EXPERIMENTAL INVESTIGATION OF WING LOAD CONTROL USING FLUIDIC DEVICES

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Abstract

Modern flow control methods which consist of influencing the flow in not classical but a more advanced way is one of the leading areas of research in recent years. One of the methods aims to control the load on the wing. The wing-load-control systems are developed as a means to modify a distribution of aerodynamic load on the wing in extraordinary flow conditions. Particularly, it concerns the reduction of bending loads during accelerated flight manoeuvres or sudden strong gusts. In such situations, rising bending load may lead to impairment or damage of the wing structure. In addition, strong turbulences cause discomfort to passengers.

A new concept of active flow control system based on blowing devices for the control of the aerodynamic load on aircraft wing was designed in the Institute of Aviation and tested in its low speed wind tunnel. As a result of the numerical studies, focused on alleviation of excessive aerodynamic loads, two concepts of the fluidic devices, as the most promising ones were chosen and tested experimentally, namely: the "FLUIDIC SPOILER" concept and the "DUAL TRAILING-EDGE NOZZLES" (DTEN) concept.

The paper presents the results of the wind tunnel tests of these two above mentioned active flow control systems. 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. The wind tunnel investigation were carried out at Mach number $M = 0.1$ *which corresponds to Reynold's number* $Re = 2.4\times10^6$

1 Introduction

In recent years a lot of studies have been performed to control aircraft aerodynamics in non-classic but a more advanced way. It usually refers to the usage of various flow control methods [1]. Generally, three classic techniques are used namely: blowing, suction and vortex generation [2÷7]. In the paper the usage of air blowing technique is described. This technique can be used both in the incompressible as well as compressible boundary layer conditions. It has been the subject of studies in many laboratories [8÷11]. The main task of air blowing technique was usually to energise the boundary layer and as a result to delay the flow separation. In turn, a delay of the flow separation improves the airfoil aerodynamic performance. Such an improvement (by using air blowing system) was achieved on the Lockheed F-104 *Starfighter* [12] and later on the F4H *Phantom* [13], Mig-21 PFM and the F-8 *Crusader*.

In the works described in the paper, the blowing was not used to improve the wing aerodynamic performance, as it was done before, but to diminish its performance by an initiation of the flow separation on the upper wing surface. The flow separation causes diminishing of the excessive aerodynamic loads in airplane off-design conditions. These conditions can appear during accelerated manoeuvres or sudden gusts. Such an appearance of violent loads can damage or destroy the wing structure. Furthermore, diminishing the excessive aerodynamic loads can improve the passengers comfort during flight by reducing aircraft vibration caused by atmospheric turbulence.

In some of the existing passenger planes and military aircrafts, the classic aircraft control surface such as spoilers, ailerons or flaps are used to avoid the wing overloading. Such a system of load control was first applied on Lockheed C-5A “Galaxy” (symmetrical aileron deflection) [14, 15]. Next, it was used on Lockheed L-1011-500 and Northrop B-2 Spirit [16, 17]. Nowadays, a lot of commercial aircrafts like Airbus A320, A330, A340, A380 and Boeing 787 use ailerons, spoilers, and elevators as a means of active control for gust load reduction [18, 19].

Mechanical complexity of the classic load control solutions on one hand, and the development of the modern flow control techniques, on the other hand, are reasons for an investigation of new airplane load control methods. One of them is the usage of active flow control by air blowing. The basic advantage of this flow control method in comparison with the classic ones is their significantly shorter reaction time.

The paper presents results of experimental tests of two new concepts of active flow control system. This system was designed in the Institute of Aviation and tested in its low speed wind tunnel T-3 (5 m diameter test section). For these tests the model of semi-span wing (2.4 m span), equipped with two kinds of fuidic devices named the “FLUIDIC SPOILER” and the “DUAL TRAILING-EDGE NOZZLES” (DTEN) was used. The wind tunnel tests which included balance, pressure distribution and strain measurements as well as flow visualization tests were performed at Mach number M = 0.1.

