoidal dependence of C_μ *vs. t*, shown in Figure 6. For the former scenario, the duty cycle was $DC = 0.5$ while for the latter one it was $DC = 0.225$.

When analysing the results of the conducted simulations, first of all, the following global aerodynamic characteristics of the blade segment were taken into consideration:

- C_L - lift coefficient,
- C_D - drag coefficient,
- C_m - pitching moment coefficient.

Additionally, a thorough analysis of time-variable local flow parameters was conducted, focusing at:

- Pressure Coefficient (C_P) distributions in selected cross-section of the blade segment,
- Flow Velocity Magnitude (V) contours, made at the selected cross-section of the flow region.

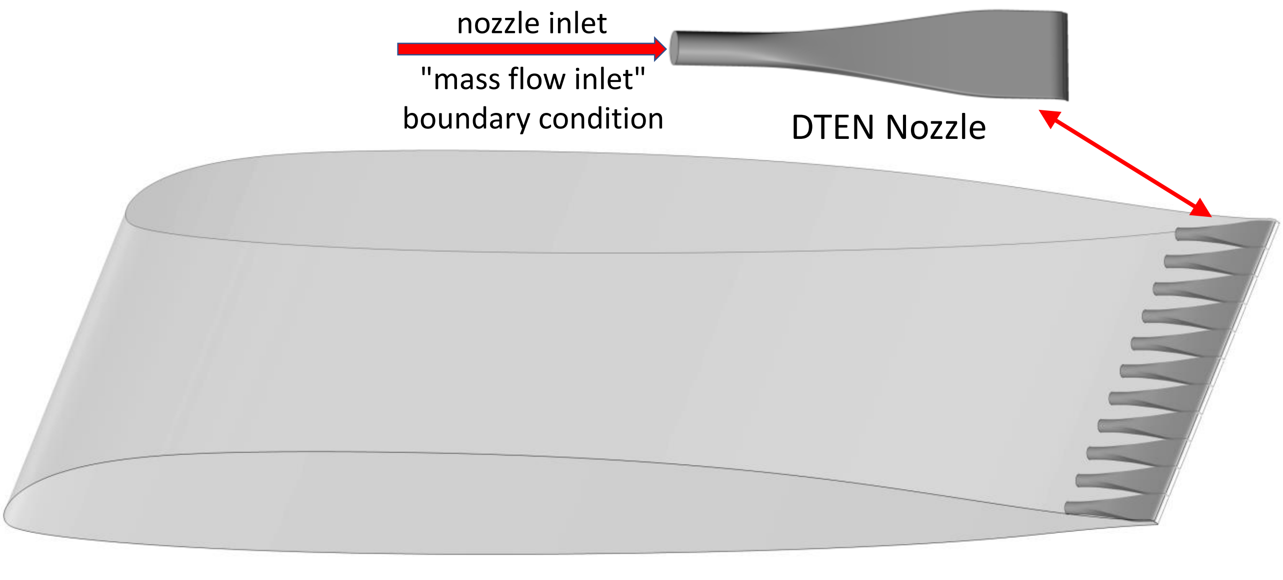

Figure 4 – Computational model of a segment of the main-rotor blade equipped with a row of DTEN nozzles.

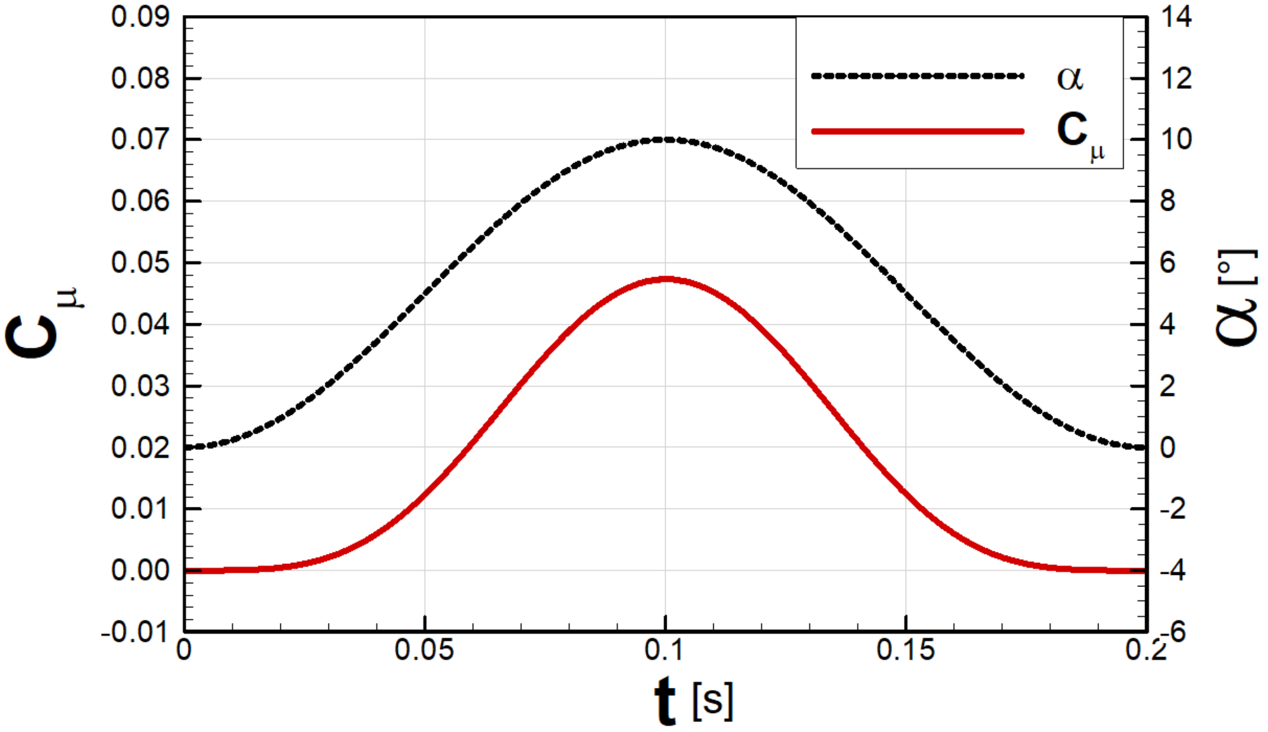

Figure 5 – The Angle of Attack (α) and Blowing Momentum Coefficient (C_μ) as functions of time (t) during one period of oscillations of the blade segment, for the configuration "DTEN (Sinusoidal)". Duty cycle $DC = 0.5$.

