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WING-LOAD CONTROL BASED ON THE "LEAKY WING" CONCEPT

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***Keywords**: wing load control, flow control, fluidic devices, CFD, URANS simulations*

Abstract

A non-conventional solution of wing-load control, protecting the wing structure against excessive loads, has been presented. The solution utilises a system of transverse ducts connecting upper and lower surface of the wing. In normal flight conditions the ducts are closed. When monitored wing loads begin to grow and are approaching to assumed threshold, the ducts are being opened, initiating natural air flow through them. It is assumed that the flow through the ducts is able to initiate or enhance a separation of main flow on the wing suction side, which leads to mitigation of excessive loads acting on the wing structure. The paper presents results of computational investigations concerning the proposed solution.

Nomenclature

C_D	- drag coefficient
C_L	- lift coefficient
C_m	- pitching moment coefficient
C_N	- wing-section bending-load coefficient
C_P	- pressure coefficient
L	- lift force
M	- Mach number
M_{br}	- wing root bending moment
n	- load factor n=L/W
V	- local velocity of air flow
V_{flight}	- flight velocity
V_{gust}	- gust velocity
W	- weight of aircraft
η	- distance from a root chord of the wing
$_{(0)}$	- subscript denoting typical flight conditions

1 Introduction

Wing-load-control systems are being developed as a means to stabilise flight parameters or mitigate aerodynamic loads acting on critical elements of wing structure. Such systems are designed for use in extraordinary flight conditions, particularly during accelerated flight manoeuvres or sudden gusts. In such situations, rising bending loads may lead to fatigue damage of the wing. Reduction of bending loads may be obtained by modification of spanwise distribution of aerodynamic load, especially in outer part of the wing as it is shown in Fig. 1.

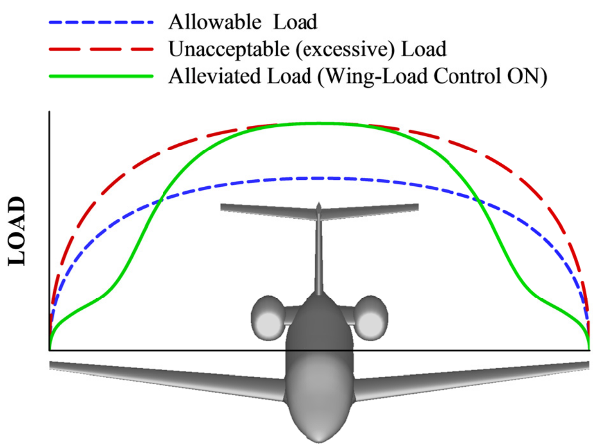

Fig. 1 General idea of wing-load-control system used to alleviate unacceptable loads of the aircraft wing.

Traditional wing-load-control systems utilise solutions like deflections of control surfaces. Good example of such approach is the wing-load-control system of the Lockheed C-5A Galaxy [2], where symmetrical deflections of ailerons are used for reduction of wing loads while deflections of elevators ensure balance of pitching-moment. The system operates in closed-loop with accelerometers on wing tips as detectors of conditions of excessive aerodynamic loads. Apart from traditional mechanical load-control actuators, innovative systems, including new mechanical actuators [3] and fluidic flow control actuators are being developed and tested. The examples of fluidic flow control concept may be air-jets blowing perpendicularly to wing surface [4] and circulation control by blowing in the trailing-edge area [5].

2 Research Background

Application of the wing-load-control technology improves safety and comfort of aircraft flight and allows building lighter wings of high aspect ratios which favours reduction of induced drag and in consequence reduction of Direct Operating Costs of the aircraft. Therefore the development of wing-load-control systems is a subject of many researches.

The European project STARLET, co-financed by the Clean Sky Joint Undertaking, Institute of Aviation and Ministry of Science of Poland, has been focused on application of fluidic devices for the active control of wing load.

One of investigated in this project devices, was a matrix of mini nozzles located in outer part of the wing. In this solution, named "fluidic spoiler", the air jets blown from the nozzles perpendicularly or obliquely are expected to influence strongly the main flow on the wing, leading to its separation and in consequence to alleviation of bending load acting on the wing structure. Such "fluidic spoiler" might be activated in extraordinary flight conditions when excessive bending loads threaten a fatigue damage of the wing.

The second solution investigated in the project STARLET was a system of specially shaped nozzles of D-TEN type (Dual, Trailing-Edge Nozzle) located at a wing trailing edge. Such a system, if activated, strongly changes a flow-velocity circulation around the wing by utilising the Coanda effect, which gives considerable change (in the case: alleviation) of aerodynamic loads acting on the wing structure.