The study was carried out within the framework of the European project STARLET (Clean Sky Partnership). In 2015 project STARLET was awarded the first prize as the best European Project performed within Clean Sky Partnership.

2 Fluidic Device Concept

Basing on the numerical studies [20, 21], in which a number of different solutions of fluidic devices allowing an alleviation of excessive aerodynamic loads were investigated as the most promising two concepts were chosen. These concepts (“FLUIDIC SPOILER” and “DUAL TRAILING-EDGE NOZZLES”) were implemented on the half wing model and tested experimentally in the T-3 wind tunnel.

2.1 Fluidic Spoiler Concept

The Fluidic Spoiler system used the matrix of 540 mini nozzles which blow air on the upper wing surface. They were manufactured on a removable panel (Fig. 1) and arranged in nine rows (located at the 59 ÷ 92% of the wing span and 45 ÷ 65% of the wing chords (every 2.5%). Two Fluidic Spoiler basic configurations were tested experimentally, i.e. with the nozzles blown air in direction normal to the upper wing surface (marked as FS-90) or inclined (marked as FS-45) to it at an angle of 45^0 (blowing against the flow), Fig. 2. Similarly, like in a classic spoiler the Fluidic Spoiler forces flow separation diminishing the wing load.

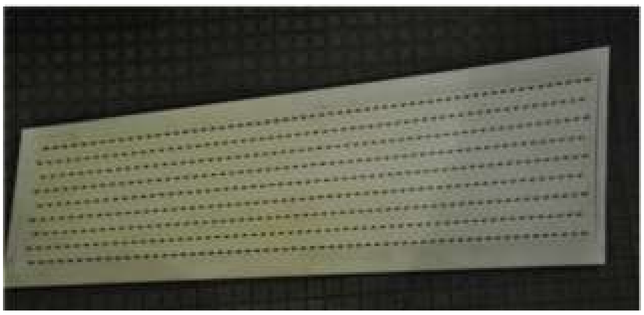

Fig. 1. The panel with matrix of blowing nozzles

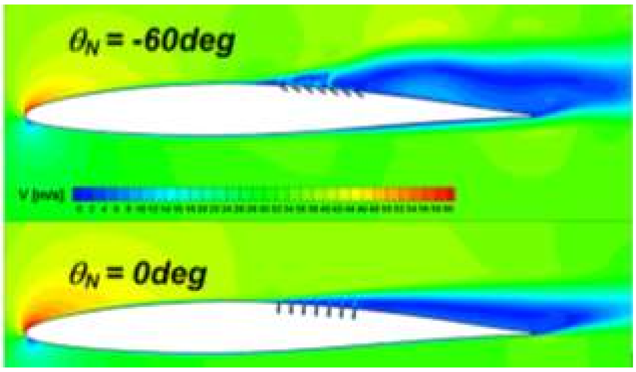

Fig. 2. The FLUIDIC SPOILER concept [20]

2.2 Dual Trailing Edge Nozzle (DTEN) Concept

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

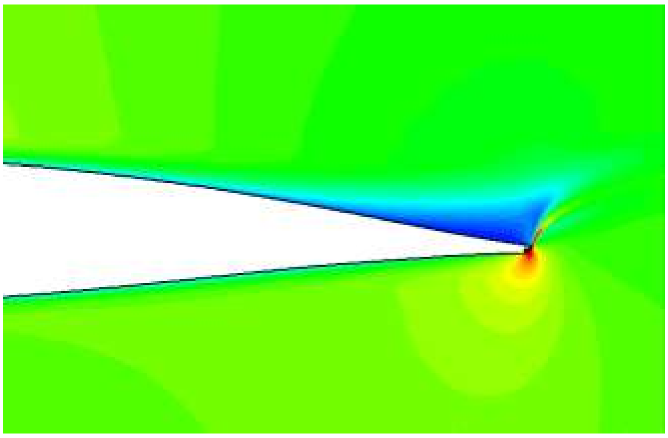

Fig. 3. The DUAL TRAILING-EDGE NOZZLES concept [20]

