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Enhancing the High-lift Properties of a Supercritical Wing by Means of a Modulated Pulse Jet Actuator

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In this experimental investigation, a pulse flow control system on a high-lift device of a wing with a NASA SC(2)-0714 airfoil within the Reynolds number range of the take-off and landing phases, is proposed. In this study, an innovative method of signal modulation has been used in order to simultaneously exploit the benefits of both low and high excitation frequencies in one actuator driving signal that are known to be effective in separation control. It is observed that the lift and drag coefficients are improved due to the use of modulated pulse jets compared to the simple pulse jet.

Keywords: Flow Control, High-lift configuration, Pulsed jet, Burst modulation, aerodynamic efficiency

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In recent years, active flow control methods such as blowing, synthetic jets, plasma actuators, etc. have been widely used to improve the aerodynamic performance of airfoils [1–4], high lift devices [5,6], delta wings [11], wind turbines [11], and turbomachinery blades [11]. The aim of flow control strategies on airfoils and wings is to eliminate or mitigate flow separation, which is generally accelerated by an adverse pressure gradient. Most flow separation elimination techniques rely on three methods: direct injection of high momentum flow near the surface, mixing enhancement, and momentum redistribution in the boundary layer by convective streamwise vortices [12].

The efficiency of air blowing control can be significantly raised using a pulsed jet rather than a continuous jet. Primarily, the advantage of using the pulsed jet in the separation control is to save the mass flux over a certain period, but furthermore, the investigations showed that the pulsation stimulates additional eddies and introduces periodic vortical structures to the separating boundary layer [13]. These vortical structures improve the turbulence mixing between the low momentum boundary layer close to the surface, and the outer part of the boundary layer in the cross flow with high momentum. Therefore, the momentum only transfers within the flow itself and not only from the flow control actuator system. As a result, net mass flux requirements and energy consumption could be reduced.

On the other hand, previous studies showed that the most effective separation control is obtained at the excitation frequency in the range of natural instability frequency of the separated shear layer. The literature clearly illustrated that the strategy of coupling between periodic excitation and the unsteadiness of the flow has significant improvements in flow control efficiency [13]. The separated flow on the lifting surfaces such as airfoil is characterized by two dominant instabilities; the roll-up of vortices in the shear layer, and the large scale vortex shedding in the separated wake of the airfoil [14]. The low-frequency excitation produces large vortical structures that convect downstream and increase flow mixing that lead to the flow reattachment [15]. In contrast, the high-frequency excitation forms smaller vortices that cause the apparent aerodynamic shape modification of the surface. This modification leads to proper changes in pressure gradient and consequently suppresses the flow separation [16]. The corresponding excitation frequencies for these two approaches are at least an order of magnitude apart, typically O(1) and O(10) for the low and high frequencies, respectively.

In the current study, a novel modulated pulse jet method has been used to increase the aerodynamic efficiency of high-lift devices with the approach of reducing injected air consumption. This is a type of fluidic actuator making it possible to organize a simultaneous injection of high momentum flow near the surface and generating spanwise and streamwise vortices for the momentum redistribution in the boundary layer and mixing enhancement. In this method, the waveform of the excitation signal is modified by introducing burst modulation, which allows the simultaneous use of the benefits of high (by carrier signal) and low (by modulating signal) excitation frequencies. Although the modulated excitation signal has previously been used in many flow control applications such as plasma actuator [17–19] and synthetic jet [20], it is the first time that the burst modulation has been implemented for the excitation signal of a pulsed jet generated by a fast-switching solenoid valve with square waveform. The literature review showed that the modulated excitation had a marked effect on the aerodynamic characteristics compared to simple sinusoidal signals in plasma and synthetic jet