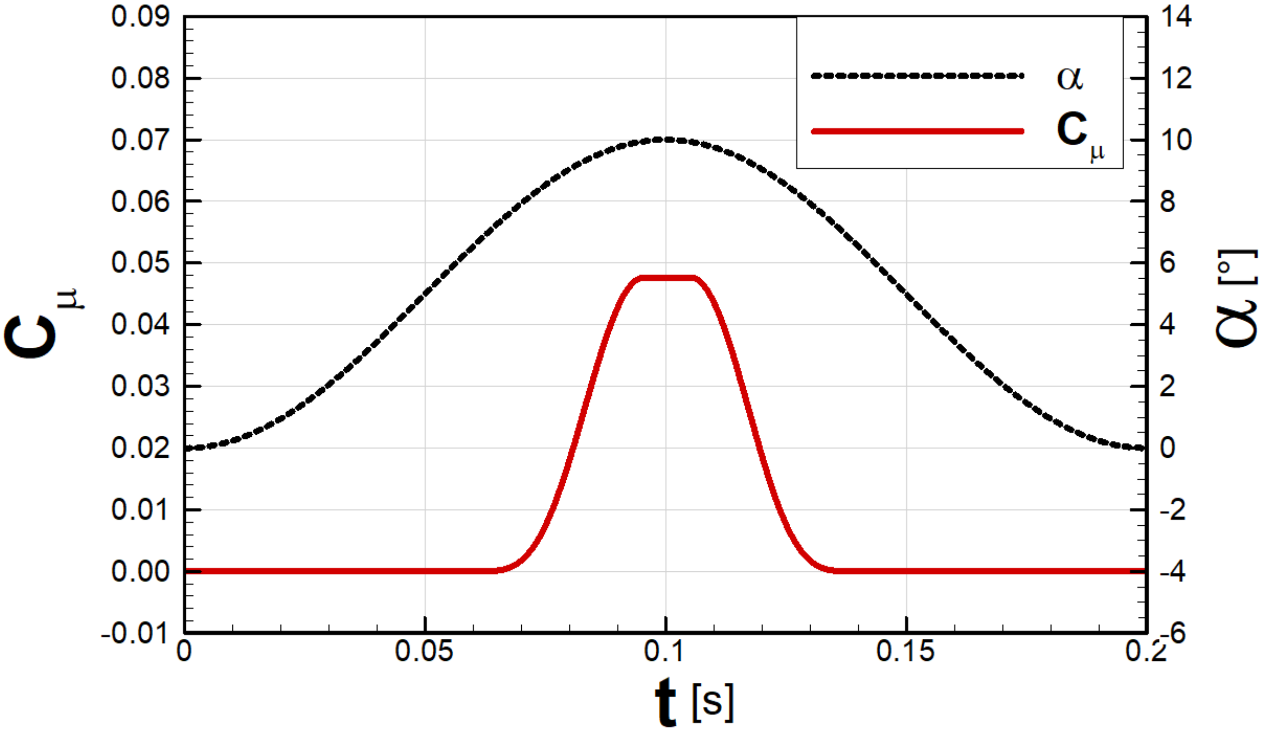

Figure 6 - The Angle of Attack (α) and Blowing Momentum Coefficient (C_μ) as functions of time (t) during one period of oscillations of the blade segment, for the configuration "DTEN (Ramp)". Duty cycle $DC = 0.225$.

4. Results of Computational Simulations

In the results presented below, arrows indicate the direction of changes of angle of attack (alpha) or direction of changes of given flow parameter corresponding to current changes of angle of attack. In particular symbol "↑" means a phase of the growing angle of attack, while "↓" indicates a phase of dropping in this parameter.

Global, unsteady aerodynamic characteristics for the blade-segment configuration "DTEN (Sinusoidal)" and the "Clean Blades" configuration are compared in Figure 7 - Figure 9. The Figures show, that the configuration with a pulse blowing active, compared to the reference configuration, is characterized by significantly higher values of the lift coefficient C_L- up to 74% increase in the case of the maximum angle of attack and a higher value of derivative: $dC_L/d\alpha$. Moreover, as shown in Figure 8, for the same values of the drag coefficient C_D, the configuration "DTEN (Sinusoidal)" achieves significantly greater values of the lift coefficient C_L than the reference configuration, which proves that in virtually the entire range of angles of attack, this configuration is characterized by significantly greater aerodynamic efficiency, i.e. lift over drag coefficient. However, this is accompanied by a significant increase in the negative pitching moment coefficient, especially at the highest angles of attack, as shown in Figure 9.

A similar phenomenon is also observed when comparing the global unsteady aerodynamic characteristics of the "DTEN (Ramp)" configuration and the reference configuration "Clean Blades", as shown in Figure 10 - Figure 12. In this case, the maximum increase in the lift coefficient C_L is approx. 75.5% and increase in the derivative $dC_L/d\alpha$ is similar as in the previous case. The significant differences in the global aerodynamic characteristics between the "DTEN (Sinusoidal)" and "DTEN (Ramp)" scenarios are mainly observed just for lower angles of attack, which is obvious when within this range of angles of attack we are comparing the pulse-blowing intensities applied in both compared cases (see Figure 5 and Figure 6). In particular, if we define the "pulse blowing actuation" efficiency (η) as follows:

$$\eta = \frac{C_{L(a)} - C_{L(i)}}{C_\mu} \tag{3}$$

where $C_{L(a)}$ and $C_{L(i)}$ are the lift coefficients for the cases of pulse blowing active and inactive, respectively, and the C_μ is the blowing momentum coefficient for the case of blowing active then we can notice that for the highest angle of attack (α = 10 deg):

- η = *15.78* for the "DTEN(Sinusoidal)" scenario,
- η = *15.47* for the "DTEN(Ramp)" scenario.

However, it worth emphasising, that this high "pulse blowing actuation" efficiency has been achieved within the duty cycle DC=0.5 for the "DTEN(Sinusoidal)" scenario and DC=0.225 for the "DTEN(Ramp)" scenario. This means that the "DTEN(Ramp)" scenario of pulse blowing gives similar profits in main-rotor performance improvement (within the range of retreating blade azimuths), but is much more economic than the "DTEN(Sinusoidal)" scenario.

Similar differences between the scenarios "DTEN (Sinusoidal)" and "DTEN (Ramp)" can be seen in Figure 13 and Figure 14, where for both of these scenarios, the contours of the flow velocity magnitude are presented in snapshots made for selected moments of the blade motion, described by current values and phases of the angle of attack:

- minimum: $\alpha = 0^o$,
- average - in an increasing phase: $\alpha=5^o$↑,
- maximum: $\alpha=10^o$,
- average - in a decreasing phase: $\alpha=5^o$↓.