3 Wind Tunnel

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

The T-3 Institute of Aviation low-speed wind tunnel is a closed-circuit continuous-flow wind tunnel with a 5 m diameter open test section and 6.5 m in length. The maximum air velocity in the wind tunnel test section is 90 m/s, which corresponds to Reynolds number per meter Re = 6.2×10^6. The flow in the test section is relatively uniform with a longitudinal turbulence level of about 0.5 percent. Test section airflow is produced by 7-m diameter 8-bladed fan powered by a 5.6 MW AC motor.

4 Semi-Span Wing Model

Experimental tests of the effectiveness of the proposed active load control devices were carried out with the usage of the semi-span wing model of 2.4 m span. The model was situated in the wind tunnel test section in a vertical position (Fig. 4). To preserve the flow symmetry the endplate was used. The semi-span wing model was fixed at its base to two wall balances, i.e. 5 component (front balance) and 3 component (rear balance).

During the wind tunnel tests the series of the measurements were carried out, namely:

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

- balance measurements of the semi-span wing model aerodynamic characteristics with the usage of two wall balances,
- load distributions measurements along the half-wing model span with the usage of eight strain guage bridges,
- pressure distributions measurements along two chosen semi-span wing model chords situated in a spoiler area,
- mass flow rate measurements using ultrasonic flowmeter,
- flow visualization test on the upper half-wing model surface using a short white threads

The fluidic devices installed on the semi-span wing model were supplied with compressed air from the air supplying system, which consisted of a compressor, a control valve, a flow-meter and a pipes system. The compressed air was directed to the pressure chamber and next to the active flow control devices, Fig. 5.

Fig. 5. The system of pipes supplying active load control devices with air

5 Wind Tunnel Tests Results

5.1 Tests Program

The wind tunnel investigation of the proposed wing load control devices were carried out at Mach number M = 0.1 (which corresponds to Reynold's number Re = 2.4×10^{6}) and in the range of air mass rate (m) blowing from their nozzles m = 0 ÷ 0.3 kg/s (every m = 0.05 kg/s).

The experimental investigation of the wing load control using the proposed FLUIDIC SPOILER included studies of a number of sub-configurations for the nozzles blown air in direction normal to the upper wing surface (FS-90) or inclined to it (FS-45). Individual sub-configurations have been marked in the following way, Tab.1:

Tab.1. FLUIDIC SPOILER sub-configurations

No	Sub-configurations*	Maximum of the air jet velocity (for m_{max})
1	111111111	≈60 m/s
2	111111000	≈90 m/s
3	000111111	≈90 m/s
4	111100000	≈110 m/s
5	001111000	≈110 m/s
6	000001111	≈110 m/s
7	110000000	≈150 m/s
8	000001100	≈150 m/s
9	000000011	≈150 m/s

* "1" at n-th position means that n-th row of nozzles is active, while "0" means non-active n-th row of nozzles. The first position on the left is closer to the wing leading edge.

Additionally, the maximum value of the air jet velocity achieved during the tests for each of the FLUIDIC SPOILER sub-configurations is presented in Tab.1.

To estimate the effectiveness of the proposed fluidic devices the bending moment coefficient C_{BMA} was introduced, defined in Eq. 1.

$$C_{BMA} = (M_{B0}-M_B)/ M_{B0} \quad (1)$$

where:

M_{B0} - root bending moment for the smooth wing (without fluidic device).

M_B - root bending moment (for the wing equipped with fluidic device).

5.2 Sample Test Results

In Fig. 6÷9 the influence of the FLUIDIC SPOILER in FS-90 and FS-45 configurations on the wing bending moment distribution for two sub-configurations (000001100 and 111111111) and at $\alpha = 10^0$ and m = 0.15 kg/s is presented.

