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MODIFICATION OF AERODYNAMIC WING LOADS BY FLUIDIC DEVICES

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Abstract

Airplane wing load control systems are designed for modification/redistribution of aerodynamic loads in order to decrease risk of structural damage in conditions of excessive loads, to improve passenger comfort in turbulent atmosphere or to act as flight control systems. Classical examples include systems involving symmetric deflections of ailerons reducing wing root bending moments (Lockheed C-5 Galaxy) or deflections of spoilers stabilizing landing approach path (Lockheed TriStar). The fast development of Micro Electromechanical Systems and their application in Flow Control System opens the perspectives of designing practical wing load control systems based on fluidic actuators, modifying local aerodynamic loads by inducing changes to flow, for example, by inducing flow separation in the boundary layer or modifying Kutta condition on the trailing edge. This is the principle of operation of novel concepts of flow control actuators proposed by Institute of Aviation and discussed in the paper. The systems include actuators in the central part of the wing section, reducing local lift similarly to classical spoilers and actuators on the modified trailing edge, acting similarly to ailerons. The potential advantages in comparison to classical devices include potentially shorter reaction time because of avoiding the necessity of moving large surfaces against high dynamic pressure, which is important in conditions of fast-changing loads in turbulent atmosphere.

Keywords: *transport, aircraft engineering, mechanical engineering*

1. Introduction

Classical solutions of Active Load Control (ALC) on airplane lifting surfaces involving deflection of classical control devices (ailerons, spoilers) and mechanical/hydro-mechanical control systems, in spite of their high reliability acquired through decades of development show some disadvantages that limit their further development. The most essential ones are the consequences of the necessity of moving large control surfaces against high dynamic pressure, especially at high flight speed, which makes it difficult to obtain short reaction times and induces high strains in the actuators and their control systems. Currently there is a need of new approaches to overcome these difficulties in ALC. Some approaches involve the design of additional control surfaces, dedicated solely to tasks involving ALC in flight conditions requiring load alleviation [5], which may be located on outer parts of wings, even in front of the leading edge and controlled by mechanical systems. An entirely new approach involves Active Flow Control (AFC) technology, which change flow conditions on wing surface and, in consequence, change aerodynamic loads. Active Flow Control is generally understood as flow control involving introduction of small amounts of energy into the flow in order to obtain some desired effects, such as delaying flow separation, extending the area of laminar flow, etc. The means of application of the energy include usually blowing jets, suction, synthetic jets with intermittent blowing and suction or flow acceleration by other effects, such as plasma flow. This technology is currently in the stage of moving from laboratory investigations into flying objects.

The accomplished examples of this technology include so far unmanned aerial vehicles where flow control technology has been proven to be able to eliminate classical ailerons [6, 7]. Research on the possibility of applying the AFC technology on the airplanes of commercial transport class is progressing, and it includes not only investigations of the aerodynamic effects of the technology, but also investigations of cost and system mass in comparison with traditional systems, as in [4] where the Airbus A320 airliner was chosen as basis for the analyses.

2. Scope of the present work

The present work concentrates on essential aspects of the proposed by Institute of Aviation approaches for the modification of airplane wing load distribution by fluidic actuators in order to achieve alleviation of wing-root bending moment in conditions of sudden increase of aerodynamic loads, e.g. in sudden gusts or in rapid manoeuvres. The gust loads are one of the main sources of fatigue damage to wing structure. The proposed concepts of ALC are intended to achieve significant aerodynamic load reduction on outer parts of wings, and, in consequence, to decrease the wing-root bending moment. Based on literature study two alternative concepts of modification of aerodynamic wing loads by AFC technology was proposed. The first of them, called “Fluidic Spoiler” involves the application of micro-jets in the central area of wing section, approximately, where the classical spoiler is located. This is area, where large amount of lift is being produced and its reduction on outer parts of wings might significantly reduce the wing-root bending loads. The mechanism of the reduction of the aerodynamic load involves achieving large-scale flow separation, as in case of traditional spoiler, but with potential benefits of avoiding the need of moving large surface against high dynamic pressure. Instead, the primary effects of the blowing jets are concentrated in the boundary layer where flow velocities are lower. The basic schematic view of the concept of micro-jets in the spoiler region is shown in Fig. 1. It is expected, that in final configuration, applicable to airplane wings these nozzles will be arranged in a chequered fashion, i.e. each nozzle will be followed by a space in chord wise as well as in span wise direction.

