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LOAD CONTROL OF NATURAL-LAMINAR-FLOW WING VIA BOUNDARY LAYER CONTROL

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Abstract. *The concept of Smart Micro Vanes (SMV) has been developed and investigated through computational simulations. The concept may significantly extend the applicability of natural-laminar-flow-and-high-aspect-ratio wing for modern, low-cost transport aircraft. The proposed device is an array of deployable micro-vanes (turbulators) located at a front part of the suction side of the wing. In nominal, cruise flight conditions the SMV are hidden in order not to trip the laminar boundary layer. In transonic flow, in extraordinary conditions of sudden gust the SMV are deployed to force laminar-turbulent transition of boundary layer on the suction side of the wing. This causes sudden drop of lift force acting on the wing and significant reduction of a danger of buffet onset. Both these phenomena are beneficial and desirable in the context of active control of aerodynamic loads acting on the wing structure. The paper presents results of computational simulations of transonic flight of simplified model of natural-laminar-flow wing in conditions of sudden-gust appearance. The simulations have been conducted for the case of clean model wing as well as for the same wing equipped with Smart Micro Vanes, deployed automatically (simulation of simple close-loop control) to protect the wing structure against excessive aerodynamic loads.*

1 INTRODUCTION

Reduction of operational costs of modern transport airplanes is one of key goals of contemporary Aeronautical Engineering. The goal is trying to be achieved by reduction of both the aerodynamic drag and weight of aircraft [1]. For transport airplanes operating at transonic air speeds, the main drag components are: induced drag, friction drag and wave drag. Reduction of each of the drag components is achieved by different means. Reduction of induced drag can be achieved by application of higher-aspect ratio wing, but this leads to increased aircraft weight. For this reason a design solution based on active flow control that make it possible to build lighter high-aspect-ratio wings are in demand. On the other hand the known solution for reduction of friction and wave drag is transonic, natural-laminar-flow wing. This solution has, however, significant drawbacks in unsteady flow. In cases of rapid changes of flight conditions, as in sudden gusts the loads on laminar wing grow more rapidly than on turbulent wing and buffet oscillations leading to structural damage of wing may appear earlier than for turbulent wing.

Taking into account all above pros and cons concerning application of Natural Laminar Flow (NLF) technology for wings of low-cost transport airplanes operating at transonic speeds, one may conclude, that such approach needs application of smart devices controlling the flow on the wing and loads acting on the wing in extraordinary flight conditions. In contrast to classic wing-load-control systems protecting the wing structure against excessive loads, such a system for the NLF wing should also protect the transonic flow on the wing against the buffet onset.

The interaction between boundary layer and transonic effects on the NLF wing has been investigated within the FP7 project TFAST (Transition Location Effect on Shock Wave Boundary Layer Interaction). Based on results of computational investigations conducted within the project [2], the authors of the paper have developed concept of Smart Micro Vanes (SMV). This concept may significantly extend the applicability of natural-laminar-flow-and-high-aspect-ratio wing for modern, low-cost transport aircraft. The proposed smart device is an array of deployable micro-vanes (small, thin plates) located at a front part of the suction side of the wing. In nominal, cruise flight conditions the SMV are hidden inside the wing in order not to trip the laminar boundary layer. It is assumed that the SMV are deployed to force laminar-turbulent transition of boundary layer generally in two situations:

1. In extraordinary conditions of sudden gust in transonic flow:
    - to alleviate growing aerodynamic load acting on the wing
    - to reduce a danger of buffet onset (as well as wing buffeting)
2. Optionally, in takeoff-and-landing conditions (low speed, high lift) to avoid a danger of laminar-stall appearance at high angles of attack (which is well known drawback of laminar airfoils and wings).

The paper presents results of computational simulations of transonic flight of simplified model of NLF wing in conditions of sudden-gust appearance. The simulations have been conducted for the case of clean NLF wing as well as for the same wing equipped with Smart Micro Vanes, activated (deployed) to protect the wing structure against excessive aerodynamic loads.

2 RESEARCH SUBJECT AND METHODOLOGY

The computational investigations of SMV applied for wing-load control via boundary-layer control were conducted for the case of simplified model of wing segment presented in Figure 1. The segment was built based on V2C laminar airfoil designed by Dassault Aviations especially for investigations of SWBLI in the TFAST project. Two configurations of the wing have been investigated: the clean wing (with fully retracted micro vanes) shown on the left side of Figure 1 and the wing equipped with SMV, which were retracted or deployed depending on current flight conditions. The latter configuration in nominal cruise flight conditions looked exactly the same as clean-wing configuration. In sudden-gust conditions, when aerodynamic loads exceeded given threshold, the SMV were deployed and investigated configuration looked as it is shown on the right side of Figure 1.

