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The objective of the STARLET project was to check the usability of flow control actuation systems as developed in the past for load control purposes. The aim of the load control was reduction of high, off-design wing loads. Two locations of the actuation on wing profile were chosen: the first one was the region of spoiler, where significant values of lift occur in off-design conditions and the second one was the trailing-edge region strongly influencing the velocity circulation around the airfoil, where flow actuation could also reduce wing loads in off-design conditions. The project conditions required the development and low-speed wind tunnel testing of the fluidic actuators performing the load-alleviation function.

The project started with a literature study in order to determine current state-of-the-art solutions and directions of investigations, to gather reference data for evaluation of the effectiveness of the concepts developed in the STARLET project and to define practical requirements and guidance for designing effective load control solutions. The main conclusions of the literature study were that a) producing flow separation on the suction side of the wing by blowing air through a system of nozzles is a viable strategy for significant reduction of lift in off-design load conditions; it is even likely that the natural pressure difference between the pressure and suction sides of the wing could be exploited for this goal, b) that despite the small thickness of the trailing edge successful concepts producing the Coanda effect in this region were in the past exploited for load control, and c) that for fluidic load control the very important guiding principle, and often hard to achieve is obtaining gradual aerodynamic effect in response to gradual control impulse. Apart from this, practical parameters for assessing the effectiveness and reference data was gathered.

In order to meet the project objectives two concepts of fluidic load control were developed: the first one, designated as Fluidic Spoiler consisted of an array of nozzles in the central part of wing section emanating streams of compressed air and generating this way a large area of separated flow on the suction side of the wing. The nozzles were arranged in a chequered fashion: each nozzle was followed by a space in the span-wise as well as in the chordwise directions. The second concept, designated Double-Trailing-Edge Nozzle (DTEN) consisted of two, different-length, upward-directed nozzles in the modified trailing-edge that generated the Coanda effect and negative pressure on the lower side of the trailing edge and at the same time diverted the flow upwards. Both concepts exploited pressure chamber inside the wing model to feed the systems of nozzles with compressed air. The concepts were implemented on a moderate-sweep, 4.6-aspect-ratio, 2.4 m. half-span wing model designed for investigations in the 5m-diameter low-speed wind-tunnel of Institute of Aviation.

The design of the fluidic load control concepts was conducted with significant support from CFD flow simulations. In the initial phase two-dimensional (2D) simulations and two-and-a-half simulations (narrow wing strips of constant chord) were conducted in order to determine the most promising locations of the nozzles and blowing directions of the Fluidic Spoiler. The design and optimisation of the shape of the DTEN nozzles was also conducted at this stage of the project. The flow simulations indicated that the expected load alleviation could be obtained by blowing air in the direction normal to wing surface or in upstream direction, at an non-zero angle between the jet stream and wing surface. For practical

reasons concerning the design of nozzles the blowing angles were investigated in the range from 30° from surface upstream to 30° from surface downstream. It was also concluded that the chequered arrangement of the nozzles achieves the expected design goals of producing flow separation while being at the same time technologically feasible. The results of flow simulations indicated at the same time that similar maximum values of load alleviation could be obtained from the Fluidic Spoiler and from the DTEN actuator.

Based on the results of flow simulations the details of the Fluidic Spoiler and DTEN concepts were designed. The active part of the Fluidic Spoiler was the nozzle system. This system was designed as integral element, with the nozzles being the voids in the material, to be produced by three-dimensional printing technology, being at the same time the upper wall of the pressure chamber and fragment of upper (suction) surface of the wing model. Due to cost constraints this element was produced in two versions: one with nozzles normal to the surface and the second one with the nozzles deflected 45° from normal towards the flow. Both versions had nine rows of 60 nozzles, each nozzle 2,5mm by 5mm, wider side spanwise. As planned, the nozzles were arranged in a chequered fashion.

The DTEN actuator was designed as a system of three-dimensional nozzles, provided with air from the same pressure chamber as the nozzles of the Fluidic Spoiler by pipes reaching the vicinity of the trailing edge. In this configuration the upper wall of the pressure chamber was solid. The nozzles of the DTEN actuator changed shape gradually from circular pipe to narrow, upward bent channels, acommodated in the trailing-edge region, separated by vertical and spanwise-oriented walls responsible for obtaining the Coanda effect.