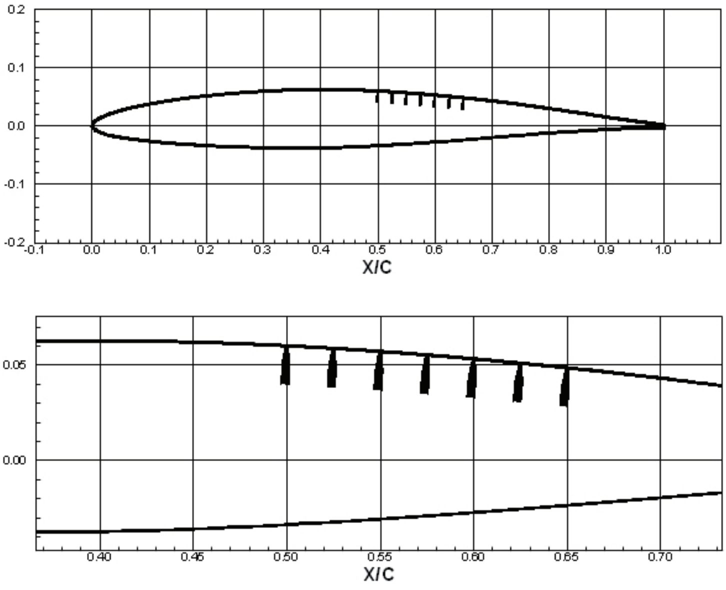

Fig. 1. Schematic view of the nozzles of the proposed fluidic actuator acting similarly to classical spoiler

The second proposed concept involves modification of the velocity circulation in a wing cross section, which, according to Joukovsky formula is directly responsible for the lift force. This is achieved by blowing air in the trailing edge region. The research in this area has been conducted through the decades, since the 1960-ies by NASA and resulted in the design of the "General Aviation Circulation Control Airfoil" based on well-known in General Aviation airfoil GA(W)-1 [1, 3]. The researchers in NASA obtained a solution producing the Coanda effect on a modified trailing edge, equipped with circular central element, separated from the airfoil upper and lower surfaces by blowing slots. The further development of this technology, involving rotating the central torus around eccentrically located axis resulted in the development of lateral control system, alternative to ailerons applied in the "DEMON" unmanned aerial vehicle, designed by Cranfield University [6]. The present research is aiming at alternative way of development of the Coanda effect by applying a set of two nozzles directing airflow upwards. (Fig. 2). The most important feature of the solution of Institute of Aviation, in contrast to the above mentioned solutions is, that the air flow from both nozzles is directed in the same direction, as opposed to the NASA and Cranfield solutions where the final flow direction is the result of the difference of intensities of air blowing in opposite directions from the slots between the central torus and wing upper and lower surfaces.

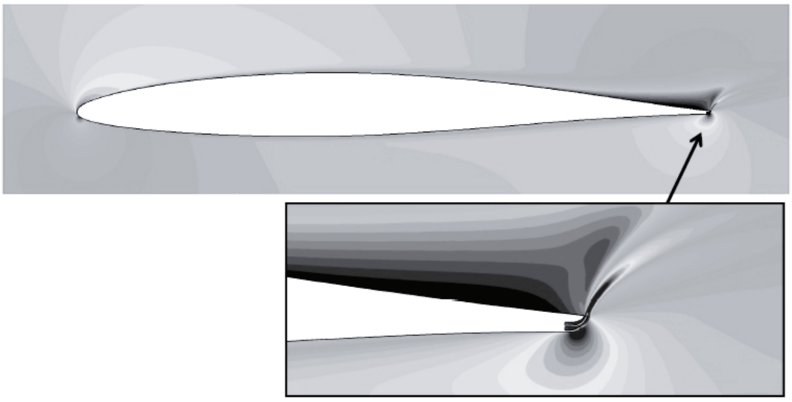

Fig. 2. Mechanism of circulation control inducing the Coanda Effect in the Fluidic Aileron configuration

3. Results of the investigations

The Flow Control concepts proposed by Institute of Aviation were designed considering classical load control solutions – spoilers and ailerons – as baseline solutions for comparison of the efficiency of novel designs with them. For the determination of aerodynamic characteristics of all the tested solution – classical and innovative ones – simulations based on solution of URANS equations were conducted using k-omega 2-equation turbulence model implemented in the ANSYS FLUENT solver. The investigations were conducted for NACA 64A210 airfoil at angle of attack of 8° and Mach number 0.1, Reynolds number Re=2.3 million. These conditions were chosen in order to make easier future comparison with the results of wind tunnel tests.