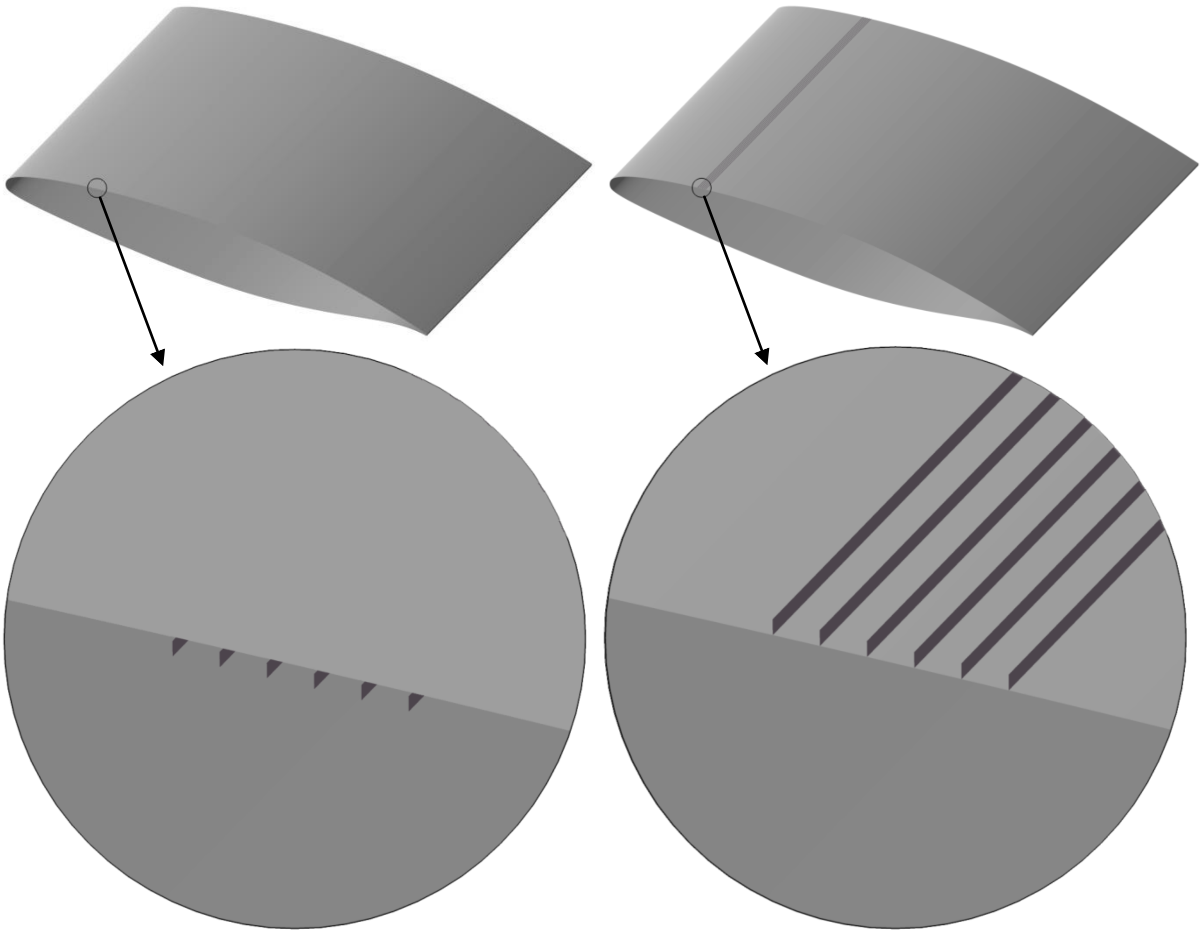

Figure 1: Investigated model of NLF-Transonic Wing equipped with Smart Micro Vanes.
Left side: Clean NLF Wing with retracted SMV. Right side: Wing with fully deployed SMV.