The main obstacle in practical application of both above-mentioned solutions is a difficulty in providing required air mass flow rate to the nozzles, which needs adequate additional sources of overpressure. Alternatively, an utilisation of natural sources of overpressure may be taken into consideration. Such approach may be reasonable especially in the case of "fluidic spoiler" concept, because this solution needs relatively low level of overpressure, necessary for its proper work. Therefore the presented study is focused on answering the question: is it possible to develop the "fluidic spoiler" concept, utilising only natural flow phenomena, without the need of application of additional sources of overpressure?

3 Research Subject and Methodology

The studies described in the paper focused on two main topics:

1) Development of the concept of "fluidic spoiler", fed only by natural sources of overpressure. The design process aimed at choice of possible best solution, being the best compromise between design constraints and required high efficiency of alleviation of excessive wing load.
2) Simplified simulations of work of the developed wing-load-alleviation system in conditions of sudden gust, with strongly increasing momentary bending load acting on the wing structure.

Both above tasks were realised based on CFD simulations, conducted using the URANS solver ANSYS FLUENT [1]. The computations focused mainly on 3D cases, though within preliminary design stage, a 2D approach was also utilised, mainly to conduct simplified optimisation and sensitivity analysis. The URANS simulations were conducted using unsteady, compressible, viscous model of the flow with SST k-ω model of turbulence. Computational mesh was of high quality and resolution, especially within the region of boundary layer and in proximity of air ducts.

The subject of 3D investigations was the swept wing (Fig. 2) of aspect ratio 7.7, mean aerodynamic chord 3.5m and span 25m. The wing sections were built based on the airfoil NACA64A210.

4 "Leaky Wing" Concept

The concept of the "Leaky Wing" has been developed as a particular case of "fluidic spoiler", utilising only natural sources of overpressure, accessible in flight conditions favouring occurrence of excessive aerodynamic loads acting on the wing structure. During the design process of the concept, a number of requirements and constraints were taken into consideration, including the simplicity and feasibility of the concept, minimal interference with the wing structure (which could weaken the structure) and high efficiency, reliability and response rate of the proposed system in mitigating excessive aerodynamic loads. Finally developed concept looks as it is shown in Fig. 2.

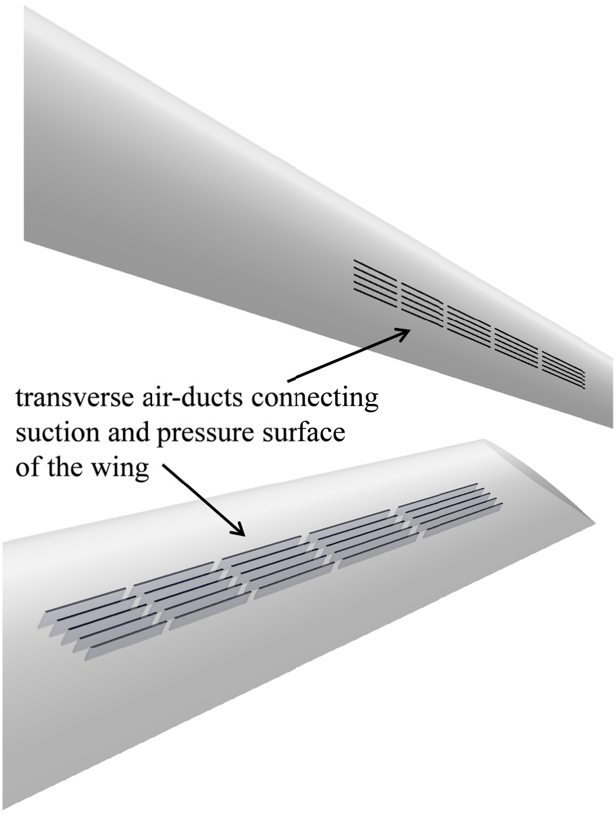

Fig. 2. The "Leaky Wing" concept.

The proposed concept consists of a matrix of transverse ducts connecting upper and lower surface of the wing. The ducts should be placed rather in outer part of the wing, because this part is a source of largest bending moments acting on the wing structure. On the other hand, such placement of ducts may be risky because of possible unfavourable influence of "fluidic spoiler" on the aileron effectiveness. However this aspect needs further investigations.

In normal flight conditions, the ducts are closed, preferably in such a way as not to interfere with the flow around the wing. In extraordinary flight conditions, when excessive bending loads of the wing may occur (e.g. during sudden gusts, accelerated manoeuvres, etc.) the transverse ducts are opened, which should initialise intensive air flow through the ducts, being the effect of considerable difference of static pressure between the suction and pressure sides of the wing. Such phenomenon is typical for the flight conditions with occurrence of high aerodynamic loads of the wing. After opening the air ducts, the flow through them is expected to initiate the separation of the main flow on the wing suction side. In situations when main-flow separation already exists before opening the ducts, it is expected that flow through the ducts may enhance effects of existing separation. In both cases, the opening of the ducts in high-wing-load flight conditions, should decrease difference in static pressures on suction and pressure side of the wing, this way decreasing aerodynamic loads acting on the wing structure.

