

FLOW VISUALIZATION OF THE WING MODEL EQUIPPED WITH LOAD CONTROL FLUIDIC DEVICES

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Abstract

In the extraordinary off-design flight conditions, such as accelerated manoeuvres or sudden gusts, wing-bending moments may grow rapidly. This may lead to damage of the wing structure. To alleviate the excessive aerodynamic loads in off-design conditions the wing-load-control systems basing on blowing devices were developed. Proposed in these work fluidic devices could be an alternative to the conventional mechanical solutions, such as symmetrical deflections of ailerons or deflection of spoilers. As a result of the CFD studies, among many considered concepts, three solutions were chosen as the most promising. Two of them, namely Fluidic Spoiler and Dual Trailing Edge Nozzles, were tested in IoA low speed wind tunnel. Fluidic Spoiler consisted of the matrix of mini nozzles located on an upper wing surface in its tip part. Air jets blown from the nozzles were influencing the main flow around the wing, leading to flow separation and as a result, to alleviation of wing bending moment. Dual Trailing Edge Nozzles system consisted of the specially shaped nozzles, located at a wing trailing edge. The system utilises the Coanda effect to change a flow circulation around the wing, leading to spanwise redistribution of aerodynamic loads. The paper presents results of the flow visualization tests carried out on the half wing model equipped with load control fluidic devices. Flow visualization was performed using a fluorescent threads illuminated with ultraviolet light. The main objective of the research was to determine the flow separation areas and its character, associated with additional air blowing on the wing surface. The experimental tests were performed in low speed wind tunnel T-3 (5-meter diameter test section) in the Institute of Aviation. For these tests the model of semi-span wing (2.4 m span), situated vertically on the endplate in wind tunnel test section was used. Wind tunnel test were performed at Mach number $M = 0.1$. The study was carried out in the framework of the European project STARLET.

Keywords: applied aerodynamics, load control, fluidic devices

1. Introduction

A control of aircraft aerodynamics in non-classical but more advanced way is a subject of many experimental and computational works. For this purpose, various methods of flow control were used [1]. Historically, flow control techniques based on three classical methods, namely blowing, suction and vortex generation [2-7]. Flow control by blowing on the incompressible and compressible boundary layer has been the subject of research and analysis for decades [8, 9]. In many papers [10, 11] the effect of blowing using different slot types, thicknesses and angles of blowing was investigated experimentally.

In most of the studies about the flow control by blowing, the main task of an air injection was to energise the boundary layer to delay the flow separation phenomenon and as a result to improve the airfoil aerodynamic performance. Here, the blowing was used to the wing load control. The necessity to provide a wing load control is associated with the presence of extreme flight conditions, such as accelerated manoeuvres or sudden gusts, when wing-bending moments may grow rapidly. As an effect of load control technology development, it is possible to design structures having longer fatigue life or such that are lighter and more economic throughout their life. It is also possible to diminish drag during the airplane mission by adjusting the wing load distribution to current flight conditions. The improvement of the passengers comfort during the flight, by reducing aircraft vibration caused by atmospheric turbulence, is also important thing.

To avoid the wing overloading, which can result in damage of the airplane structure various techniques can be used. So far, the conventional way to reduce the load on the aircraft wings was usage of classic aircraft control surface such as spoilers, ailerons or flaps. An example of such a solution is the system of symmetrical aileron deflection, applied on Lockheed C-5 “Galaxy” aircraft [12]. The primary purpose of the C-5 Load Control system, called Active Lift Distribution Control System (ALDCS), was to shift the wing spanwise centre of pressure inboard and reduce the possibility of wing damage, due to presence of extreme flight conditions.

Mechanical complexity of the classic structural solutions on the one hand, and the development of the modern flow control techniques, based in many cases on Micro-Electro-Mechanical Systems (MEMS) on the other hand, are reasons for exploring a new airplane load control methods, such as active flow control solutions. It is a very important thing, that the modern flow control techniques can be significantly faster than conventional methods, allowing a rapid reaction to flow conditions change on the aircraft lift surfaces, or to control the flight of an UAV objects [13].

The paper presents results of the flow visualization tests of a new concept of active flow control system. This system, based on blowing devices was designed in Institute of Aviation and tested in IoA low speed wind tunnel T-3. For these tests the model of semi-span wing (2.4 m span), equipped with two kinds of fluidic devices named the “FLUIDIC SPOILER” concept and the “DUAL TRAILING-EDGE NOZZLES” (DTEN) concept, was used. Wind tunnel test, comprising flow visualization, and balance, pressure distribution and strain measurements, were performed at Mach number $M = 0.1$.