Classical spoiler of 10% airfoil chord (Fig. 3) was selected as baseline for the assessment of the aerodynamic characteristics of the "Fluidic Spoiler" concept. Its performance was evaluated for increasing deflection angles from 0 to 25 degrees. The results of the computations – dependence of unsteady force coefficients on time and dependence of time-averaged force and moment coefficients on spoiler deflections are shown in Fig. 4 and 5.

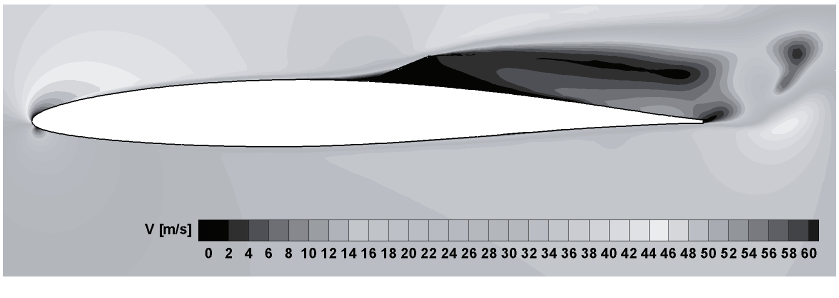

Fig. 3. Flow velocity contours for baseline configuration with classical spoiler. NACA 64A210 airfoil at Mach number M=0.1 and Reynolds number Re=2.3 million. Angle of attack 8°, spoiler deflection 10°

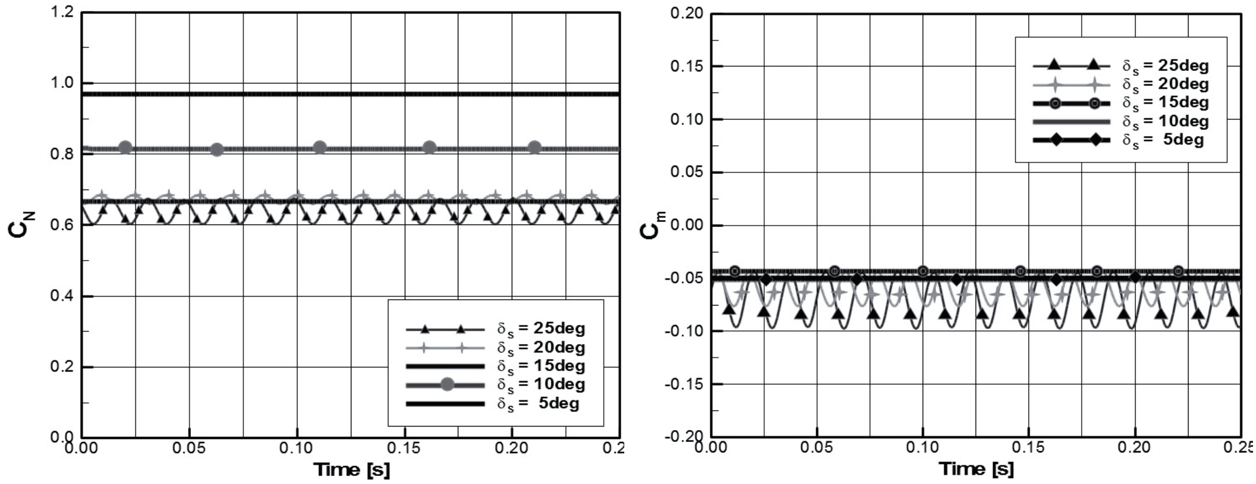

Fig. 4. Time dependence of unsteady normal force and pitching moment coefficients obtained for different spoiler deflections

For the fluidic devices, the analogous parameter to spoiler or aileron deflection is nozzle mass flow rate. It may be expressed as dimensionless blowing momentum coefficient (C_μ) for comparing the effects of nozzle blowing at different values of flow velocity and wing area:

$$C_\mu = \frac{\dot{m}\cdot V_J}{q_\infty \cdot S}, \tag{1}$$

where:
$\dot{m}$ – mass flow rate,
V_j – jet velocity,
q_∞ – reference pressure,
S – wing area.