Such a process of the air-duct opening is presented in Fig. 3. These are the results of 2D, URANS simulation of flow around the "leaky airfoil". During the presented simulation the lift coefficient of the airfoil dropped down from 1.02 to 0.60, which is the result of strong flow separation that occurred after opening the ducts.

Similar simulation in 3D case is presented in Fig. 4. In this case, the activation of the "Leaky Wing" system caused the alleviation of wing-root bending moment (M_{br}) approximately 18% of its value measured when air ducts were closed in the same flight conditions. This is the effect of considerable changes in spanwise distribution of aerodynamic loads, which is shown in Fig. 5. The differences in pressure coefficient (C_P) distribution along selected cross-section of the wing, are presented in Fig. 6. The C_P distribution for air ducts opened is typical for strongly separated flows, while the C_P distribution for air ducts closed is typical for fully attached flows.

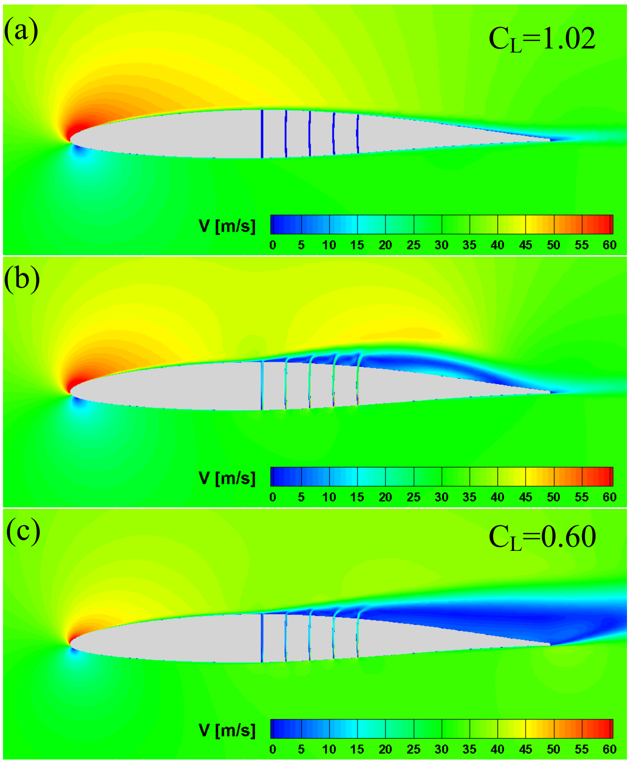

Fig. 3. Process of opening of the transverse ducts. Velocity-magnitude contours around the "leaky airfoil". (a) – ducts closed, (b) – initial stage of duct opening, (c) ducts opened, fully developed separated flow

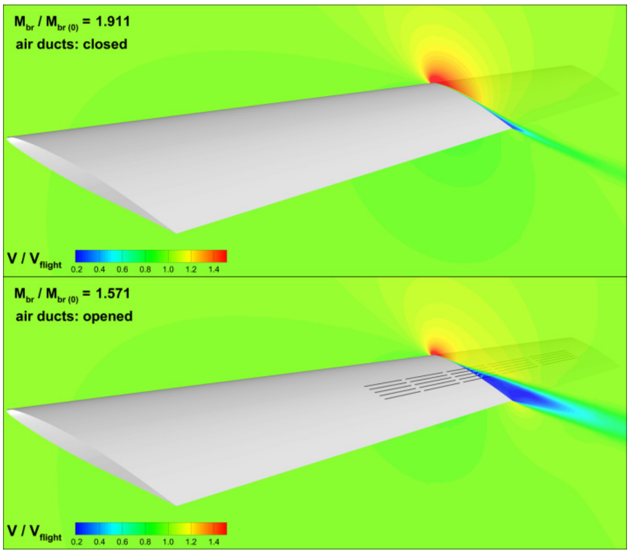

Fig. 4. Effect of the "Leaky Wing" system inactive (air ducts closed) and active (air ducts opened) on the flow velocity contours around the wing suction surface.