For $\alpha = 0^o$ and $\alpha = 10^o$, the flow field visualizations for both pulse-blowing scenarios are similar. In particular, for the highest angle of attack $\alpha=10^o$, in both cases, a stream of highly accelerated air jets is nearly perpendicular to the local chord of the blade, which demonstrates well the Coanda effect. For the transition phases: $\alpha=5^o$↑, and $\alpha=5^o$↓ this stream is slightly weaker for the "DTEN

(Sinusoidal)" scenario and invisible for the "DTEN (Ramp)" scenario. A similar phenomenon can be observed in Figure 15 and Figure 16, where the distributions of pressure coefficient (C_P) in the cross-section of the blade segment in selected phases of its oscillating motion (α=0º, 5º↑, 10º, 5º↓) are presented and compared to the reference configuration.

In the case of the "DTEN (Ramp)" configuration for the blade-motion phases: α=0º and α=5º↑, the distribution of CP coefficient is similar for the analogous distribution calculated for the "Clean Blades" configuration. In the case of the "DTEN (Sinusoidal)" configuration, the C_P distributions differ significantly from the reference distributions for all four considered moments of the blade motion.

5. Summary and Conclusions

The innovative fluidic device named Dual Trailing-Edge Nozzle System has been developed towards its application for flow control on helicopter-main-rotor blades. The device consists of a row of micro nozzles located at the blade trailing edge. The pulse blowing from the nozzles is activated to momentary increase the lift generated by the blade, which is useful at retreating-blade azimuths in a fast flight of a helicopter. Conducted computational simulations concerning the implementation of the developed fluidic system at a simplified model of the main-rotor blade, indicated the high potential of the developed device in performance improvement of a helicopter. Related to global aerodynamic characteristics, the system showed a significant increase of the blade lift coefficient, of order 75% compared to a classic rotor blade configuration, without any active-flow-control devices. This large increase in a lift (here considered just for a case of the retreating blade in a helicopter fast flight) has been achieved with relatively high energetic efficiency. The increase in the lift coefficient observed has been about 15-16 times higher than the value of the Blowing Momentum Coefficient, related to the energy inputs necessary to generate the appropriate momentum of the air streams flowing out of the micro-nozzles. Separate studies, devoted to duty-cycle optimisation, indicated that the above profits in helicopter performance improvement can be achieved even for the duty cycle coefficient of order 0.2. For this purpose, the ramp scenario of pulse blowing activation is recommended. However, it will be possible to fully confirm the suitability of the developed fluidic system based on the DTEN device to increase the helicopter performance in a high-speed flight only when the entire system is thoroughly tested on the computational model of the complete helicopter. This challenging task is planned as the next stage of the research presented in this paper.

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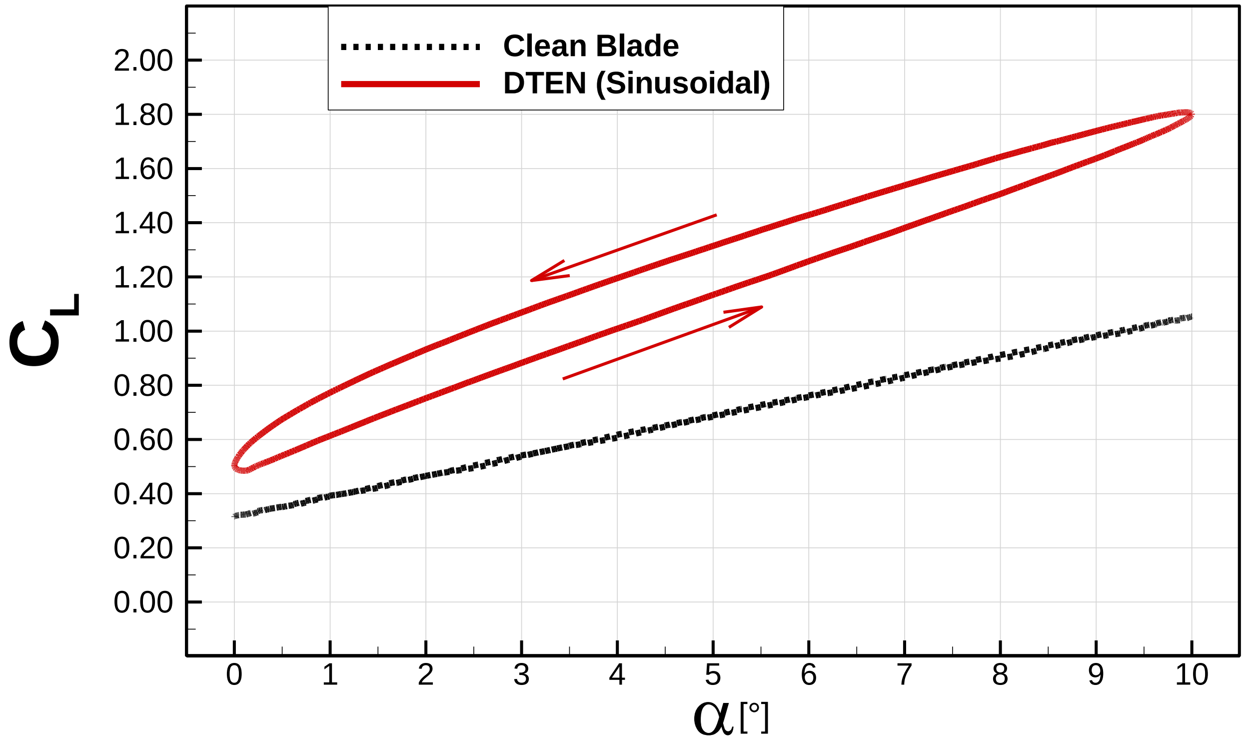

Figure 7 – Comparison of dependences of the lift coefficient (C_L) on the angle of attack (α) for the "clean blade" and "sinusoidal" scenarios of supplying DTEN nozzles with compressed air.