2. Fluidic Devices Concepts

As a result of the numerical studies [14, 15], focused on alleviation of excessive aerodynamic loads, two concepts of the fluidic devices, as the most promising were chosen and tested experimentally, namely: “FLUIDIC SPOILER” and “DUAL TRAILING-EDGE NOZZLES” (DTEN) concepts.

- The “FLUIDIC SPOILER” concept:

This system used the matrix of 540 mini nozzles arranged in nine rows (Fig. 1) located at the 59-92% of the wingspan and 45-65% of the wing chords (every 2.5%). The set of the nozzles blown air in direction normal or inclined at an angle of 45° (blowing against the flow) with respect to the upper wing surface, Fig. 2. Therefore, the system worked like a classical spoiler.

- The “DUAL TRAILING-EDGE NOZZLES” (DTEN) concept

This concept consists of the specially shaped nozzles, located at the wing trailing edge. The system utilises the Coanda effect to change a flow circulation around the wing, leading to spanwise redistribution of aerodynamic loads, Fig. 3.

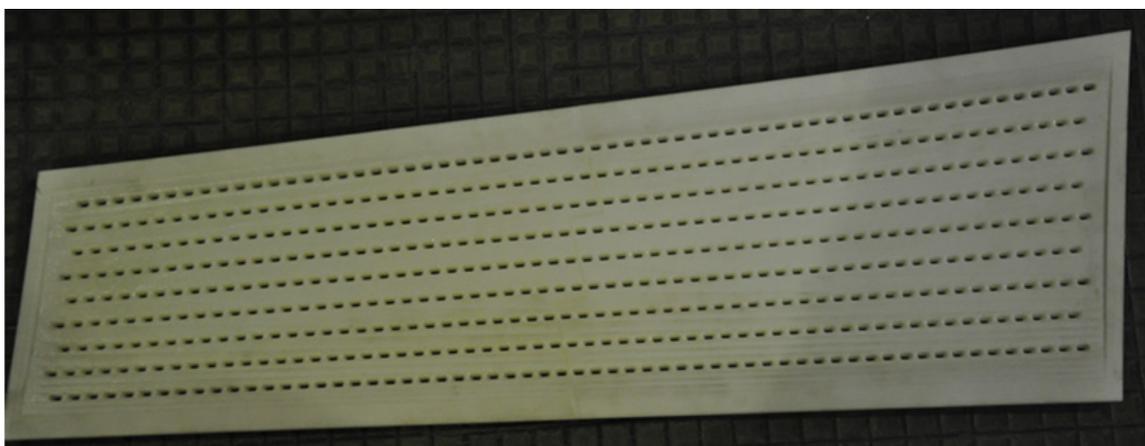


Fig. 1. The panel with matrix of blowing mini nozzles

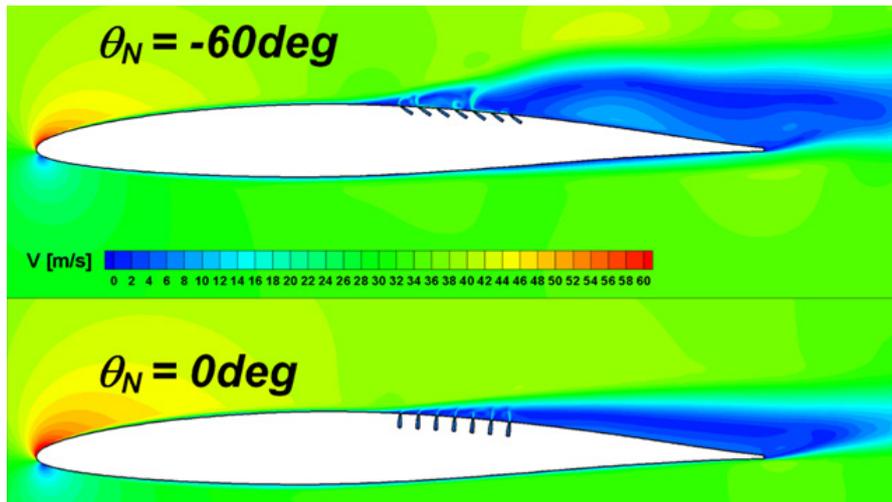


Fig. 2. The “FLUIDIC SPOILER” concept [14]