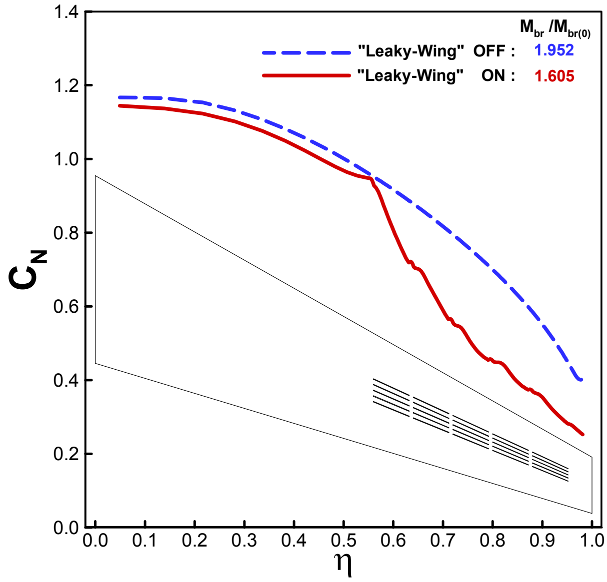

Fig. 5.Comparison of spanwise distribution of aerodynamic bending-load coefficient (C_N), for the "Leaky Wing" system OFF and ON.

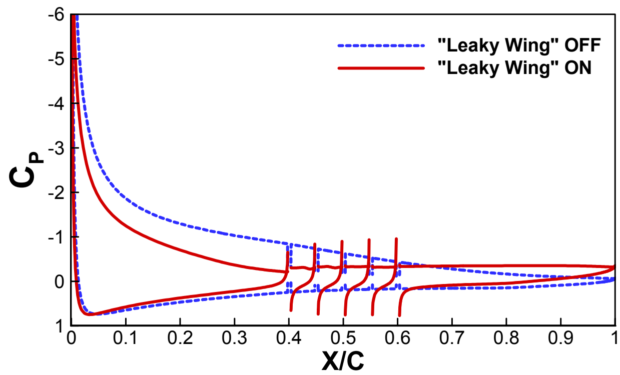

Fig. 6. Comparison of pressure coefficient (C_P) distribution in a cross section of the wing, for the "Leaky Wing" system OFF and ON.

5 Effectiveness and Response Rate of the "Leaky Wing" Concept in Sudden-Gust Conditions

The effectiveness and response rate of the "Leaky Wing" concept in sudden-gust conditions, were the subject of studies conducted using 3D URANS simulations. The simulations concerned a typical cruise flight of aircraft, during which a sudden, vertical gust of air was occurring. To verify proper work of the complete system of wing-load alleviation, a simplified model of load-monitoring system was introduced in simulations. It was assumed, that the system would consist of several accelerometers as it has a place in real systems [2]. In mathematical model of the load-monitoring system, at every time moment of the flight simulation, the system measured current value of load factor n=L/W, where L is the current lift force acting on aircraft and W is the weight of the aircraft.

In conducted URANS simulations, the sudden gust was modelled as additional, vertical component of free stream velocity vector, by defining appropriate far-field boundary conditions. Typical gust profiles, utilised in presented below simulations, respectively at flight speed M=0.20 and M=0.45, are shown in Fig. 7. The times of attack and decay phases of the gust were assumed 0.2s, while the sustain phase lasted approximately 0.5s. The maximal vertical velocity of gust (V_{gust}) in reference to the flight velocity (V_{flight}) was selected for every simulation so as to ensure the occurrence of the load factor n approximately 2.

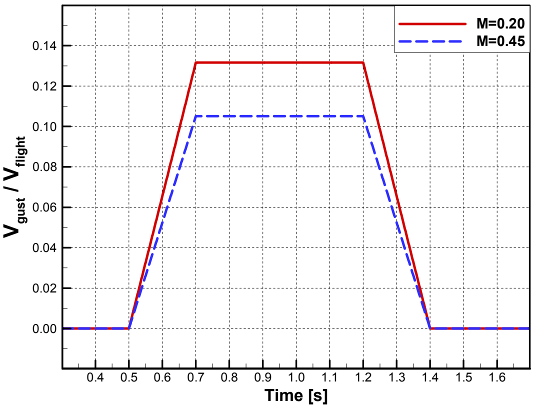

Fig. 7. The gust profiles utilised in conducted URANS simulations at flight speed M=0.20 and M=0.45.

Simple closed-loop-control (CLC) system, controlling bending load of the wing structure, was introduced based on the assumption, that the system alleviating excessive wing loads would be activated when the measured load factor exceeded a certain activation threshold (n>1.3) and would be deactivated when the decreasing load factor dropped down below a certain deactivation threshold (n<1.2). In the case of "Leaky Wing" concept, the activation and deactivation of the system meant respectively opening and closing of air ducts connecting lower and upper surface of the wing.