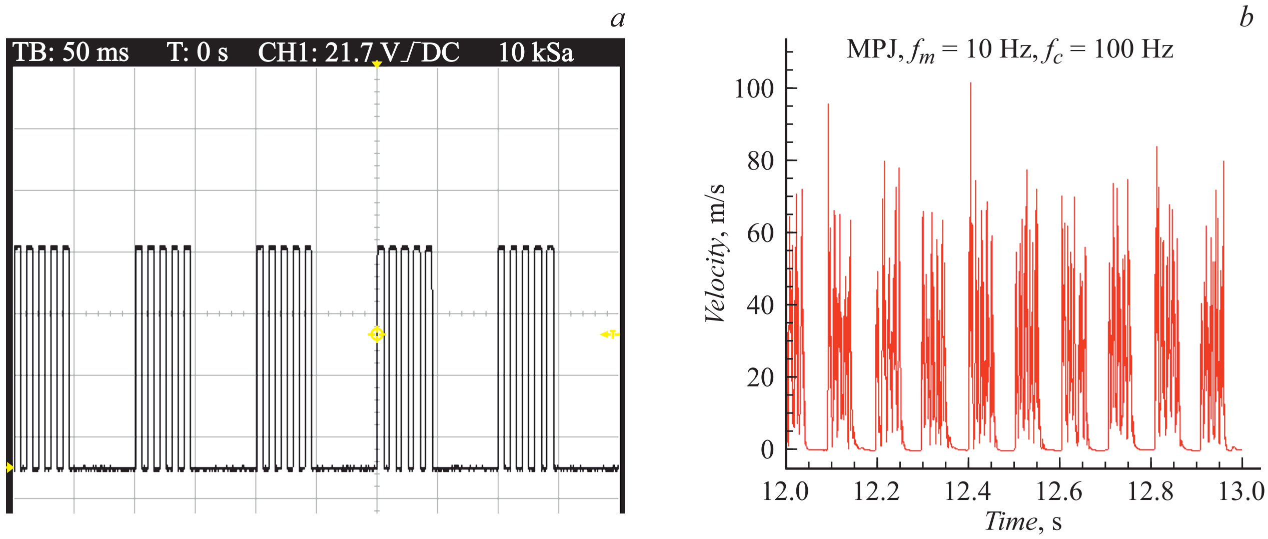

Figure 1. Signal burst modulation. *a* — voltage waveform on oscilloscope, *b* — instantaneous velocity of a modulated pulse jet.

actuators on a laboratory scale but their low momentum injection has led to the inability of these flow control devices in industrial applications that have high reliability requirements.

In this study, a two-dimensional wing model with NASA SC(2)-0714 airfoil was selected. The wing model was designed as a two-element high-lift configuration that consisted of a main element and a single-slotted trailing-edge flap, which had a chord length ratio of 1/4. The wind tunnel model had a wingspan of 1.5 m and a chord length of 0.6 m.

In these experiments, the pulsed jets were brought into the flow on the suction side of the trailing-edge flap through the actuator system. The actuator system was equipped with sixteen electro-mechanical fast-switching valves, a compressed air pipeline, and a PLC system. The valve was a commercial unit (FESTO MHJ9-QS-4-MF) that could run with feeding pressures of 0.5–6.0 bar. The standard nominal flow rate of the valve is 100 l/min. The PLC system was used to set the valve in terms of the on/off situation, the duty cycle, and the pulsing frequency. The PLC system makes it possible to generate a burst modulated signal.

The compressed air was pipelined through the compressor into the valves. The amplitude of the pulsation was set by a standard pressure regulator, which was installed in front of the compressor exit to filter and set air pressure of 6 bar. Then, the pipeline was branched into the valves through a manifold. The exits of the valves were connected to the settling chambers somehow each valve fed one individual settling chamber. Each chamber was closed with a cover and a pair of slots was integrated into the cover. The arrangement of the slots was designed as a vortex generator shape with diverging (common-flow-down) configuration. The array of slot pairs was distributed along the flap shoulder and was positioned at 40% of the flap chord length. The outlet flow from each slot produces a vortex in addition to direct momentum injection.

All actuators were operated in phase and the jet velocity followed the driving signal of the valves. To ensure the correct operation of the device and the voltage applied to the valves, a sample of voltage excitation has been examined by an oscilloscope. Figure 1, *a* shows an image of the input voltage waveform to the valves on the oscilloscope for the modulation mode with a carrier frequency of 100 Hz and modulating frequency of 10 Hz, which, according to the oscilloscope values, confirmed the accuracy of the values generated by the device. Also, the effect of this excitation on the exit velocity of the jet from a single actuator was measured using the 55p11 Dantec hot-wire anemometer (at a distance of 50 mm from the valve outlet and on the centerline) in Figure 1, *b*. The instantaneous jet velocity could reach approximately 30 m/s. The effect of pulse modulation on the turbulence intensity and velocity fluctuations is somehow observed in the instantaneous velocity of the jet.