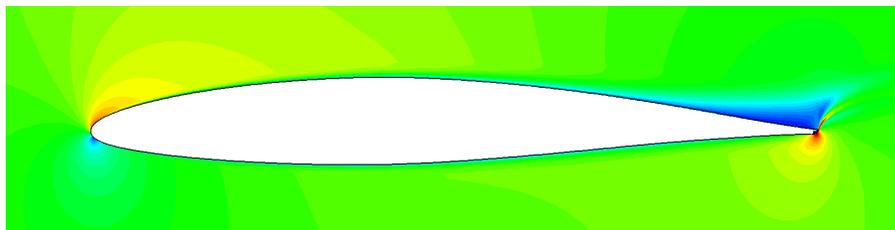


Fig. 3. The “DUAL TRAILING-EDGE NOZZLES” concept [14]

3. Wind tunnel T-3

The wind tunnel tests of the semi-span wing model equipped with active flow control devices were carried out in 5 m diameter low speed wind tunnel T-3 (IoA).

The T3 Institute of Aviation Low Speed Wind Tunnel is an atmospheric, closed-circuit tunnel with an open test section of 5-meter diameter, and 6.5 m length, which could reach velocity of 57 m/s with a dynamic pressure of 2000 N/m². The Reynolds number per meter ranges from 0 to 3.8×10^6 . The flow in the test section was relatively uniform with a longitudinal turbulence level of about 0.5 percent. Test section airflow was produced by 7-m diameter 8-bladed fan powered by a 2040 hp direct current motor.

4. Semi-span wing model

Experimental tests of the active load control systems based on additional air blowing were carried out using the semi-span wing model (2.4 m span) equipped with the proposed active flow control devices. The model was situated in wind tunnel test section in vertical position on the endplate (Fig. 4) and fixed at its base to the two wall balances, i.e. 5 component (front balance) and 3 component (rear balance). These wall balances measured both bending moment and lift force (normal to model chord at its root).

The tested fluidic devices were supplied with air from the external air supplying system, which consisted of the compressor, control valve, flow meter and pipes system, Fig. 5.

5. Flow visualization tests

Wind tunnel tests of the active load control devices installed on the semi-span wing model, were performed in IoA low-speed wind tunnel T-3 at Mach number $M = 0.1$ ($Re = 2.4 \times 10^6$ – with respect to root chord) for the selected angles of attack from the range $\alpha = 0-12^\circ$. During the tests



Fig. 4. The semi-span wing in the wind tunnel T-3

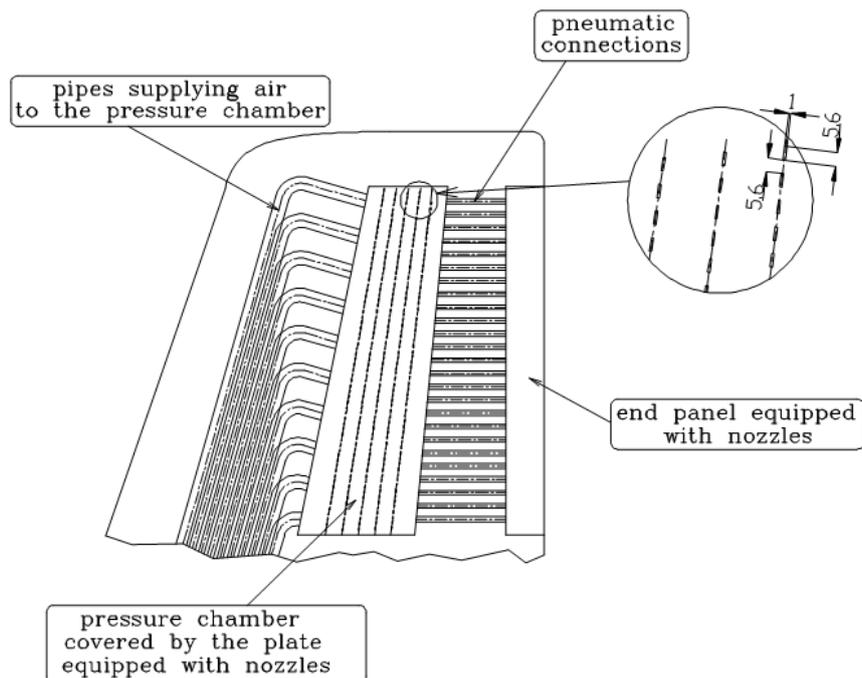


Fig. 5. The fluidic devices air supplying system

the total air mass flow rate, flowing through the nozzles of the active load control devices, was changing in the range $\dot{m} = 0-0.25$ kg/s.