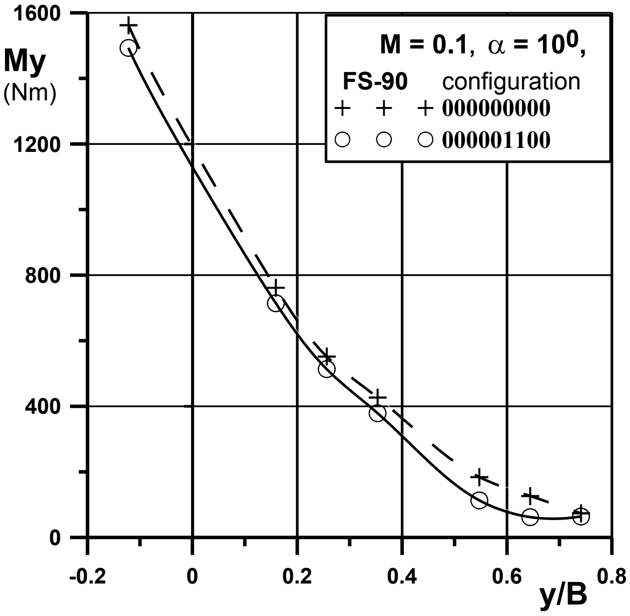

Fig. 6. The influence of the FLUIDIC SPOILER in FS-90 – 000001100 configuration on the wing bending moment (My) along its span (y)

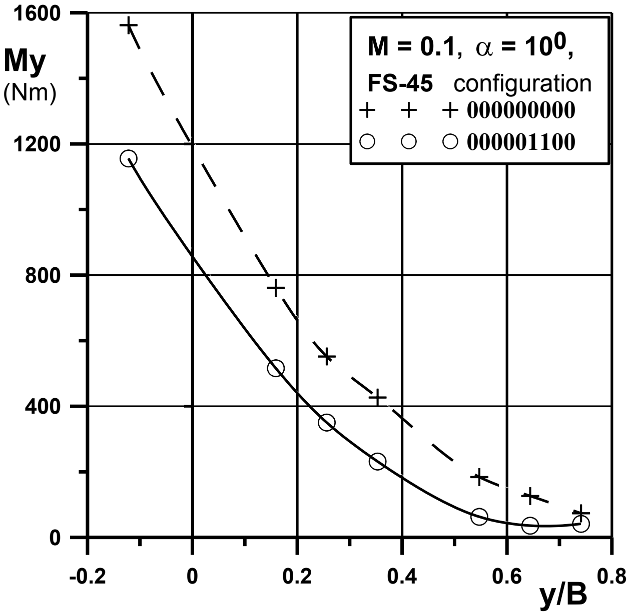

Fig. 7. The influence of the FLUIDIC SPOILER in FS-45 – 000001100 configuration on the wing bending moment (My) along its span (y)

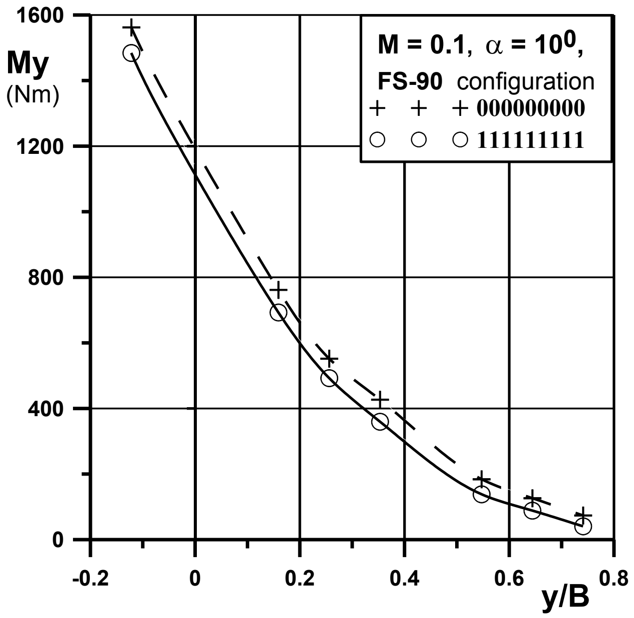

Fig. 8. The influence of the FLUIDIC SPOILER in FS-90 – 111111111 configuration on the wing bending moment (My) along its span (y)