Flow patterns in the vicinity of blowing nozzles obtained for increasing mass flow rates are presented in Fig. 6. Flow patterns obtained for increasing nozzle mass flow rate show increasing area of separation and flow recirculation behind the nozzles. As the nozzle mass flow increases, also increases the unsteadiness of the flow and amplitude of high-frequency fluctuations of the aerodynamic characteristics (Fig. 7). The amplitude of these fluctuations is similar to the amplitude of fluctuations of unsteady forces generated by classical spoiler, so it is expected that these high-frequency pressure oscillations should not pose problems in terms of fatigue strength of the wing structure.

For comparison of the efficiency of the fluidic spoiler concept with the classic spoiler, the unsteady aerodynamic characteristics were averaged over time. The results of the averaging are shown in Fig. 8 against blowing momentum coefficient.

It may be concluded, that in terms of the capability of reduction of the normal force coefficient, the efficiency of the fluidic spoiler is similar to the efficiency of the classical spoiler. For similar levels of the reduction of normal force, the increase of drag in the "fluidic spoiler" case is roughly half of the increase of drag of the classical spoiler, which is an important effect.

Similar analysis was conducted for the “Fluidic Aileron” configuration. The results were compared with results for baseline configuration of classical aileron. For the aileron of 10% of airfoil chord the values of derivatives of normal force and pitching moment coefficients with respect to aileron deflection $\partial \boldsymbol{C_N} / |\partial \delta_A|$ and $\partial \boldsymbol{C_M} / |\partial \delta_A|$ are equal to 0.066 1/deg and 0.011 1/deg respectively and this produces changes of normal force and pitching moment equal to 1.32 and 0.223 for aileron deflection of 20 degrees, which is a large deflection. The dependence of normal force and pitching moment coefficient on control parameters on blowing momentum coefficient for the fluidic device is shown in Fig. 9 and for maximum value of blowing momentum coefficient of C_μ=0.026 the change of normal force coefficient is equal to 0.82 which is 62% of the value obtained with aileron deflection. It must be noted, however, that large values of aileron deflection require overcoming dynamic pressure and inertia forces and thus may require more time than is needed to obtain desired effect on wing load distribution in turbulent atmosphere. It must be noted also, that the time rate of change of aerodynamic coefficients in Fig. 7 is the consequence of avoiding too large changes of boundary condition in time, which could cause problems with convergence of the solution. It is not a limit for any practical device.