The flight simulations in sudden-gust conditions were conducted for two flight velocities: M=0.20 and M=0.45. In both the cases, simulations were conducted twice: for the wing-load-control system active ("Leaky Wing" ON) and inactive ("Leaky Wing" OFF), when air-ducts were closed during whole simulation.

5.1 Flight Simulation at M=0.20

The flight at speed M=0.20 was simulated in conditions of 0.9s-lasting gust, including 0.2s phases of the gust attack and decay (Fig. 7). During the simulation of flight with inactive load-alleviation system, the load factor n grew from 1.0 for nominal cruise flight conditions, up to 2.35 during the gust. In case of flight with active load-alleviation system, the system was activated (air ducts were opened) when load factor exceeded the activation threshold 1.3 and was again deactivated when load factor dropped down below 1.2. Time histories of load factor for both cases: inactive and active system of wing load alleviation, are compared in Fig. 8.

Fig. 9 compares time histories of wing-root bending moment (M_{br}) related to its value in nominal flight conditions ($M_{br(0)}$), measured for the wing-load-alleviation system active and inactive. The time-histories show, that when the "Leaky Wing" system was active, the main-flow separation provoked by the flow through opened ducts (at n>1.3), weakened considerably the wing-root bending moment. The alleviation achieved approximately 17% at the time when the highest value of wing-root bending moment were achieved.

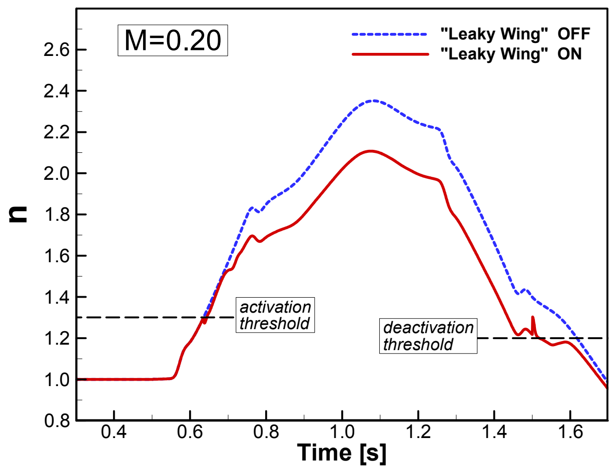

Fig. 8 Time histories of load factor n, measured for the wing-load-alleviation system OFF and ON, at flight speed M=0.20.

Analysing Fig. 9 it may be concluded that the response rate of the "Leaky Wing" system at flight speed M=0.20 was satisfactory. When air ducts were opened, the system started alleviation of wing-root bending moment during 0.06s and after next 0.06s it achieved nearly steady level of alleviation.

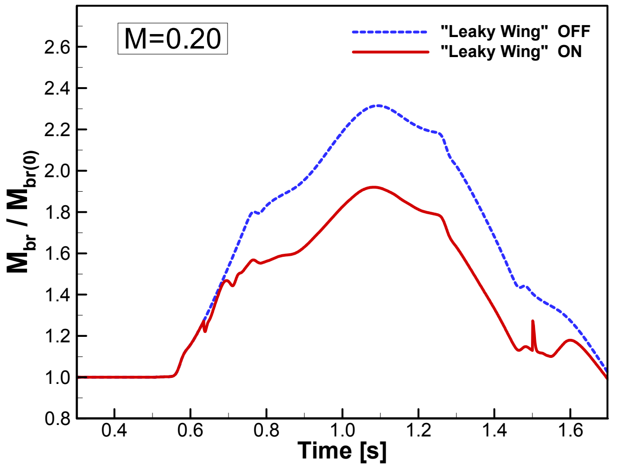

Fig. 9. Time histories of wing-root bending moment (M_{br}) related to its value in nominal flight conditions ($M_{br(0)}$), measured for the wing-load-alleviation system OFF and ON, at flight speed M=0.20.

Fig. 10 presents the flow-velocity-magnitude contours around the wing, capture during two flight simulations when the "Leaky Wing" system was inactive and active. Presented results concern the flight speed M=0.20 and the time moment when the highest values of wing-root bending moment were measured.