The following model configurations were tested.

- Smooth wing model,
- Wing model with Fluidic Spoiler – nozzles directed perpendicularly to the upper wing surface (FS 90),
- Wing model with Fluidic Spoiler – nozzles inclined at an angle of $\Theta_N = -45^\circ$ to the upper wing surface (FS 45),
- Wing model with Dual Trailing-Edge Nozzles (DTEN).

The Fluidic Spoiler panel was equipped with nine rows of nozzles. In the description of the Fluidic Spoiler configuration, “1” indicates the opened row of nozzles, “0” indicates the closed row of nozzles (e.g. 111100000 means that the first four rows – in front of flow direction, are opened and the five at the rear are closed).

Flow visualization was performed using fluorescent threads, illuminated with ultraviolet light. Flow visualization images were recorded using a camera.

In Fig. 6, the flow visualization on the smooth wing (without fluidic devices, a reference configuration) at $\alpha = 0^\circ$ is presented. As it can be seen, the flow is undisturbed on the whole upper wing surface.

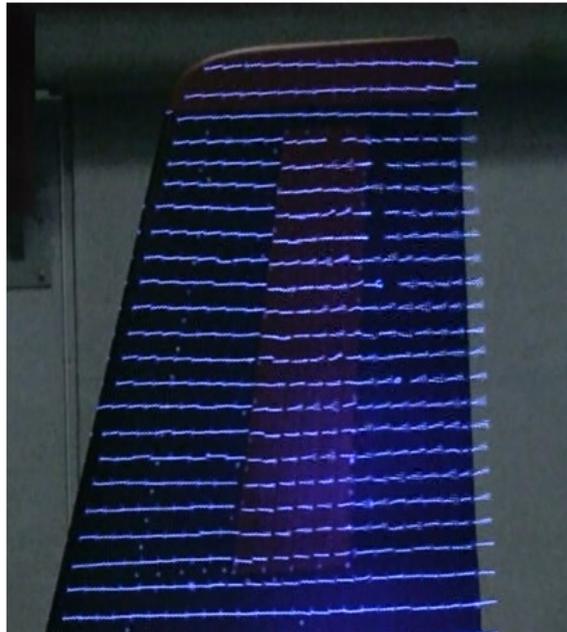


Fig. 6. The flow visualization on the smooth wing

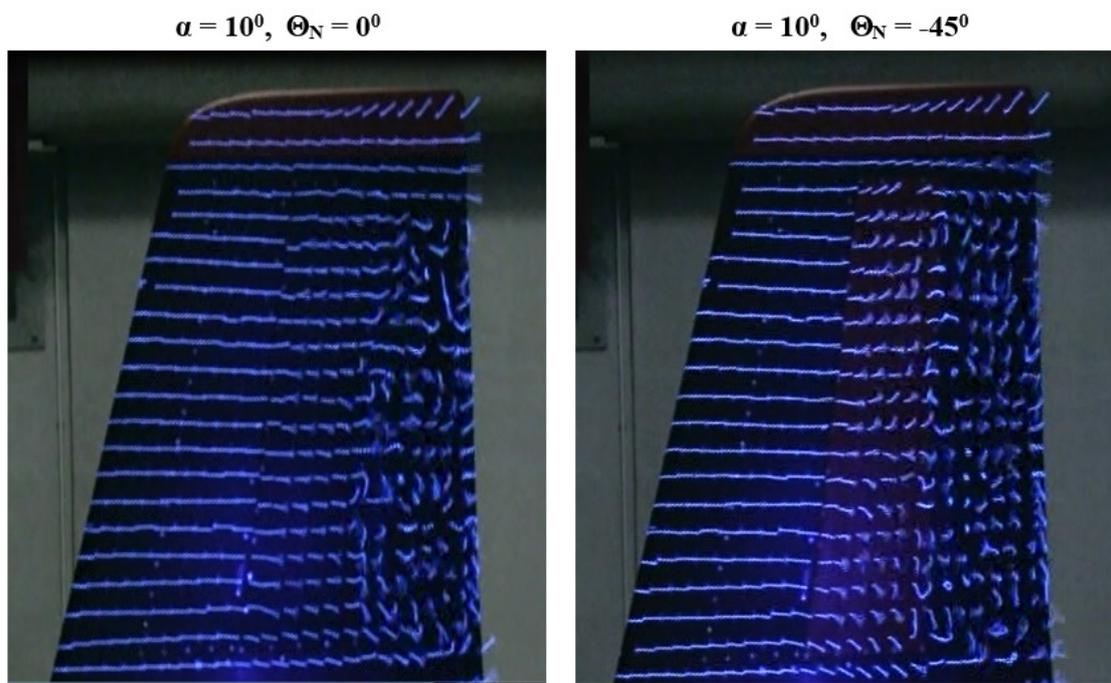


Fig. 7. Comparison of the flow visualization patterns with usage of Fluidic Spoiler with nozzles inclined at $\Theta_N = 0^\circ$ and $\Theta_N = -45^\circ$ for $\alpha = 10^\circ$

In Fig. 7 the flow visualization of the semi-span wing equipped with Fluidic Spoiler with nozzles directed perpendicularly to the upper wing surface ($\Theta_N = 0^\circ$) and inclined at an angle of $\Theta_N = -45^\circ$ to this surface, at $\alpha = 10^\circ$ and $\dot{m} = 0.15 \text{ kg/s}$ is presented. In this Figure, the difference in the effect of Fluidic Spoiler action due to different inclination of the nozzles is shown. For the nozzles directed