An angle of attack sweep with a fixed flap deflection is an interesting case because this condition simulates a wing in takeoff or landing phases. Therefore, the deflection angle of the trailing-edge flap was considered as 35°. In addition, the experiments were carried out in the freestream velocity of $V = 25$ m/s, giving a Reynolds number of about $1.01 \cdot 10^6$ based on the chord length. In this study, two kinds of pulsed jets were implemented to produce the flow excitation: simple pulsed jet (SPJ) with an excitation frequency of 250 Hz ($F^+ = 1.8$, $F^+ = fL/V$ where f is the excitation frequency, and L is the flap length ($L = 18$ cm), and V is the freestream velocity) for the first case and modulated pulse jets (MPJ) for the second case. The modulated pulse jets were activated with the carrier frequency of 250 Hz

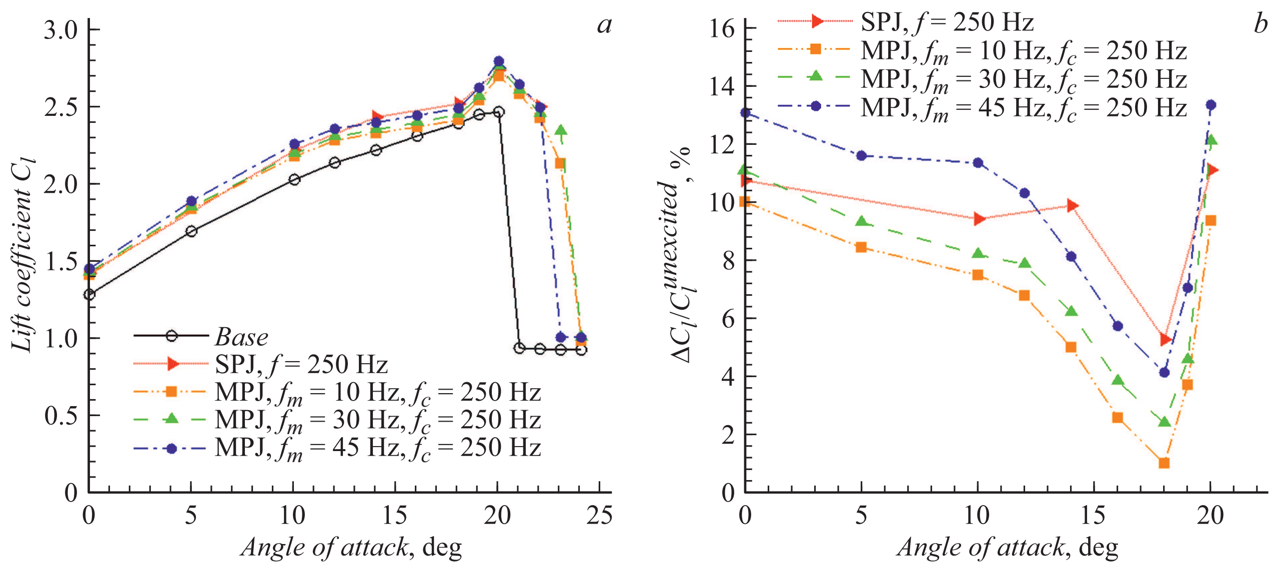

Figure 2. Lift coefficient (a) and lift increment (b) vs angle of attack with and without excitation.

($F^+ = 1.8$) and the modulating frequencies of 10, 30, and 45 Hz ($F^+ = 0.07$, 0.22, and 0.32, respectively).

In this study, the aerodynamic forces were measured by means of an external three-component strain gauge balance. Figure 2, a shows lift coefficients against the angle of attack with and without flow control excitation. In this figure, the unexcited case shows a significant loss of lift at 21° that represents the stall condition. The results of excited cases show that pulsed jets with all four excitation signals produced a considerable increase in lift coefficient for all angles of attack but there were differences in lift enhancement. These results also show that pulsed jet excitations lost their strong effect on the flow when the angle of attack was 16–18°. The reason could be related to the direction of the excitation jets and the direction of the flow through the flap slot, as well as their combination with freestream which may have changed in an unfavorable way as the angle of attack was changed. While at an angle of attack of 20° ($\alpha_{cl\,\max}$), the pulsed jet excitation posponed the flow separation on the flap surface and regained lift compared to the unexcited flow. In addition, the stall in the actuated cases was not very sudden, indicating that even in the post-stall region, the flow control system was not useless and pulsed jet excitations can improve the course of the separation. Among different excitations, MPJ excitation with a modulating frequency of 45 Hz had more excitation benefits in increasing the amount of lift compared to the SPJ. But MPJ with the modulating frequency of 10 to 30 Hz did not show significant performance compared to the 45 Hz. This demonstrates that a frequency of 45 Hz could probably correspond to the first subharmonic or harmonic of the natural instabilities (vortex shedding frequency in the uncontrolled flow). This is in agreement with the observations of previous experimental studies on the excitation frequency on airfoils experiencing a boundary layer separation. The majority of studies in different Reynolds numbers introduced an optimum dimensionless frequency within the range $0.3 < F^+ < 4$ [13].