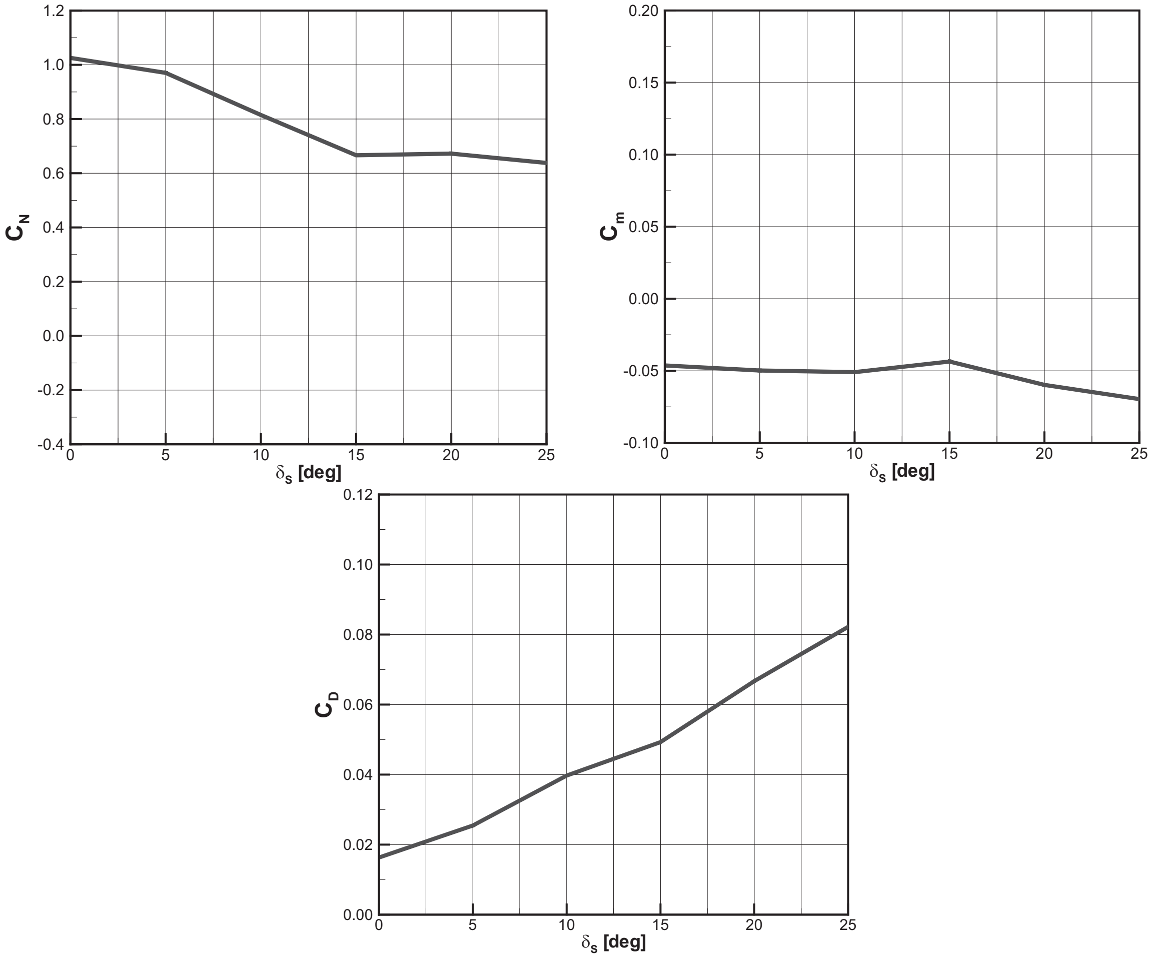

Fig. 5. Dependence of coefficients of normal force, pitching moment and drag force, averaged over time on classical spoiler deflection angle

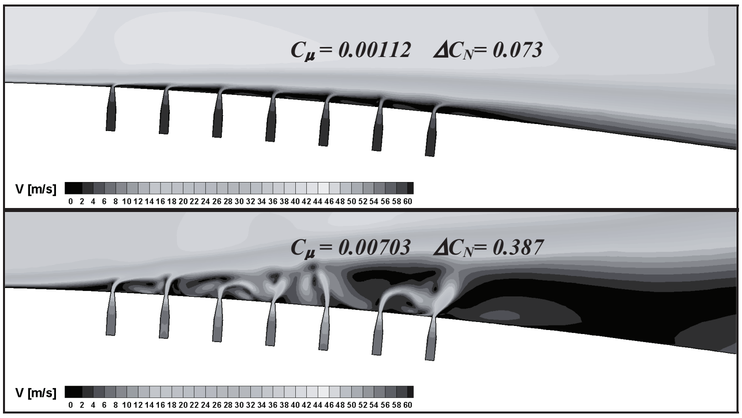

Fig. 6. Flow velocity contours for “fluidic spoiler” configuration and different blowing mass rates. Angle of attack 8°