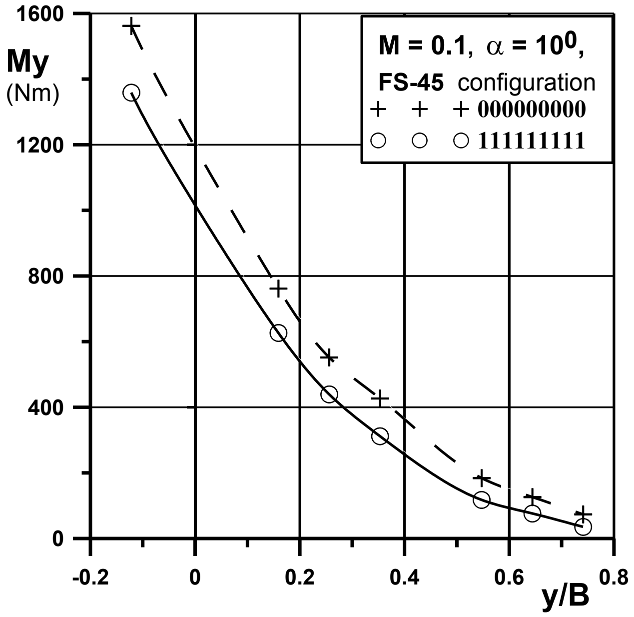

Fig. 9. The influence of the FLUIDIC SPOILER in FS-45 – 111111111 configuration on the wing bending moment (My) along its span (y)

Basing on the tests results presented above, it can be concluded that FLUIDIC SPOILER action can diminish a wing bending moment and its efficiency significantly depends first of all on the angle of nozzle deflection with respect to the upper wing surface. In the case of FLUIDIC SPOILER equipped with nozzles blowing air against the flow direction (FS-45 configuration) the decrease of root (y/B = 0) wing bending moment ΔM_B was few times greater than in the case of air blowing perpendicularly to the upper wing surface (FS-90 configuration). This was achieved for the same air mass flow rate and the same average air jet velocity and depends on the average air jet velocity. Furthermore, FLUIDIC SPOILER efficiency depends on the average air jet velocity (which rises with the air mass flow rate increase) and this in turn depended, in the presented wind tunnel tests, on the number of blowing nozzles active. For the same value of the used air mass flow rate the average air jet velocity increase with the diminish of the number of blowing nozzles active.

In Fig. 10 the influence of air mass flow the DUAL TRAILING-EDGE NOZZLES (DTEN) on the wing bending moment distribution at α = 10^0 and m = 0.158 kg/s is presented.

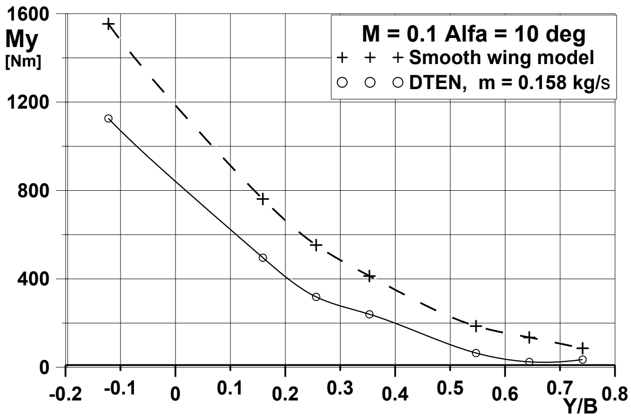

Fig. 10. The influence of the DUAL TRAILING-EDGE NOZZLES (DTEN) on the wing bending moment (My) along its span (y)

The Fig. 10 shows that with the same value of air mass flow rate, the efficiency of the DUAL TRAILING-EDGE NOZZLES (DTEN) may be comparable with the efficiency FLUIDIC SPOILER in FS-45 – 000001100 configuration.