The wing-flight simulations were conducted through solution of Unsteady Reynolds-Averaged Navier-Stokes Equations (URANS) using ANSYS FLUENT solver [3]. For the modelling of investigated phenomena the four-equation Transition SST turbulence model was applied. This model solves additional four equations on four unknown variables: k – turbulent kinetic energy, ω - specific dissipation rate of k, γ - intermittency (probability of boundary layer being turbulent) and Re_θ - Reynolds number based on boundary layer momentum thickness. Second-order spatial and temporal discretisation of URANS equations was applied.

In conducted simulations, instead of finite-span wing segment, the infinite-span wing was investigated, utilising periodicity conditions at the ends of wing segment. The chord of the wing was C=0.2m.

During the wing-flight simulations, the effect of sudden gust was modelled by sudden growth of angle of attack, which was achieved by physical rotation of computational mesh.

The effect of deployment of SMV was realised through a change of status of cell walls modelling physical surfaces of deployed vanes. In case when the vanes were retracted, the surfaces had status "interior" while for fully deployed vanes they had status "wall".

In conducted CFD simulations, a simple Closed-Loop Control (CLC) of wing loads was introduced. It was assumed that during the flight, the control system is monitoring current values of load factor (n), defined as the ratio:

$$n = L / W \tag{1}$$

where L is a current lift force acting on the wing and W is a weight of aircraft. According to assumed CLC algorithm: the load/flow control system was activated (SMV were deployed) when for increasing load factor it exceeded the assumed activation threshold n=1.3.

Similar approach using time-accurate solution of URANS equations was already applied for analysis of reduction of aerodynamic loads in gust as an effect of fluidic wing-load-control devices [4],[5].

3 SIMULATION OF TRANSONIC FLIGHT OF NLF WING IN SUDDEN-GUST CONDITIONS

3.1 Flight Conditions

In conducted computational simulations, the nominal, cruise flight conditions were assumed as follows:

- Mach number: M=0.7
- Reynolds number: $Re=2.67 \cdot 10^6$
- Lift coefficient: $C_L = 0.76$

The assumed sudden-gust model was realised through change of current angle of attack - physical rotation of computational mesh with angular speed 5deg/s. As a result, the gust velocity profile presented in Figure 2 was applied in the conducted simulations. In presented results, only the gust-velocity-growth phase was taken into consideration.

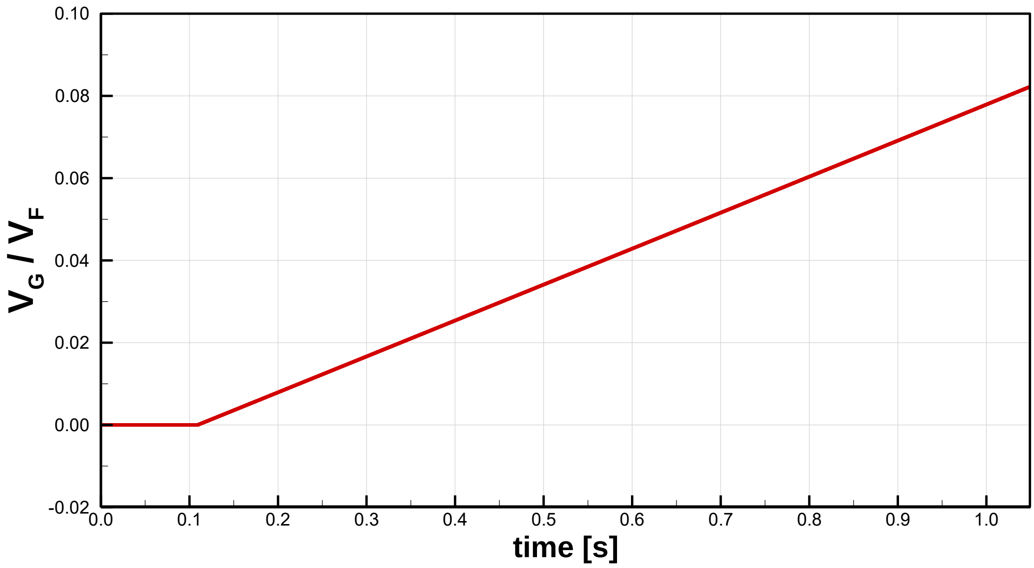

Figure 2: Assumed model of sudden-gust conditions. Time-variable gust velocity (V_G) related to flight velocity (V_F) during the gust-velocity-growth phase.

Within the TFAST project, several different positions and heights of SMV were investigated from point of view of their effectiveness and suitability for wing-load-control purposes. In the presented simulations only the configuration of six rows of SMV of height of 0.125% of wing chord, located at 20% of wing chord (see Figure 1) was investigated, because such configuration seemed to be optimal based on previously conducted research [2].