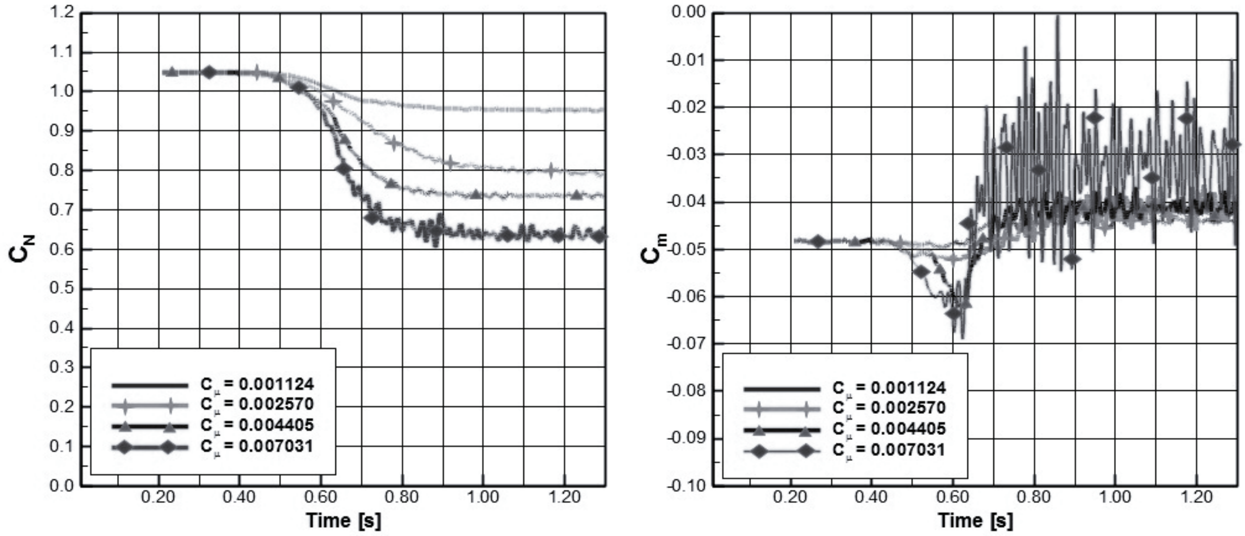

Fig. 7. Time dependence of unsteady normal force and pitching moment coefficients obtained for different blowing momentum coefficients

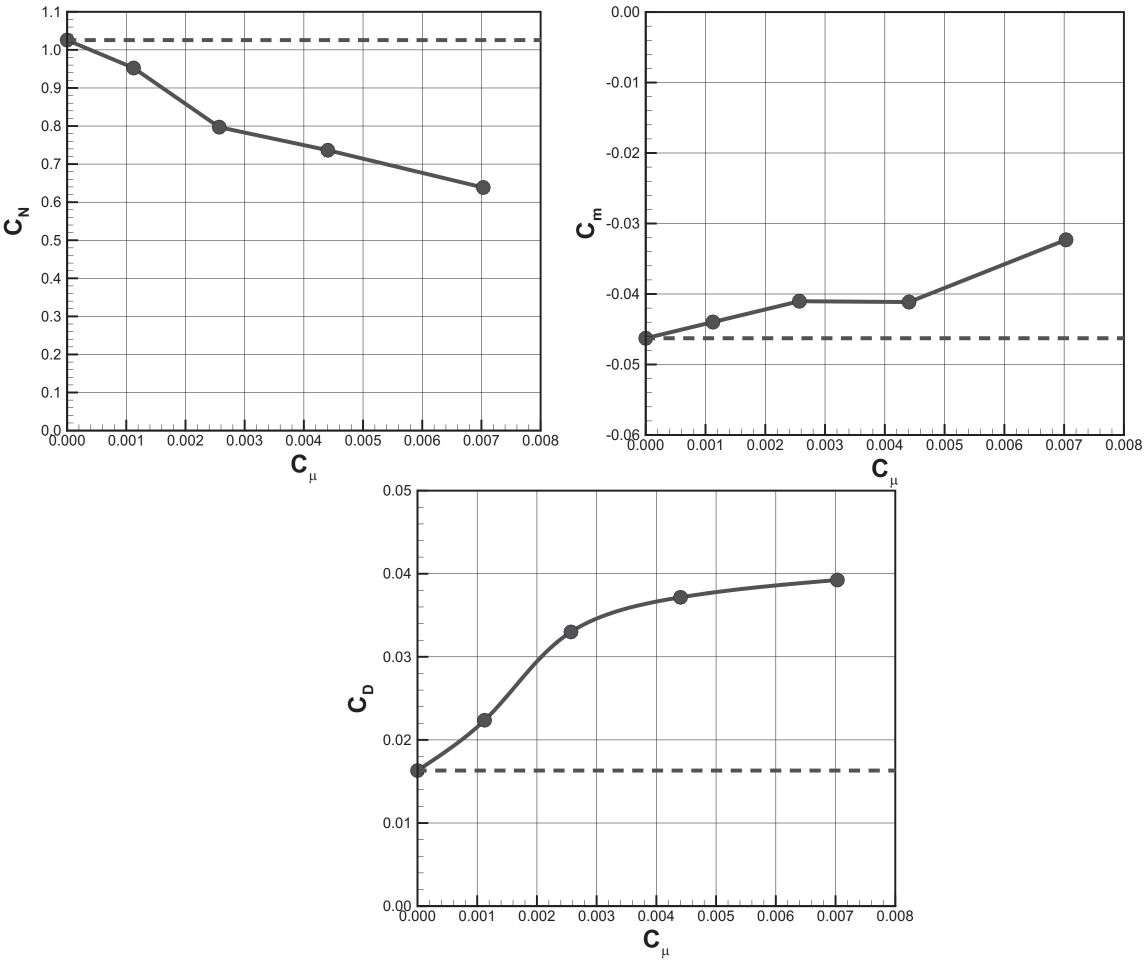

Fig. 8. Dependence of coefficients of normal force, pitching moment and drag force of the "fluidic spoiler" configuration, averaged over time on blowing momentum coefficient