In Fig. 11 the influence of a mass flow rate on the root bending moment coefficient C_{BMA} for FLUIDIC SPOILER in FS-45 configuration (with sub-configurations: 000001100, 111100000 and 111111111) and DUAL TRAILING-EDGE NOZZLES (DTEN) at α = 10^0 is presented.

It can be seen that among presented in Fig. 11 fluidic devices the most effective seems to be DUAL TRAILING-EDGE NOZZLES system and FLUIDIC SPOILER in FS-45 configuration with two rows of active nozzles.

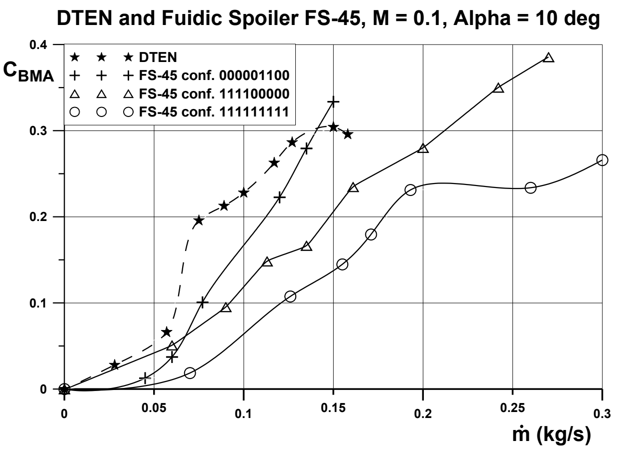

Fig. 11. The influence of a mass flow rate on the root bending moment coefficient C_{BMA} for FLUIDIC SPOILER and DTEN at $\alpha = 10^0$

6 Conclusions

The paper presents the results of the wind tunnel tests of the two proposed active flow control systems, namely: FLUIDIC SPOILER with the nozzles blown air in direction normal to the upper wing surface or inclined to it at 45° (and moreover in several sub-configurations) and DUAL TRAILING-EDGE NOZZLES (DTEN). The experimental tests were performed in low speed wind tunnel T-3 in the Institute of Aviation. For these tests the model of semi-span wing situated vertically on the endplate in wind tunnel test section was used. The wind tunnel investigation were carried out at Mach number M = 0.1 which corresponds to Reynold's number $Re = 2.4\times10^6$.

Experimental wind tunnel test lead to the following conclusions:

- Wind tunnel tests of two proposed fluidic flow control devices showed that a significant bending moment decrease could be achieved for the chosen configurations of the tested devices. During the tests up to 35% root bending moment diminishing was achieved.
- The "Fluidic Spoiler" FS-45 equipped with the nozzles blowing the air against the flow (in tested cases it was 45^0), with respect to the upper wing surface is much more effective, than equipped with the nozzles blowing the air perpendicularly to the upper wing surface. This conculsion relates to the all tested sub-configurations of the FLUIDIC SPOILER which differ each other in a number of active rows of air jet nozzles.
- An increase of the air jet velocity diminish the wing bending moment and as a result increase the efficiency of the tested fluidic devices.
- In the case of usage FLUIDIC SPOILER, equipped with the nozzles blowing air in the direction perpendicular to the upper wing surface and with low air jet velocities ($V < 15 \div 50$ m/s) the effectiveness of this fluidic device is low.
- Generally, it can be noticed that using the same number of rows of air jet nozzles active in FLUIDIC SPOILER device, any change of their positions in a blowing panel (i.e. change of sub-configuration) does not affect fluidic device effectiveness.
- Among the tested fluidic devices configurations the most effective seems to be DTEN and Fluidic Spoiler FS-45 with the two rows of nozzles active.

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