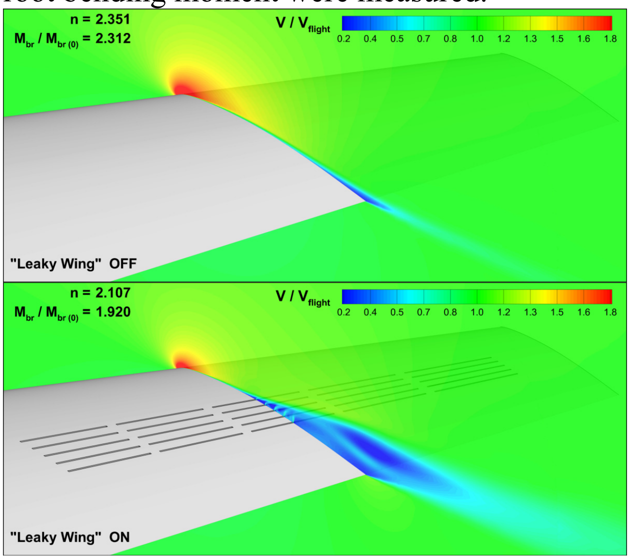

Fig. 10. Flow-velocity-magnitude contours around the wing for the highest values of wing-root bending moment. Comparison of cases with inactive (OFF) and active (ON) "Leaky Wing" system. Flight speed M=0.20.

Fig. 11 presents spanwise distributions of aerodynamic bending-load coefficient (C_N) for the two compared cases. Considerable reduction of wing bending loads is visible in the region of location of air ducts. This is an effect of flow separation initiated by natural flow through the ducts. Differences between chordwise distributions of pressure coefficient (C_P) in the wing section cutting the air ducts, for two compared cases ("Leaky Wing" inactive and active) and flight speed M=0.20, are presented in Fig. 12. The pressure distribution for "Leaky Wing" active is typical for flow separation, while for "Leaky Wing" inactive the pressure distribution is typical for fully attached flow.

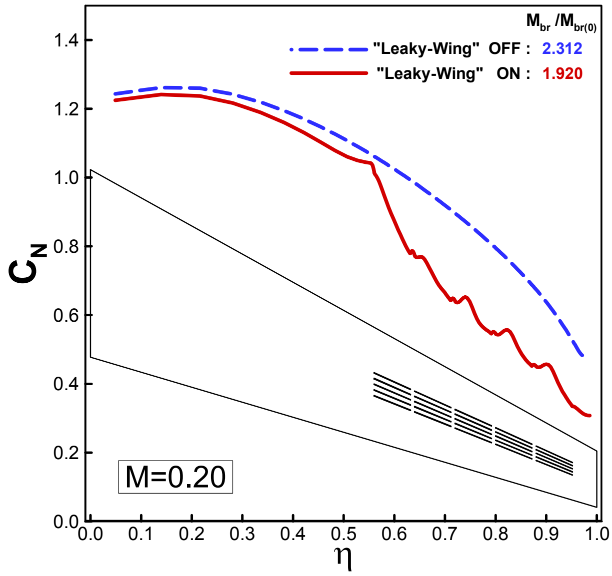

Fig. 11. Comparison of spanwise distribution of aerodynamic bending-load coefficient (C_N), for the "Leaky Wing" system OFF and ON. The case of the highest values of measured wing-root bending moment at flight speed M=0.20.

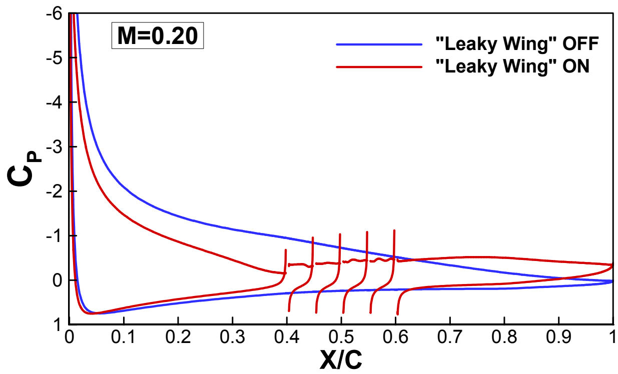

Fig. 12. Comparison of chordwise distribution of pressure coefficient (C_P), for the "Leaky Wing" system OFF and ON. The case of the highest values of measured wing-root bending moment at flight speed M=0.20.

5.2 Flight Simulation at M=0.45

Similar to presented in section 5.1 simulations were conducted for the case of flight of isolated wing at speed M=0.45. The gust profile used in this case is presented in Fig. 7. During the simulation of flight with inactive load-alleviation system, the load factor n grew from 1.0 for nominal cruise flight conditions, up to 1.84 during the gust. In case of flight with active load-alleviation system, the system was activated (air ducts were opened) when load factor exceeded the threshold 1.3 and was again deactivated when load factor dropped down below 1.2. Time histories of load factor for both cases: inactive and active wing-load-alleviation system, are compared in Fig. 13.