In order to complement the wind tunnel investigations of the fluidic load control concepts more detailed information about the effectiveness of the designed actuators and flow details was gathered from fully three-dimensional flow simulations.. The unsteady, Reynolds-averaged Navier-Stokes equations with k-ω turbulence model were solved in order to get knowledge about the effectiveness of the devices as well as of the steadiness of the flow pattern and aerodynamic loads. Due to constraints of computing time and large size of the computational problem only one blowing direction of the Fluidic Spoiler was simulated, but different numbers of active rows were also investigated. The results indicated that in blowing normal to wing surface the maximum effectiveness of load alleviation, measured by the reduction of wing-root bending moment was approximately 15% at mass flow of 0.270 kg/s and was obtained with two rows active. However, the flow pattern was strongly fluctuating and the noticeable effects of load alleviation occured at nozzle mass flow rate higher than 0.1 kg/s, whereas the configurations with larger number of active rows produced more steady flow pattern and became effective at very low non-zero values of nozzle flow. For all rows active the alleviation effect was lower (12%) at the same mass flow rate but the dependence of load alleviation level on nozzle mass flow rate was almost linear. For intermediate configuration (five active rows) the wing-root-moment alleviation level was 13% at the same mass flow rate but unsteady flow effects produced fluctuation of aerodynamic loads while increasing the nozzle mass flow rate. The results of flow simulations revealed also that the DTEN actuator was working in two modes: for lower values of nozzle mass flow rate, up to 0.1 kg/s the nozzles were acting similar to a Gurney tab, deflecting the flow but without producing the Coanda effect. Only after reaching this value of nozzle mass flow rate the Coanda effect appeared and upward deflection of flow behind the trailing edge was accompanied by appearance of a negative pressure region in the lower part of the trailing edge, supporting the load alleviation effect. The maximum wing-root alleviation level was 32% and this was achieved at nozzle mass flow rate of 0.15 kg/s. The side-effect of this concept was a nose-up increase of the pitching moment which was equal to $\Delta Cm=0.068$ at the maximum load alleviation effect. For the Fluidic spoiler the pitching moment changes were lower; depending on the location of the number and location of the active rows the pitching moment changes did not exceeded the value of $\Delta Cm=0.001$, positive or negative, depending on the chord position of the active nozzles. It must be noted, however, that changes of pitching moment occur also with the traditional load-alleviation systems, such as symmetrical deflections of ailerons on the Lockheed C-5 Galaxy aircraft. They have to be countered by compensatory deflection of elevators.

Wind-tunnel tests of the designed fluidic load control systems were conducted in the 5m-diameter wind tunnel of the Institute of Aviation. The Mach number was M=0.1 and Reynolds number, based on the mean geometric chord was $Re=2.4*10^6$. For the Fluidic Spoiler the results of the wind tunnel tests qualitatively confirmed the results of numerical flow simulations conducted for nozzles directed normal to wing surface. The alleviation effect for all active nozzle rows active was more linearly dependent on the mass flow rate than was for lower number of active rows and for two rows active the noticeable effects of load alleviation occurred at nozzle mass flow rate higher than 0.1 kg/s, as in the flow simulations. Maximum values of wing-root bending moment reduction were, however, 30% higher than predicted by the flow simulations. A likely reason for this effect was absence in real flow, or lower intensity of small vortices that appeared near the nozzles in the numerical solution and produced local suction. The values of static pressure measured in the vicinity of the nozzles were higher than predicted in flow simulations. More information could be obtained from PIV scans, however, the PIV technique was not applied in these investigations. In contrast to numerical flow simulations that required large amount of computational time, in wind tunnel experiment larger number of nozzle configurations could be investigated. The experiment confirmed the conclusions of early two-dimensional and two-and-a-half dimensional flow simulations that deflecting blowing direction 45° upwind increases the load alleviation effect. Of the total number of 20 configurations differing in the number of active rows and blowing directions the most effective one was the configuration with first two nozzle rows active, deflected 45° toward the flow from direction normal to surface. The maximum wing-root alleviation level was 28% at 0.135 kg/s nozzle mass flow and at that blowing rate the saturation effect did not yet occur. This was, however, the maximum applied value of nozzle mass flow rate for this configuration due to concerns about the pressure rise in the pressure chamber inside the model and about the strength of the nozzle plate produced by the 3D-printing technology. The noticeable effects of this configuration on wing-root bending moment appeared at nozzle mass flow of 0.4 kg/s and after exceeding this value the dependence of wing-root bending moment alleviation on the nozzle mass flow was almost linear. For the DTEN actuator the wind-tunnel investigations confirmed the predictions of numerical simulations that at low values of the nozzle mass flow rate the Coanda effect does not appear or has low intensity, but the strong Coanda effect appeared at the nozzle mass flow rate of 0.055 kg/s which was similar mass flow rate to the rate necessary for activation of the most effective variant of the Fluidic Spoiler (generating flow separation on suction side of a wing). The maximum achieved wing-root bending moment alleviation effectiveness of the DTEN actuator was