3.2 Results of Simulations

Time history of flight in sudden gust conditions of two compared configurations: clean wing and wing equipped with SMV, in synthetic form is presented in Figure 3.

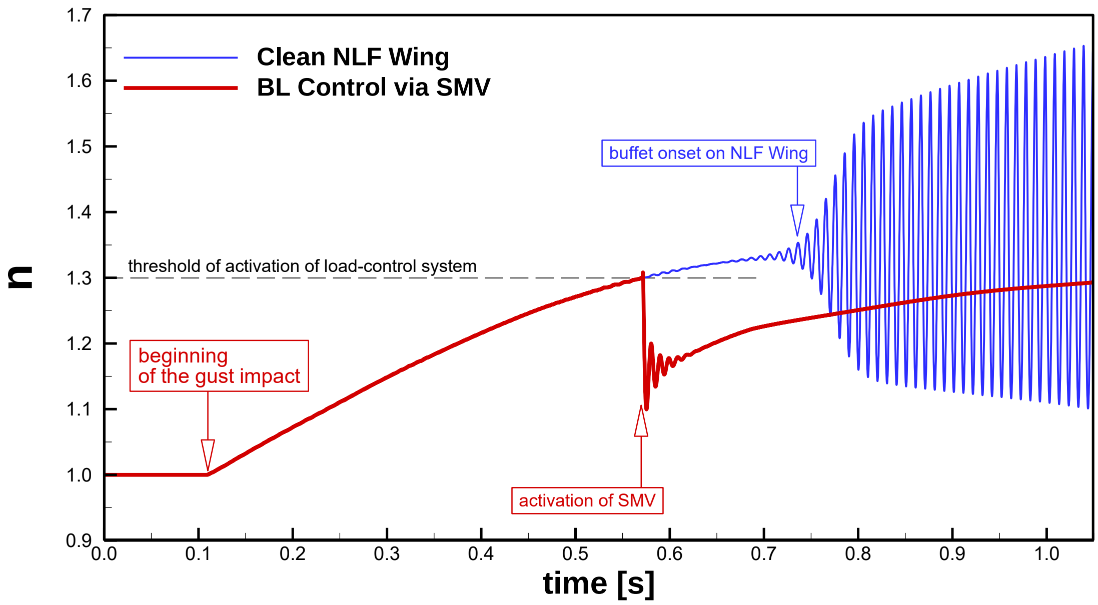

Figure 3: Comparison of time histories of load factor (n) during the sudden, growing gust, for two configurations: 1) Clean NLF Wing and 2) the Laminar Wing equipped with SMV controlling the flow inside the boundary layer.

According to assumed gust profile (Figure 2) the gust started influencing the wing loads at the moment t≈0.11s of simulation. The load factor started growing from this moment, and it exceeded the threshold 1.3 at the moment t≈0.57s. For the clean-wing configuration, the load factor continued growing smoothly until the moment t≈0.70s. Starting from this moment, the load factor for the clean-wing configuration indicated oscillations of quickly growing amplitude. These oscillations were effect of buffet onset on the suction side of the wing, due to a strong, unsteady flow separation behind the shock wave. Frequency of the observed buffet was approximately 98 Hz.

For the configuration of wing equipped with SMV, the simulation of unsteady gust load was the same as for the clean wing until the moment t≈0.57s when the load factor exceeded assumed threshold 1.3. At the moment, the SMV were fully deployed. Figure 3 shows that activation of SMV caused sudden drop of load factor of nearly 0.2. Next, for a moment, the load factor indicated some diminishing oscillations and after it continued smooth, mild increase. For the conditions, where the flow around clean wing indicated strong buffet, the flow around the wing with deployed SMV was free of any instabilities.

The same qualitative differences in the transonic flow around two compared configurations are visible in Figure 4, where the time histories of wing pitching-moment coefficient are compared.