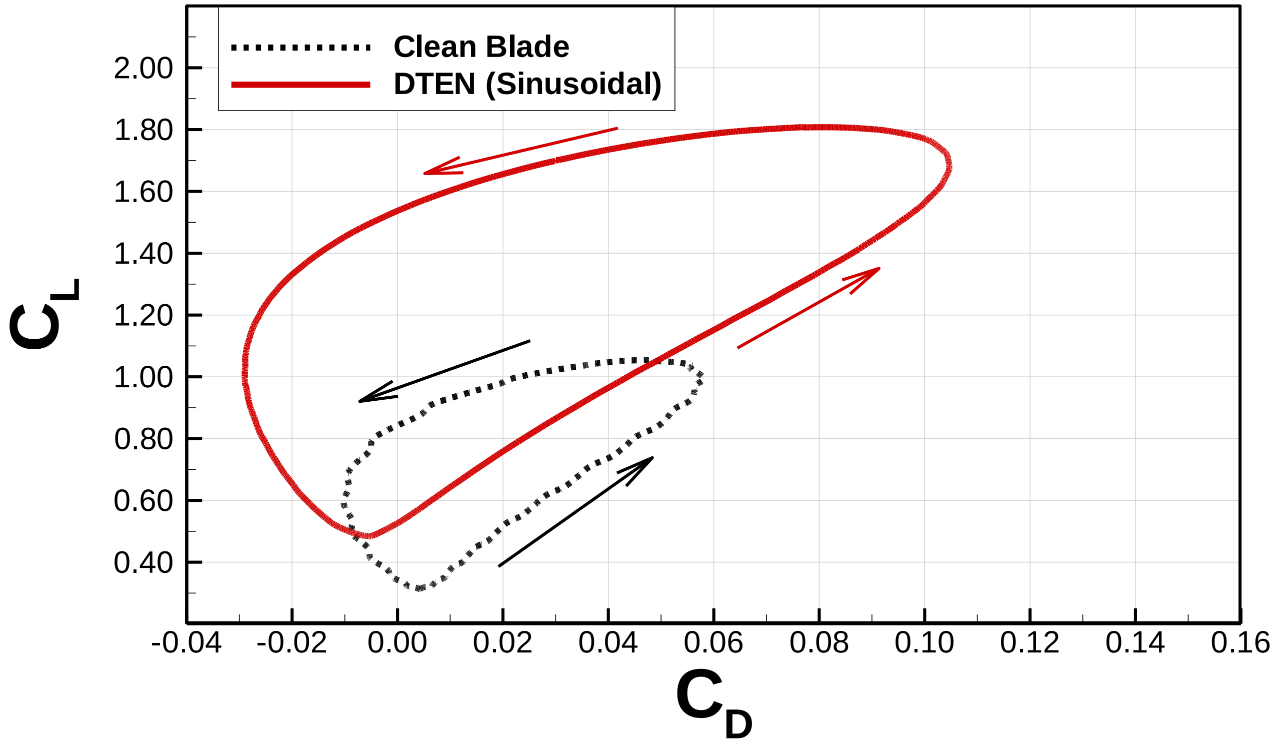

Figure 8 - Comparison of dependences of the lift coefficient (C_L) on the drag coefficient (C_D) for the "clean blade" and "sinusoidal" scenarios of supplying DTEN nozzles with compressed air.

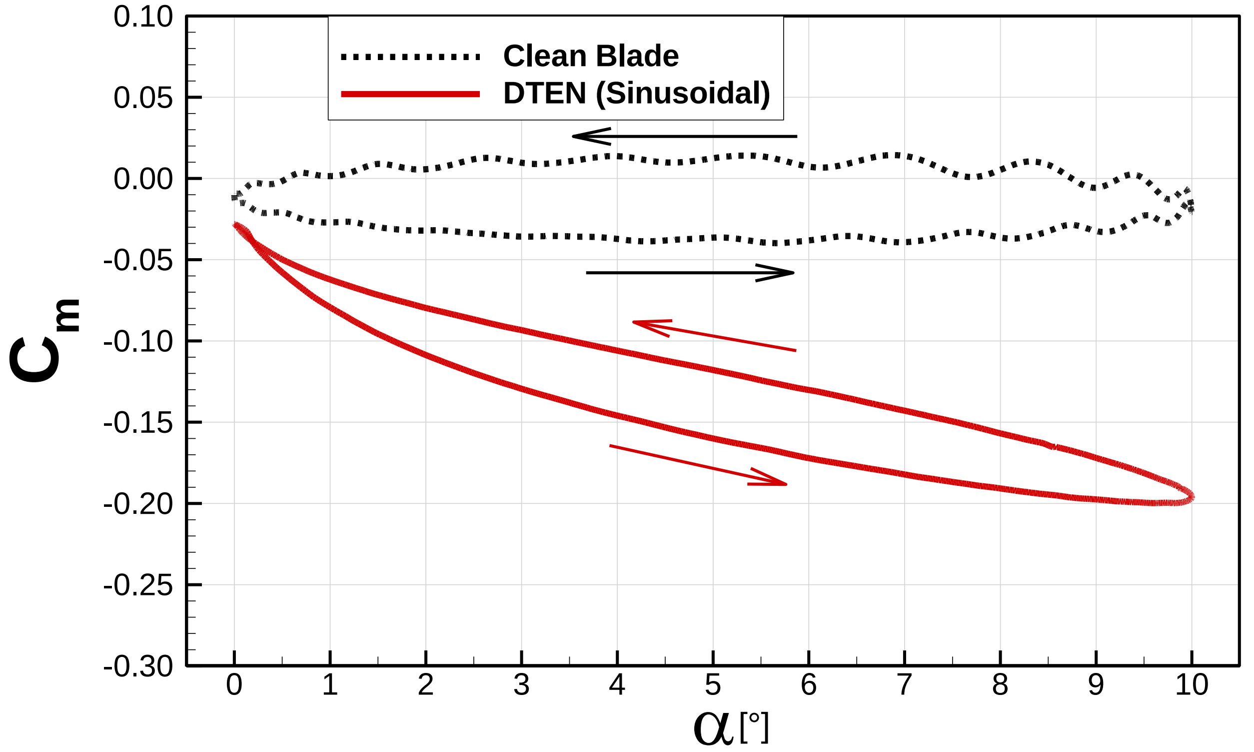

Figure 9 - Comparison of dependences of the pitching-moment coefficient (C_m) on the angle of attack (α) for the "clean blade" and "sinusoidal" scenarios of supplying DTEN nozzles with compressed air.