perpendicularly to the upper wing surface, the area of flow separation is limited to the range of wing chord from $\approx 70\%$ to 100% . In turn, for the nozzles inclined at an angle of $\Theta_N = -45^\circ$ to this surface, the flow separation area is much larger, namely covers an area from $\approx 50\%$ to 100% wing chord. This indicates that effectiveness of the nozzles inclined forward in relation to a flow direction is greater than for the nozzles directed perpendicularly to the upper wing surface.

The usage of DTEN fluidic device, which utilises the Coanda effect to change a flow circulation around the wing, limits the separation area to the surface close to the wing trailing edge, Fig. 8. However, the effectiveness of DTEN may be higher than Fluidic Spoiler.

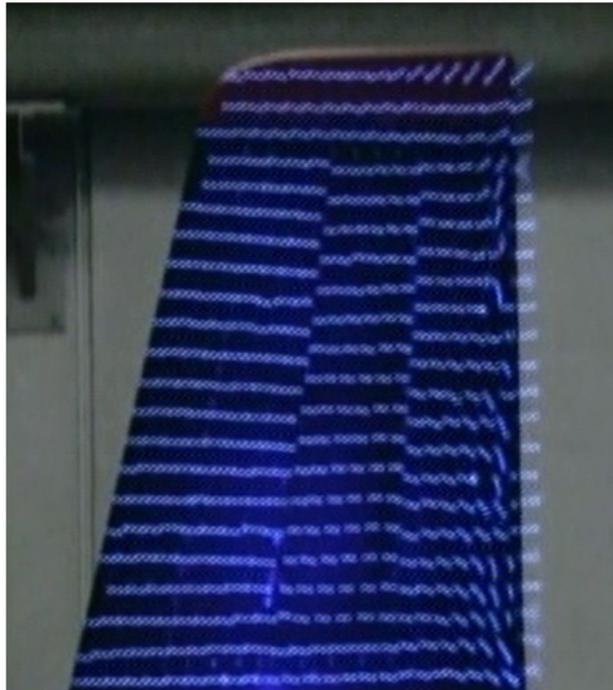


Fig. 8. Comparison of the flow visualization patterns with usage of DTEN Fluidic Device for $\alpha = 10^\circ$

In Fig. 9 the influence of the wing angle of attack on the flow separation area and its character with the usage of „Fluidic Spoiler“ (config. FS-45 with air mass flow rate $\dot{m} = 0.15 \text{ kg/s}$) is presented.

Generally, it can be seen that the change of wing angle of attack does not affect the area of flow separation, caused by the Fluidic Spoiler action. Whereas the change of the wing angle of attack causes a change in the flow separation character. For small angles of attack, close to $\alpha = 0^\circ$, the flow separation is much more intensive, than for higher ones. This means, that higher negative pressure, which occurs at higher angle of attack, stabilizes the separated flow on the upper wing surface. In addition, it can be seen that at $\alpha = 0^\circ$ detachment has a form of the large single vortex, while at $\alpha = 12^\circ$ it has a form of the two contra-rotating vortices.