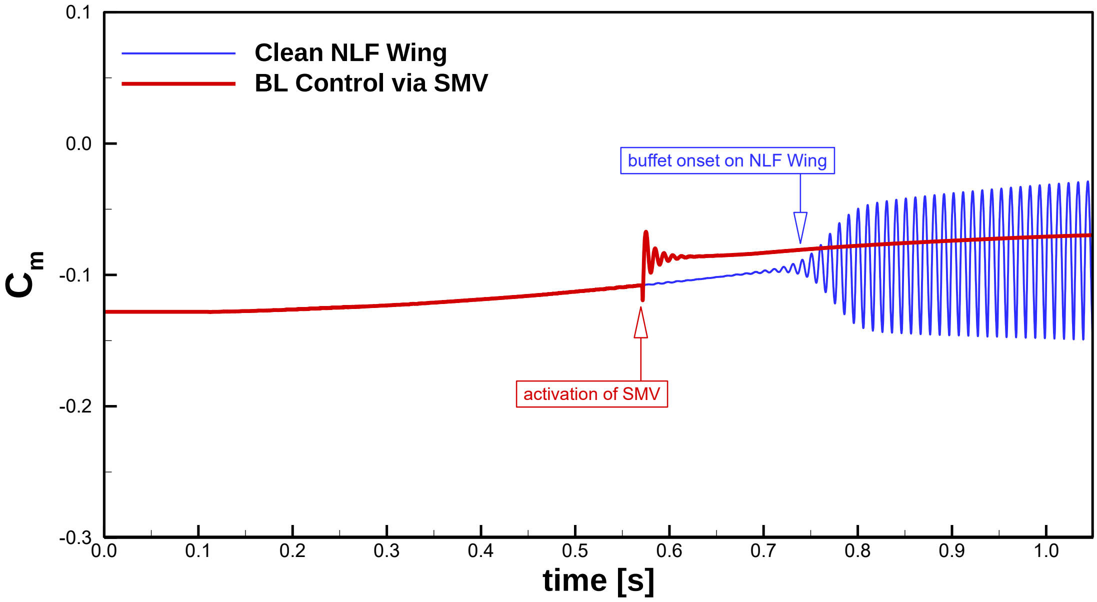

Figure 4: Comparison of time histories of pitching-moment coefficient (C_m) during the sudden, growing gust, for two configurations: 1) Clean NLF Wing and 2) the Laminar Wing equipped with SMV controlling the flow inside the boundary layer.

Figure 5, Figure 6 and Figure 7 present numerical Schlieren visualisations (contours of gradient of air density projected on appropriate direction) of shock waves in the flow around two compared configuration captured in selected moments of wing-flight computational simulations. For the moments t=0.6172 (Figure 5) and t=0.7072 (Figure 6) the visualisations show that in turbulent flow forced by the deployed SMV the shock waves are slightly weaker and located nearer the leading edge of the wing than in purely laminar flow.

Figure 7 presents Schlieren visualisations of shock waves in the flow around two compared configuration captured at the moment, when for the clean wing the strong buffet is observed. In this case the shock wave is extremely unsteady and it quickly changes its position causing quick changes of flow parameters. Extreme-front and extreme-back positions of the shock wave during the buffet observed for the clean wing are shown in upper and middle part of Figure 7. For the configuration of wing with deployed SMV, the shock wave does not indicate any instabilities.

Figure 8, Figure 9 and Figure 10 present distribution of pressure coefficient (C_P) in selected cross-section of the wing, captured for two compared configuration in selected moments of simulations. The C_P distributions presented in Figure 8 are captured at a moment shortly after achieving by the load factor (n) the threshold 1.3 and after deployment of SMV. The differences in C_P distribution clearly explain significant drop of aerodynamic load concerning the configuration with deployed SMV. For this configuration, the observed decrease in pressure difference between upper and lower surfaces of the wing is a result of deceleration of the flow on the upper surface caused by both the deployed SMV and induced by them turbulent boundary layer which is much thicker than laminar boundary layer.

In Figure 10 the unsteady C_P distributions on the clean wing captured during the strong buffet are compared with C_P distribution on the wing with deployed SMV, which does not indicate any instabilities.