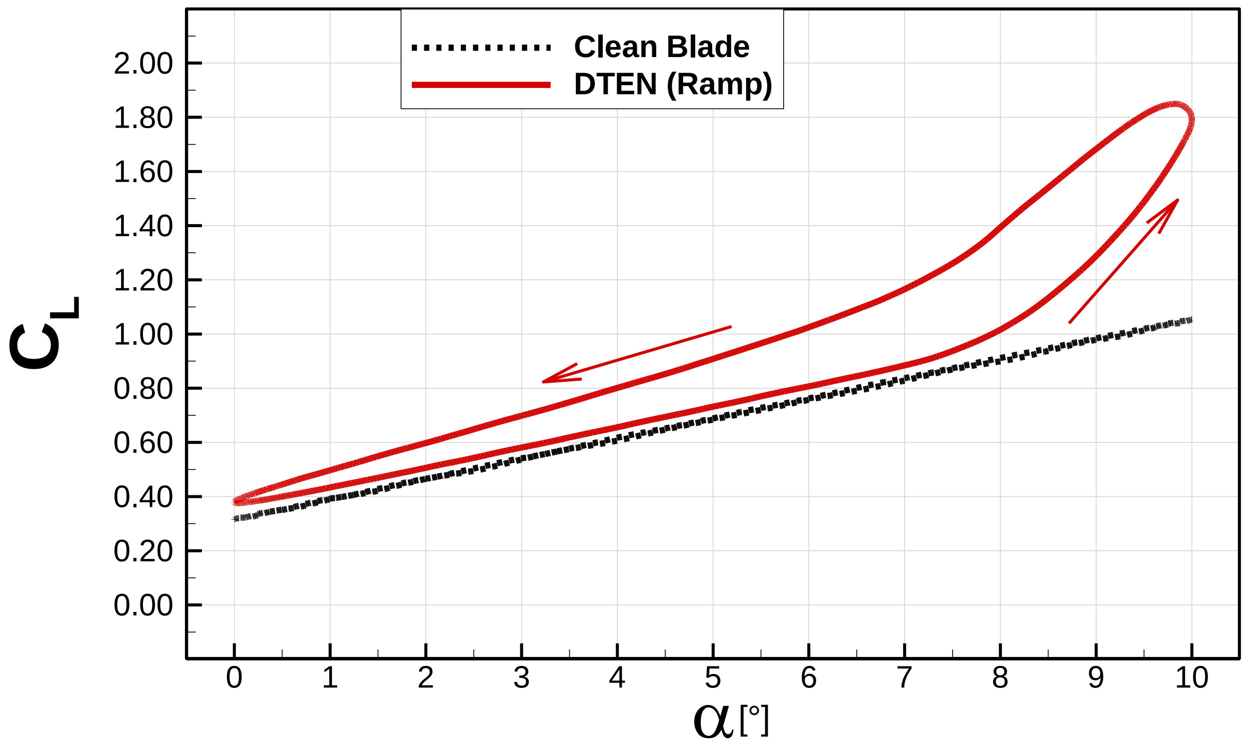

Figure 10 - Comparison of dependences of the lift coefficient (C_L) on the angle of attack (α) for the "clean blade" and "ramp" scenarios of supplying DTEN nozzles with compressed air.

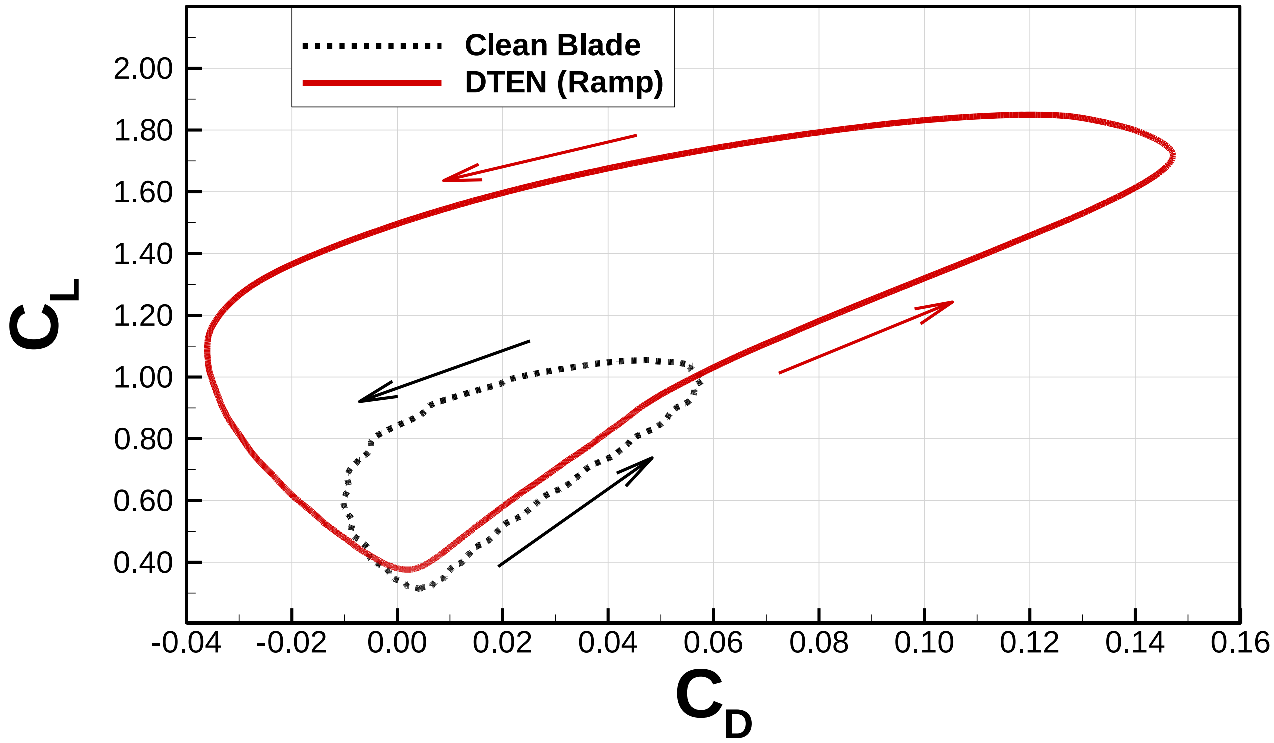

Figure 11 - Comparison of dependences of the lift coefficient (C_L) on the drag coefficient (C_D) for the "clean blade" and "ramp" scenarios of supplying DTEN nozzles with compressed air.