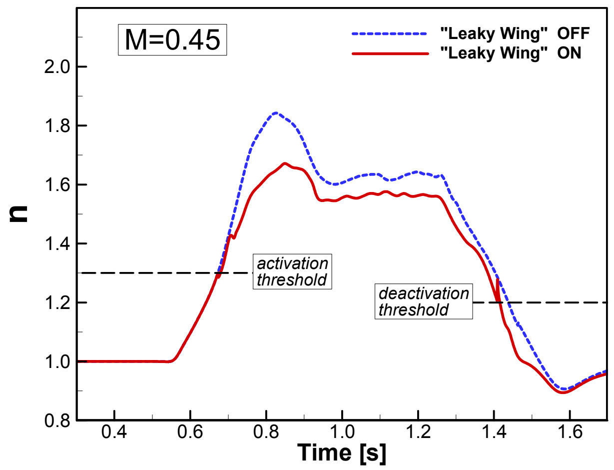

Fig. 13. Time histories of load factor n, measured for the wing-load-alleviation system OFF and ON, at flight speed M=0.45.

Fig. 9 compares time histories of wing-root bending moment (M_{br}) related to its value in nominal flight conditions ($M_{br(0)}$), measured for the wing-load-alleviation system inactive and active. The time-histories show, that when the "Leaky Wing" system was active, the natural flow through opened air ducts (at $n>1.3$), weakened the wing-root bending moment approximately 17.4%, at the time, when the highest value of wing-root bending moment were achieved. In this case, otherwise than in the case of flight at speed M=0.20, the activated flow through the air-ducts, rather amplified effects of existing separation than initialised the main-flow separation. Such conclusion may be formulated based on presented results of simulations, especially in Fig. 15 and Fig. 17.

Analysing Fig. 14 it may be concluded that the response rate of the "Leaky Wing" system at flight speed M=0.45 was satisfactory. Similarly as for the flight speed M=0.20, when air ducts were opened, the system started alleviation of wing-root bending moment very quickly (approx. 0.05s). Next, in initial stage of alleviation of wing-root bending moment, the alleviation was very effective. However in next stages the effectiveness dropped down. The reason of such phenomenon was that at flight speed M=0.45, the strong separation of main flow probably occurred also for the case of the clean wing (inactive load-alleviation system).

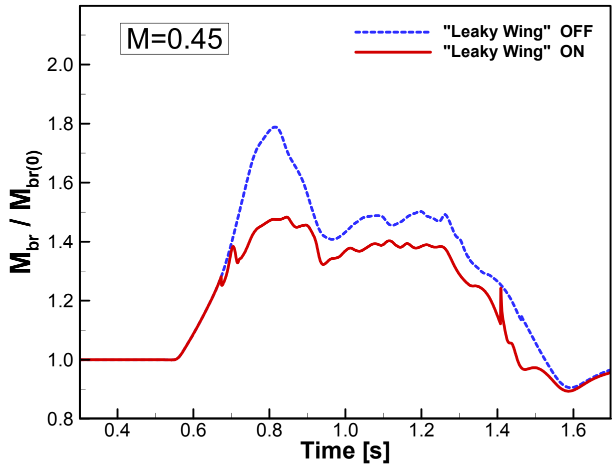

Fig. 14. Time histories of wing-root bending moment (M_{br}) related to its value in nominal flight conditions ($M_{br(0)}$), measured for the wing-load-alleviation system OFF and ON, at flight speed M=0.45.

Fig. 15 presents flow-velocity-magnitude contours around the wing, for the "Leaky Wing" system inactive and active. The snapshots were captured at the time moment when the highest values of wing-root bending moment were measured.

Fig. 16 presents spanwise distributions of aerodynamic bending-load coefficient (C_N) for the two compared cases. Considerable reduction of wing bending loads is visible in the region of location of air ducts. This is an effect of main flow separation, which was initiated or enhanced by the air flow through the ducts. Differences between chordwise distributions of pressure coefficient (C_P) in the wing section crossing the air-duct region, for two compared cases ("Leaky Wing" inactive and active) and flight speed M=0.45, are presented in Fig. 17. The pressure distribution for "Leaky Wing" system active is typical for flow separation, while the pressure distribution for "Leaky Wing" OFF looks slightly strange. However one should remember that they were measured at flight speed M=0.45 and high angle of attack, resulting from modelled vertical gust.