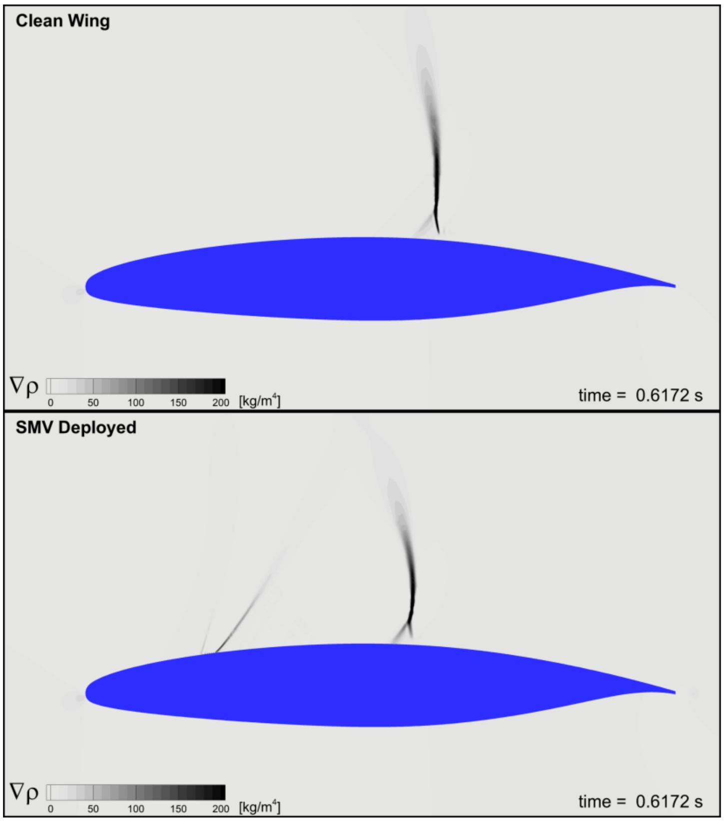

Figure 5: Schlieren visualisation of shock waves at a moment shortly after deployment of SMV. Upper graph: clean-wing configuration. Lower graph: configuration with fully deployed SMV.

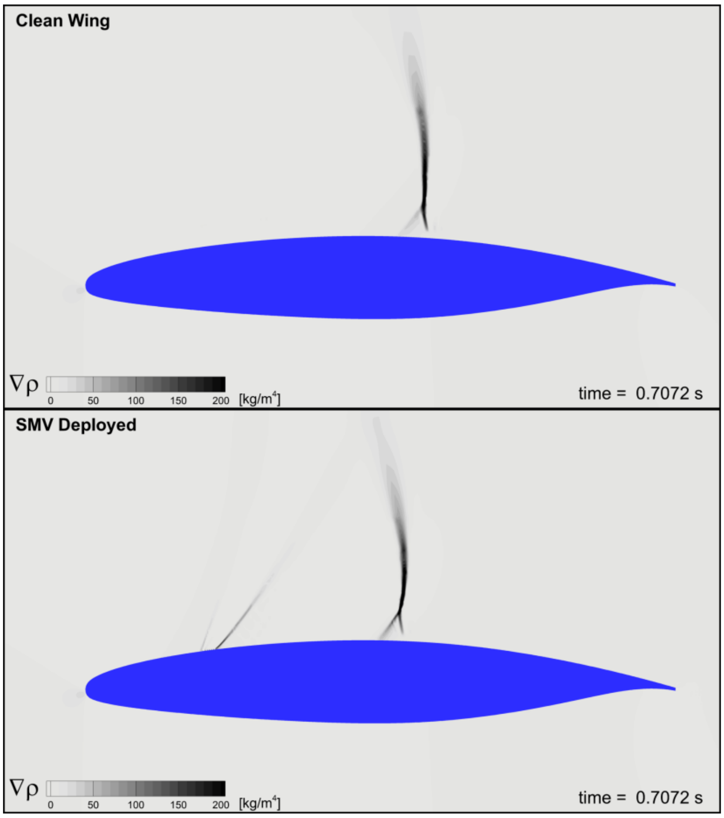

Figure 6: Schlieren visualisation of shock waves at a moment shortly before the buffet onset on the clean wing. Upper graph: clean-wing configuration. Lower graph: configuration with fully deployed SMV.