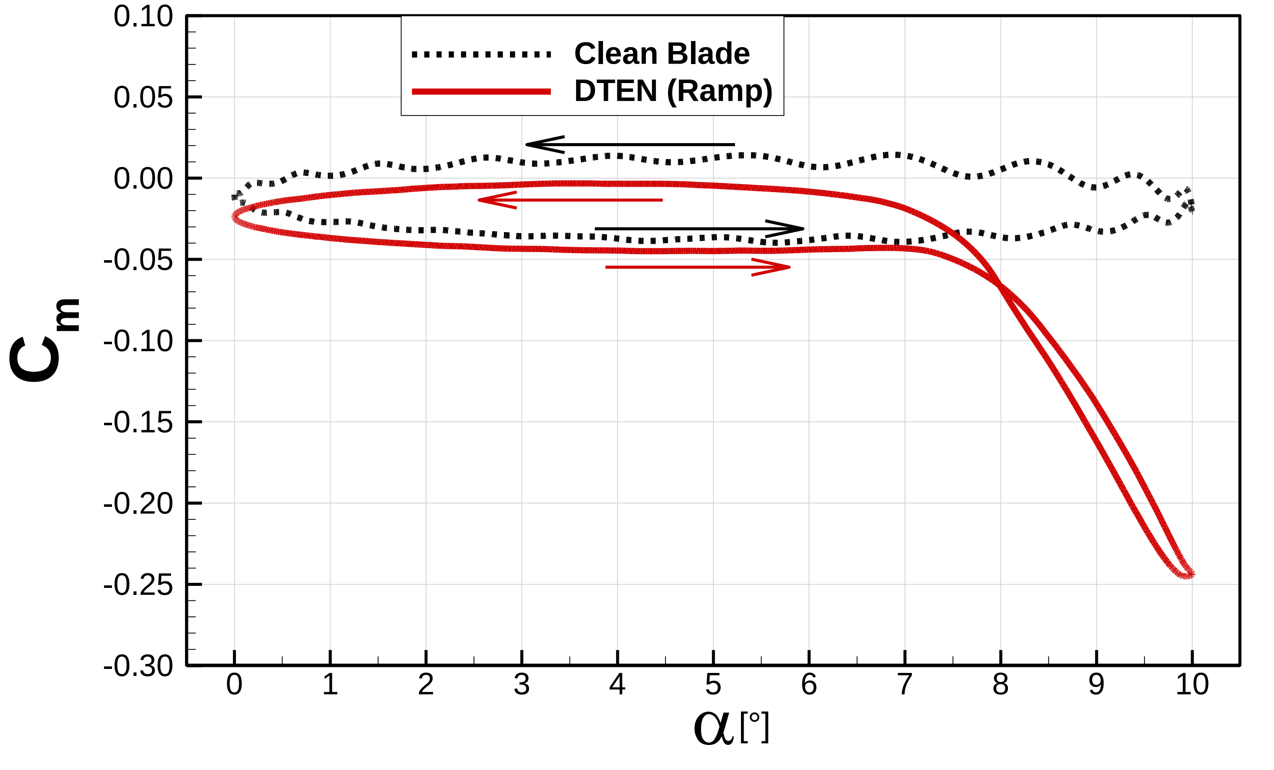

Figure 12 - Comparison of dependences of the pitching-moment coefficient (C_m) on the angle of attack (α) for the "clean blade" and "ramp" scenarios of supplying DTEN nozzles with compressed air.

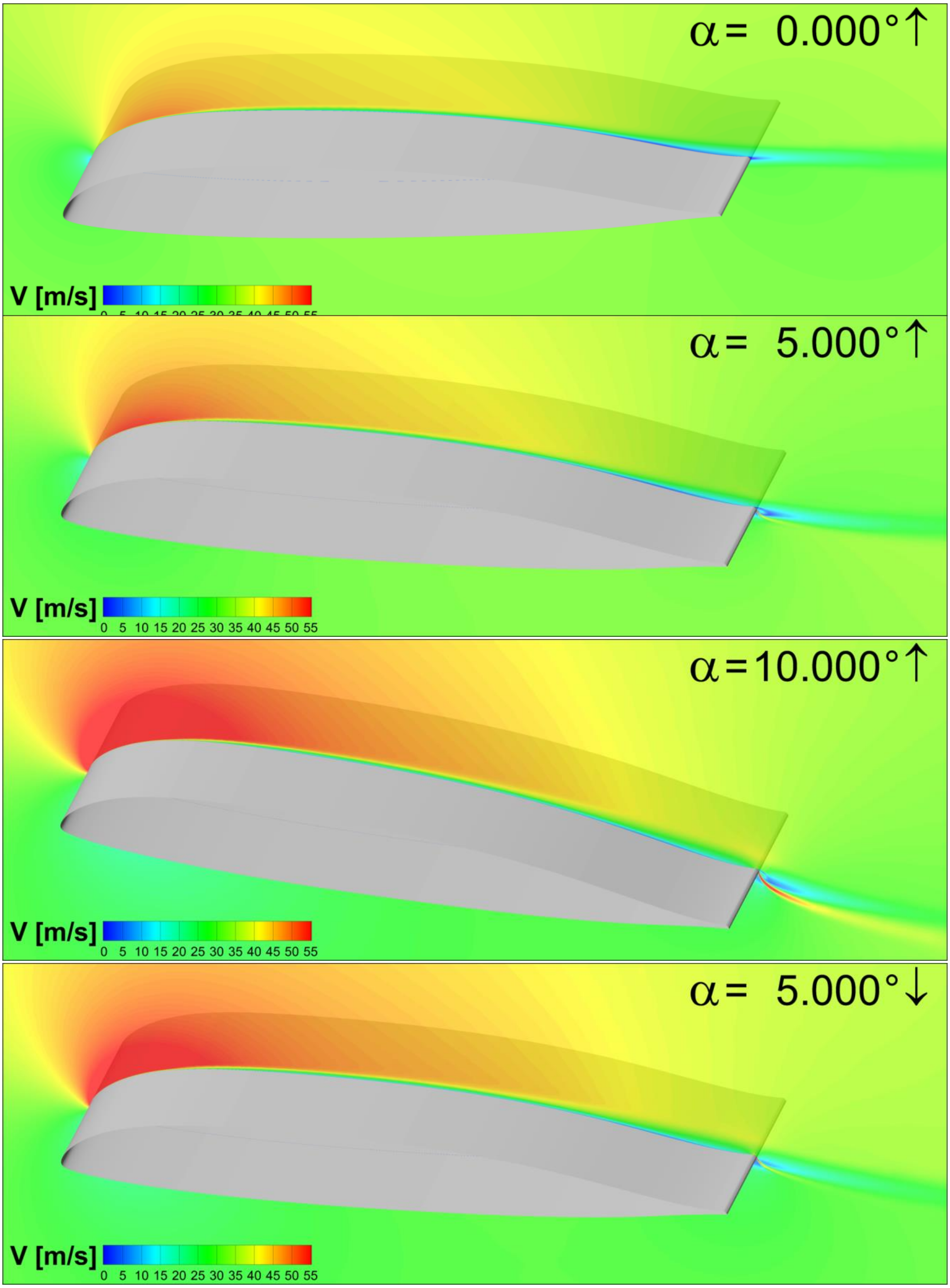

Figure 13 - The flow velocity-magnitude contours in flow-field cross section, for the sinusoidal scenario (DC=0.5) of supplying DTEN nozzles with compressed air.
Angles of attack α = 0↑, 5↑, 10↑ and 5↓ degrees.