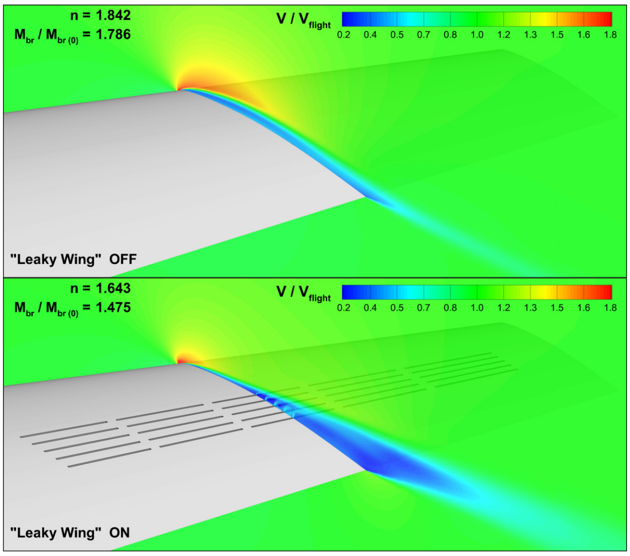

Fig. 15. Flow-velocity-magnitude contours around the wing for the highest values of wing-root bending moment. Comparison of cases with inactive (OFF) and active (ON) "Leaky Wing" system. Flight speed M=0.45.

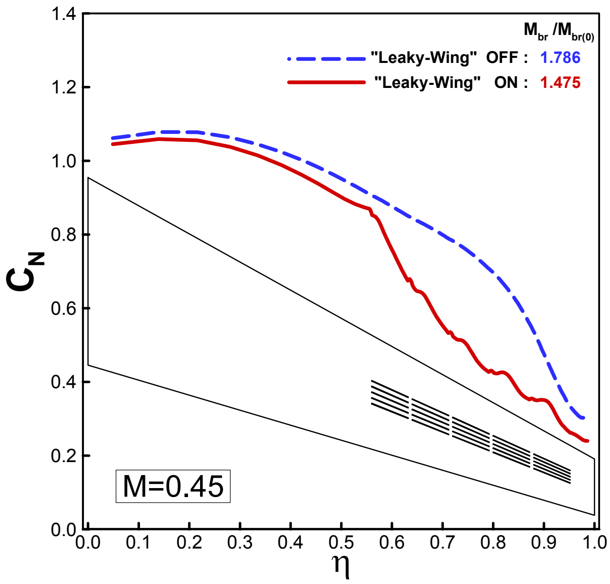

Fig. 16. Comparison of spanwise distribution of aerodynamic bending-load coefficient (C_N), for the "Leaky Wing" system OFF and ON. The case of the highest values of measured wing-root bending moment at flight speed M=0.45.

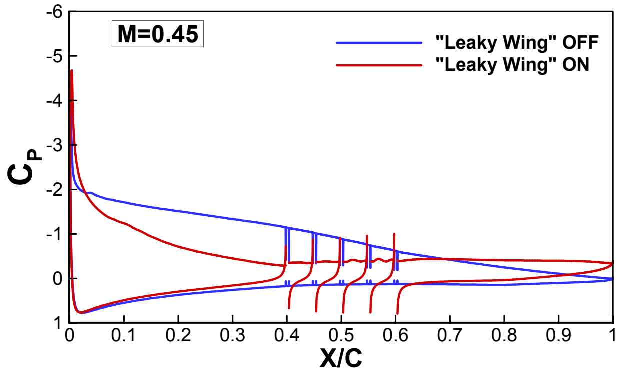

Fig. 17. Comparison of chordwise distribution of pressure coefficient (CP), for the "Leaky Wing" system OFF and ON. The case of the highest values of measured wing-root bending moment at flight speed M=0.45.

6 Summary and Conclusions

The "Leaky Wing" concept has been developed, investigated and proposed as non-conventional system, protecting the wing structure against excessive aerodynamic loads that may occur during the aircraft flight as results of sudden gusts, manoeuvres, etc. The concept utilises a system of transverse ducts connecting upper and lower surface of the wing. In normal flight conditions the ducts are closed. When a sudden growth of wing load is forecasted, the ducts are being opened, initiating natural air flow through them, which initiates or enhances the main-flow separation on the wing suction surface, finally leading to mitigation of excessive bending loads acting on the wing structure.

The effectiveness of the "Leaky Wing" concept and its response rate in conditions of sudden gust, were investigated by series of URANS simulations. The simulations were conducted for two flight speeds: M=0.20 and M=0.45. Results of the simulations confirmed, that the proposed "Leaky Wing" system quickly responds to increasing aerodynamic loads and its load-alleviation speed should be enough to protect wing structure against fatigue damage.

In the research, the measure of load-alleviation effectiveness was the relative difference between the wing-root bending moments measured for inactive and active wing-load-alleviation system. Based on conducted flight simulation, the efficiency was estimated to be around 17-18%. However the effectiveness depends on several factors, including shape, dimensions, positions and number of air ducts, so it is expected that the efficiency could be increased by optimisation of the presented concept, which is the subject of planned future research.

Although the "Leaky Wing" concept was proposed as the solution of load control of aircraft wing, this approach may be also adopted in the case of another type of lifting surfaces, exposed to excessive aerodynamic loads, e.g. the rotor blades of wind turbines.

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