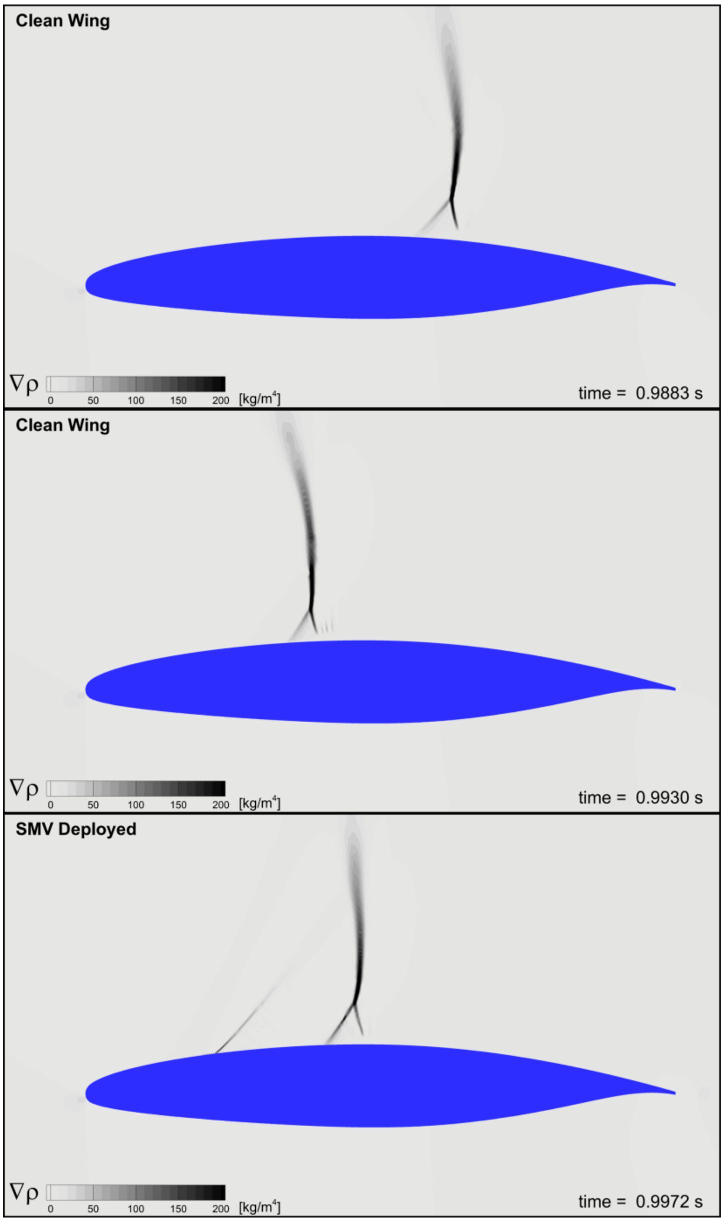

Figure 7: Schlieren visualisation of shock waves during a strong buffet on the clean wing. Upper and middle graphs: clean-wing configuration for extreme-back and extreme-front positions of the shock waves. Lower graph: configuration with fully deployed SMV and steady position of the shock wave.

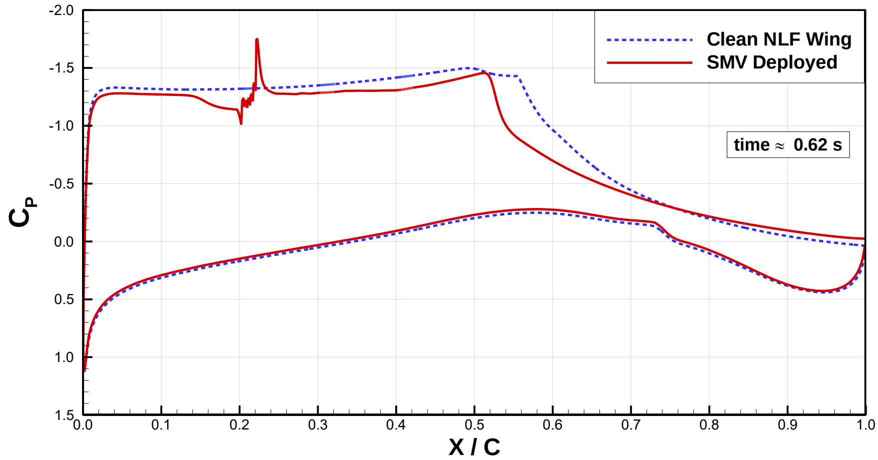

Figure 8: Comparison of pressure-coefficient (C_P) distribution on the wing at a moment shortly after deployment of SMV, for two configurations: 1) Clean NLF Wing and 2) the Laminar Wing with fully deployed SMV.