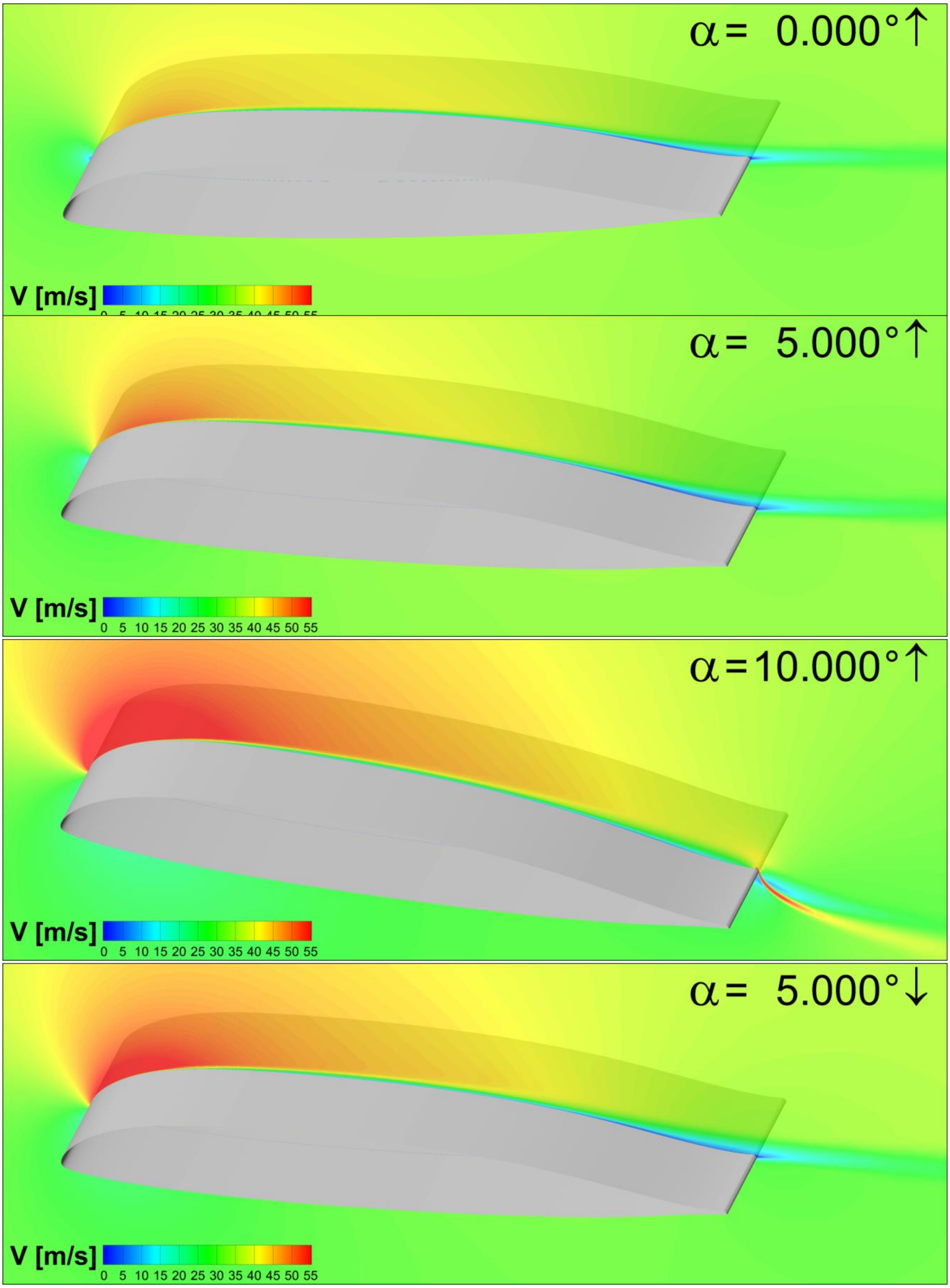

Figure 14 - The flow velocity-magnitude contours in flow-field cross section, for the ramp scenario (DC=0.225) of supplying DTEN nozzles with compressed air.
Angles of attack α = 0↑, 5↑, 10↑ and 5↓ degrees.