Figure 2, b shows the percentage lift enhancement against the angle of attack for different excitation signals. According to Figure 2, b, in low angles of attack, the MPJ with the modulating frequency of 45 Hz was the optimum excitation signal in which the maximum amount of the lift increment occurred. While the optimum excitation signal at angles of attack of 14 and 18° was the SPJ with the frequency of 250 Hz. However, at an angle of attack of 20°, MPJ again had a maximum lift enhancement by a considerable difference compared to the SPJ. The lift increment was 13.3% and 11.1% for MPJ and SPJ cases at the angle of attack of 20°, respectively.

The benefit of pulse jet excitation is even more obvious in aerodynamic efficiency, the lift-to-drag ratio (Fig. 3, a). For the MPJ excitation with modulating frequency of 45 Hz, the lift increases by up to 13.1% at the angle of attack 0° while the drag decreases by up to 20% at the same time. This behavior results in a dramatic gain of the lift-to-drag ratio by up to 42% at the angle of attack of 0°. While in this condition, the lift-to-drag ratio benefit for SPJ actuation is about 36%. Figure 3, b shows that in most cases the MPJ excitation with the modulating frequency of 45 Hz, at the same lift values, produces less drag compared to the SPJ excitation.

In conclusion, there are two advantages to using signal modulation in flow control. First, the signal modulation allowed two different (high and low) excitation frequencies to be applied on the jet simultaneously. In the field of separation control, these two different excitation frequencies can be adjusted based on the frequencies of two dominant flow instabilities. The second advantage and a notable

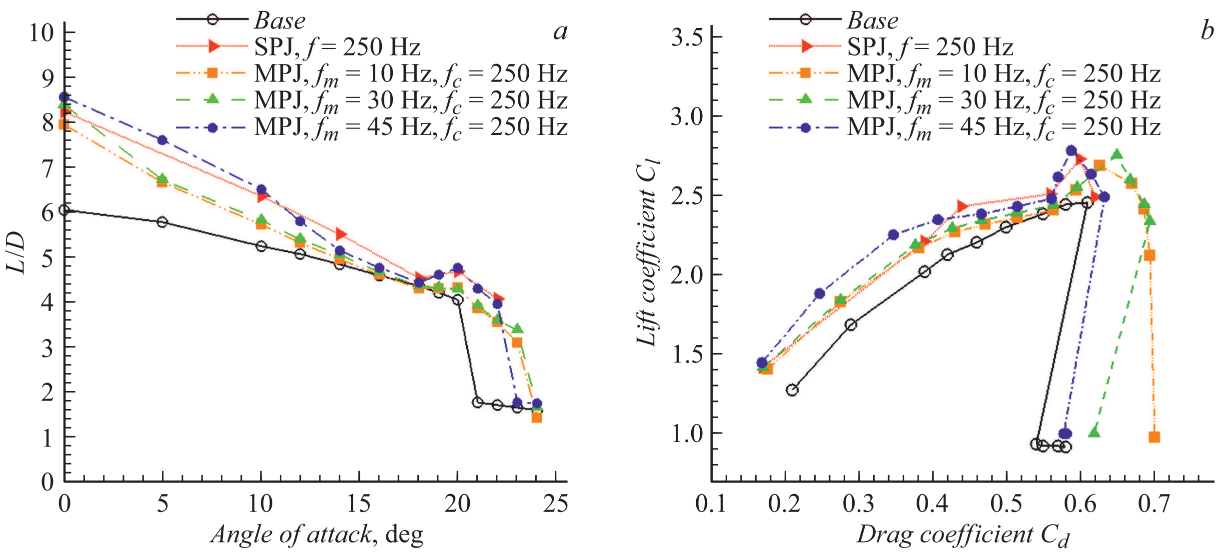

Figure 3. Lift-to-drag vs angle of attack (*a*) and drag polar diagram (*b*) with and without excitation.

feature of the signal modulation is that this method can reduce the air consumption consumed by a simple pulsed jet over a certain part of the flow control period, producing the same or even more amount of control benefits.

Conflict of interests

The authors declare that they have no conflict of interests.

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