31% which was slightly higher than for the most effective variant of the Fluidic Spoiler, but at this maximum effectiveness level the saturation effect was noticeable.

It must be noted also, that both investigated concepts had higher load-alleviation capability than traditional spoiler of 10% wing section chord. For the classic spoiler located in place of the Fluidic Spoiler the wing-root bending moment alleviation level was 21% and this was achieved at a high deflection of 35 degrees. In practical situations achieving such high deflection requires large actuation moments produced by the hydraulic system and generates large increase of drag. For fluidic Spoiler the drag increase is moderate and results from the decreased suction of the leading edge due to decreased velociity circulation. In case of the DTEN actuator there occurs another component of drag – the suction on the rounded trailing edge which acts in the rearward direction. For this reason the drag increase due to activation of the DTEN device is higher than due to deflection of aileron, but lower than due to deflection of spoiler.

Complementary actions

In order to provide more possibilities of further development of the proposed concepts some complementary actions were taken, extending beyond the original scope of the project. Positive verification of the load-alleviation capability of the Fluidic Spoiler in wind tunnel tests led to the development of its simplified version, named the "Leaky Wing" concept, and to simulations of the load-alleviation effectiveness of the developed concepts in gust conditions. The "Leaky Wing" concept doesn't rely on an independent source of high-pressure air but exploits the difference between the static pressure on the pressure and suction sides of the wing. This concept, investigated in numerical flow simulations, consists of slots connecting the pressure and suction sides of the wing. The shape and number of the channels require further optimization, but the results obtained for the initial version consisting of five blocks of slots located within external 40% of wing span, each block consisting of five slots in the central 10% of wing cross section proved capable of producing similar effects in terms of the area of separated flow to the effects of the Fluidic Spoiler fed with independent source of compressed air. Simulations of load-alleviation capability in gust conditions were conducted also for the DTEN and Fluidic Spoiler concept. The common advantage of the investigated fluidic load control concepts over the traditional spoiler in load alleviation is their rapid activation. Significant load-alleviation effects appear in the moment of activation of the nozzle flow whereas similar level of load-alleviation achieved using deflection of classical spoiler or symmetric deflection of ailerons requires large values of the deflection of these surfaces against the dynamic pressure which may require more time.

Conclusions

As a conclusion it may be stated that the results of the conducted works have proven the load alleviation effectiveness of the developed concepts. The load alleviation effectiveness of Fluidic Spoiler was higher than the effectiveness of a classic spoiler of the size of the actuating plate of Fluidic Spoiler. It must be noted, however, that the presented solutions of fluidic load control are still at very low technology readiness level (TRL2 or TRL3). More research is needed, concentrated on shape, dimensions, positions and characteristics at higher Mach numbers including possibilities of integratiion with wing structure and aeroelastic properties of wing equipped with such systems. Continuation of this research may lead to achieving technologically and economically effective solutions.