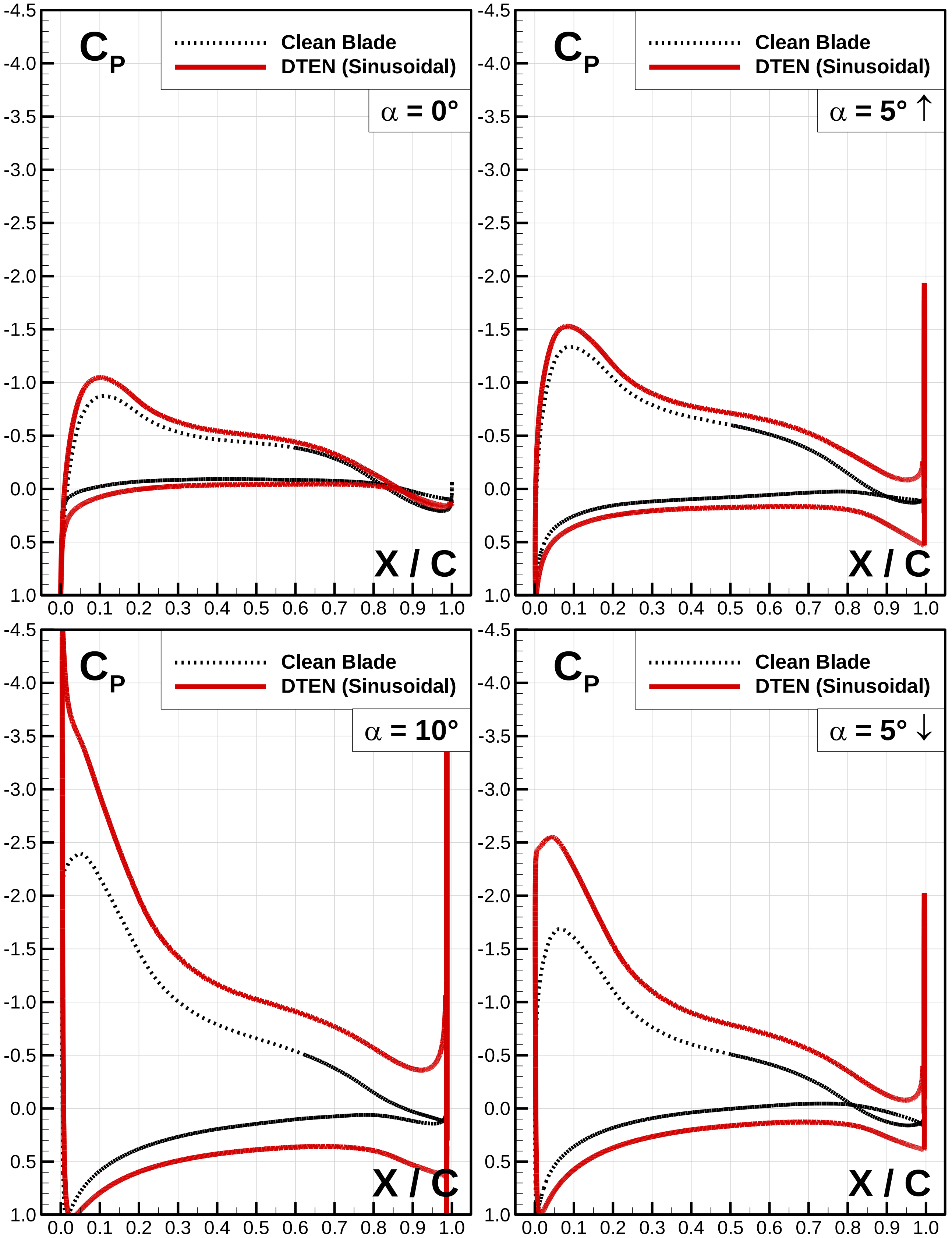

Figure 15 - Comparison of the pressure-coefficient (CP) distribution in a blade cross-section, for selected moments of blade motion, for the "blowing inactive (clean blade)" and "sinusoidal, DC=0.5" scenarios of supplying DTEN nozzles with compressed air.
Angles of attack α = 0↑, 5↑, 10↑ and 5↓ degrees.

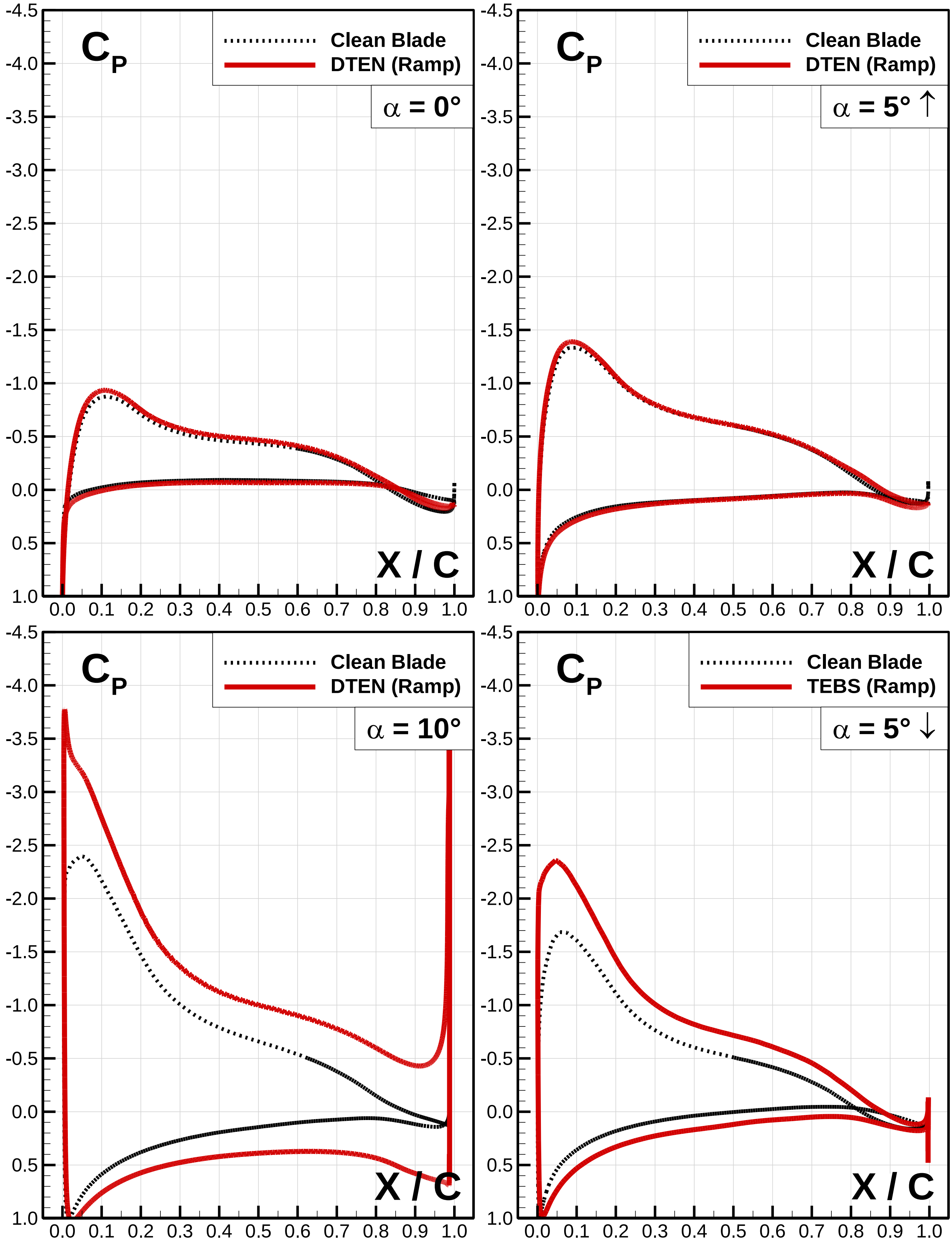

Figure 16 - Comparison of the pressure-coefficient (CP) distribution in a blade cross-section, for selected moments of blade motion, for the "blowing inactive (clean blade)" and "ramp, DC=0.225" scenarios of supplying DTEN nozzles with compressed air.
Angles of attack α = 0↑, 5↑, 10↑ and 5↓ degrees.

7. Copyright Statement

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