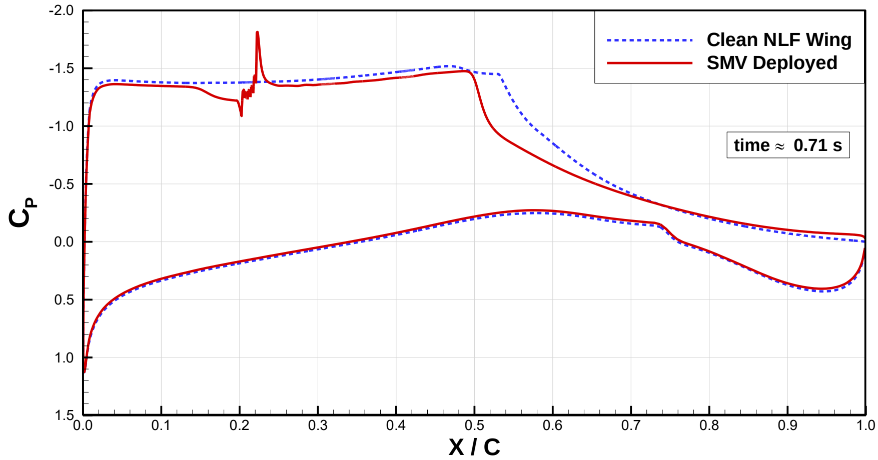

Figure 9: Comparison of pressure-coefficient (C_P) distribution on the wing at a moment shortly before the buffet onset on the clean NLF wing, for two configurations: 1) Clean NLF Wing and 2) the Laminar Wing with fully deployed SMV.

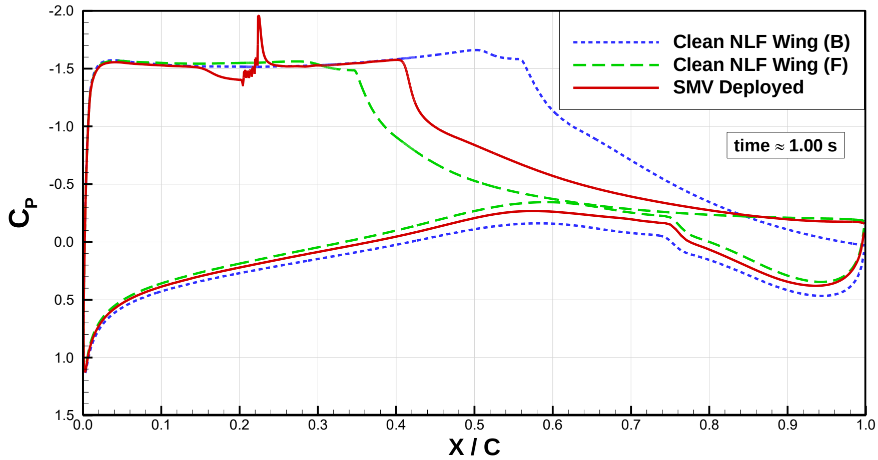

Figure 10: Comparison of pressure-coefficient (C_P) distribution on the wing during a strong buffet on the clean NLF wing, for two configurations: 1) Clean NLF Wing, two cases of extreme-front (F) and extreme-back (B) positions of shock waves and 2) the Laminar Wing with fully deployed SMV and steady position of the shock wave.

4 CONCLUSIONS

- The concept of Smart Micro Vanes has been developed and investigated through computational simulations so as to prove its potential advantages which may significantly extend the applicability of natural-laminar-flow-and-high-aspect-ratio wings for modern, low-cost transport aircraft operating at transonic air speeds.
- The proposed device is an array of micro-vanes which in extraordinary, high-aerodynamic-load flight conditions are deployed to force laminar-turbulent transition which leads to immediate drop of excessive wing load as well as to reduction of danger of transonic buffet onset.
- Conducted simulations showed that effective flow control and wing-load control may be ensured by Smart Micro Vanes of height at least 0.125% of wing chord, preferably located at 20% of wing chord.
- For the investigated configuration of wing equipped with Smart Micro Vanes, in sudden-gust conditions, observed reduction of load factor, being the effect of activation of the device, was approximately 0.2 shortly after activation and 0.1 in a further phase of the gust.
- For the investigated configuration of wing equipped with Smart Micro Vanes, in sudden-gust conditions, in contrast to the clean-wing configuration, the transonic-buffet phenomenon was not observed.

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NOMENCLUATURE

C	- wing chord
C_L	- lift coefficient
C_m	- pitching moment coefficient
C_P	- pressure coefficient
L	- lift force
M	- Mach number
n	- load factor – def. (1)
t	- time
V_G	- gust velocity (normal to flight direction)
V_F	- flight velocity
W	- weight of aircraft
Re	- Reynolds number
ρ	- density

BL	- Boundary Layer
NLF	- Natural Laminar Flow
SMV	- Smart Micro Vanes
SST	- Shear Stress Transport
URANS	- Unsteady Reynolds-Averaged Navier-Stokes Equations

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