6. Conclusions

In this paper, the results of the flow visualization tests carried out on the half wing model equipped with two load control fluidic devices are presented. Flow visualization was performed using a fluorescent threads method.

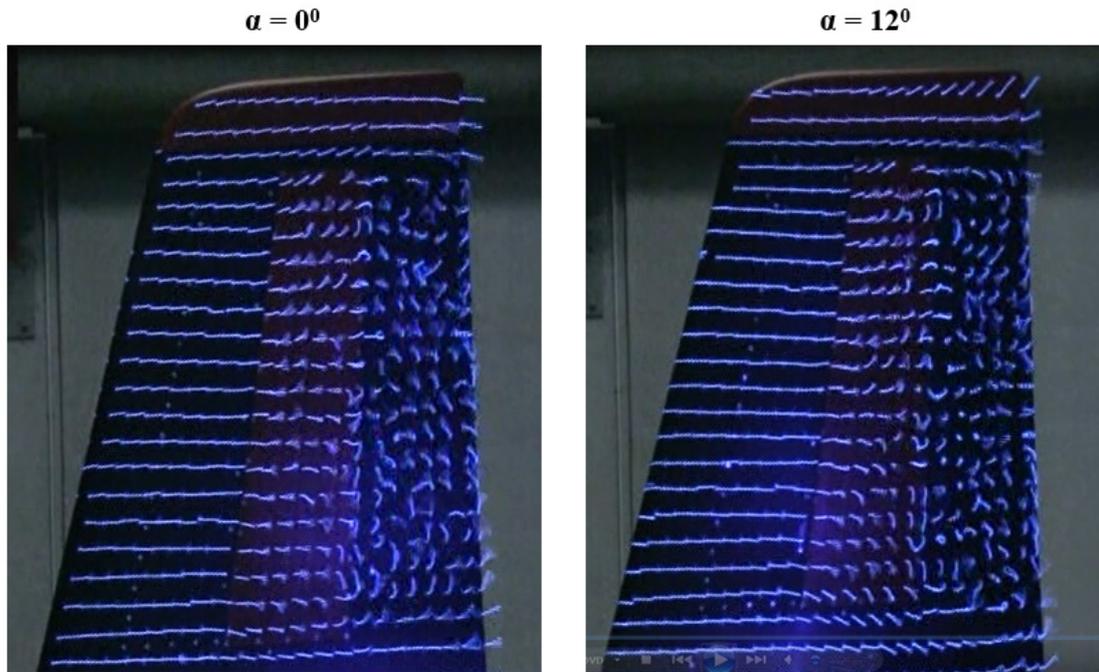


Fig. 9. Comparison of the flow visualization patterns with the usage of Fluidic Spoiler for $\alpha = 0^\circ$ and $\alpha = 12^\circ$

The experimental tests were performed in low speed wind tunnel T-3 (5-meter diameter test section) in the Institute of Aviation. For these tests, the model of semi-span wing (2.4 m span), situated vertically on the endplate in wind tunnel test section, was used. Wind tunnel test were performed at Mach number $M = 0.1$. Studies have shown that:

- the usage of Fluidic Spoiler leads to flow separation on the large area of upper wing surface,
- the effectiveness of the Fluidic Spoiler with nozzles inclined forward in relation to a flow direction is greater, than with the nozzles directed perpendicularly to the upper wing surface. It is due to the greater flow separation area. Thus, for the nozzles directed perpendicularly to the upper wing surface the area of flow separation was limited to the range from $\approx 70\%$ to 100% wing chord, while the using of the nozzles inclined at an angle of $\Theta_N = -45^\circ$ to this surface the flow separation area was much larger, namely covers an area from $\approx 50\%$ to 100% wing chord,
- the change of wing angle of attack does not affect the area of flow separation caused by the Fluidic Spoiler action, but change the flow separation character. For small angles of attack close to $\alpha = 0^\circ$ the flow separation is much more intensive, than for higher angles of attack,
- the usage of DTEN fluidic device, which utilises the Coanda effect to change a flow circulation around the wing, limits the separation area to the surface close to the wing trailing edge. However, the effectiveness of DTEN may be higher than Fluidic Spoiler.

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