In the investigations of the "Fluidic spoiler" concept, the maximum values of blowing momentum coefficients corresponded to that, applied in the investigations of the Circulation Control Airfoil [1, 3] and thus may be assumed as feasible for future investigations. Within this range the capability of the Fluidic Spoiler to decreasing the lift force is lower than that of classical aileron, but for relatively low values of blowing momentum coefficient (C_μ=0.005) 50% reduction of lift force is achieved which is more than it is possible to achieve for the "Fluidic Spoiler" configuration and classical spoiler configurations at moderate deflection angles.

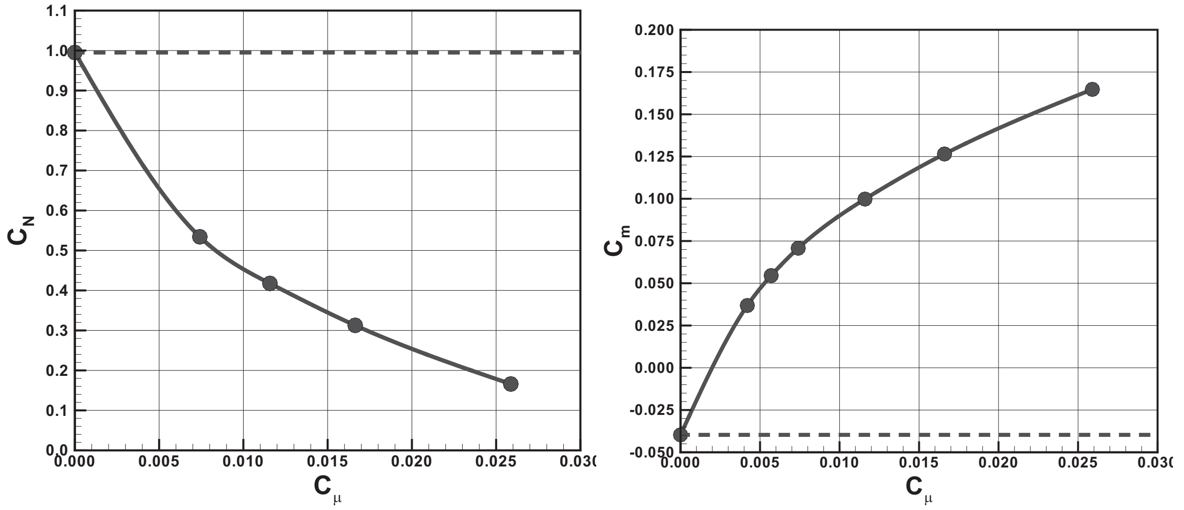

Fig. 9. Dependence of coefficients of normal force and pitching moment of the "Fluidic Aileron" on blowing momentum coefficient

For comparison of the efficiency of different fluidic devices, the Jet Efficiency Parameter is defined in [2] as $J_{ef} = \left|\Delta c_L / c_\mu\right|$. Such comparison of the efficiency of the solutions proposed the Institute of Aviation and of the Circulation Control Airfoil, based on currently presented results of numerical investigations is shown in Tab. 2.

Tab. 2. Jet efficiency parameter for the load control concepts proposed by Institute of Aviation and for earlier solutions

	IoA "fluidic spoiler"	IoA "Fluidic Aileron"	Circulation control airfoil [1]
$J_{ef} = \left\|\dfrac{\Delta c_L}{c_\mu}\right\|$	50-70	32-77	40-80

4. Conclusions

The fluidic flow control concepts proposed by the Institute of Aviation have at their current stage of development efficiency comparable to the efficiency of the solutions investigated with the Circulation Control Airfoil. The Fluidic Aileron concept has potential for further development by optimizing the nozzle flow deflection and intensity of the Coanda effect on modified trailing edge surface. The efficiency of the Fluidic Aileron in reducing the aerodynamic loads is higher than efficiency of the Fluidic Spoiler, but the latter produces higher pitching moment change, which may transform into wing twisting strains.

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