Suppression of a laminar separation by a spark discharge at a supersonic Mach number

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Abstract. The paper deals with control the shock wave/laminar boundary layer interaction (SWBLI) by a spark discharge. Incident shock wave generated by a wedge induced the separation of the boundary layer developed on the flat plate at \( M = 1.43 \). The inflow boundary layer state was laminar. The quantitative measurements were performed by PIV. It was found that a turbulent spot generated by a spark discharge suppresses the separation zone. But the thermal spot increases the loss of total pressure in the boundary layer. The effect of the discharge power on the zone of SWBLI has been studied.

1. Introduction
The modern trends in transonic aviation are connected with reducing of viscous drag. Therefore commercial airplanes of the next generations may be equipped with a laminar wing [1, 2]. Generic feature of the transonic flow near the airfoil is presence of local supersonic zone ended by a shock wave. Laminar boundary layer has weak resistance to adverse pressure gradients especially ones produced by shock waves, in contrast to the turbulent boundary layer [3]. This leads to significant flow separation that can eliminate all advantages of laminar flow. Flow separation on airfoil not only reduces the lifting force and increases drag, but also leads to additional adverse events, like unsteadiness [6, 7] including buffet [3]. It is known that separation of laminar flow usually has a greater length as compared to turbulent [4]. It was obtained [5] that for small supersonic Mach number losses of the total pressure and lifting force in SWBLI with laminar upstream boundary layer may be not worse than for turbulent conditions and this effect is more evident for high unit Reynolds numbers. The reason is fast turbulence of the shear layer in SWBLI for laminar case and significant reduction of the separation length.

Therefore it was decided that the use of electric discharge to excite perturbations should allow to reduce the size of a laminar separation bubble and suppress it. In the present paper the spark plasma actuator located upstream of the zone of interaction and controlling the laminar-turbulent transition has been studied.

2. Experimental setup
The experiments were performed in wind tunnel T-325 (ITAM SB RAS) for Mach number \( M_a = 1.43 \), total temperature 291 K and total pressure \( P_0 = 0.55 \times 10^5 \) Pa (Re\(_{\text{l}}\) = 8.5 \times 10^6 m\(^{-1}\)). Test chamber of the wind tunnel has a rectangular cross section of 160x200 mm. The configuration of the experimental model is presented in Fig. 1. Experimental model consisted of a plate with sharp leading edge occupying full span of the test section and a wedge generating a shock wave. In this series of
experiments, the wedge angle was 3-4°. This corresponds to regular reflection of a shock wave from a wall for the inviscid case. The blockage ratio of the test section was relatively high therefore the flow start was provided by extended cavities above the wedge and below the plate. To provide the same conditions near the leading edge the extension plates were installed downstream of the lower nozzle wall. The extension plates of length $L = 100$ mm were used. The experiments were done for laminar boundary layer. The figure shows that the distance from the flat plate leading edge to the center of the optical window is connected with length of the extension plate and is approximately equal to $(380 - L)$ mm. Position of the wedge was chosen to provide intersection of the shock wave with the model approximately in the center of the optical window.

![Figure 1. The draft and photo of experimental model](image)

The main measurement techniques were PIV and Schlieren visualization. Seeding of DEHS microparticles with an average size of 1 micron were used for PIV measurement.

The plasma control devices were studied in the experiments. The spark discharge (SD) was chosen to achieve high concentrations of the energy in the plasma region. The model with installed SD actuator is shown in Fig. 2. It has ceramic insert made from MACOR holding a line of flush mounted electrodes. The electrodes are placed at distance 93 mm from the leading edge. There are three pairs of the electrodes with discharge gap of 4.5 mm. Distance between the neighbor electrode pairs is 14.5 mm. All tree discharge gaps are connected in-series. The capacitors connecting the interim electrodes to the ground were used to assist the breakdown (Fig. 3).

![Figure 2. a) Model with spark discharge actuator and b) Voltage and current oscillogram](image)

Spark discharge actuator was fed by high voltage source using two transformers DAEHAN 15000V/30mA. The self-adapting scheme was used using a battery of capacitors $C_1$ connected in parallel to the actuator (Fig. 3). This capacity is charged up to discharge level and consequently discharges. This process is periodic and the period depends on the environmental conditions and total...
capacity. The discharge repetition process is self-regulated therefore the frequency is not perfectly stable. In the following discussion this frequency is deduced as \( f = 1/T \) where \( T \) is averaged period of the discharges.

PIV measurements were synchronized with plasma discharge using time delay unit. The current pulse duration in the spark was less than 1 µs (Fig. 2b) and average power for one discharge gap was estimated as \( P_{\text{dis}} = 11 \text{ Watt} \). Figure 4 shows pulse energy and frequency for several values of capacity C1.

![Stark discharge high voltage generator](image)

**Figure 3.** Stark discharge high voltage generator

3. Experimental results
Since some benefit was obtained for the transitional case \([5]\) in comparison with the laminar one it was decided to excite in the upstream boundary layer disturbances similar to obtained in the laminar-turbulent transition. Artificial turbulization by the roughness did not result in any benefit therefore the spark discharge was applied.

![Discharge pulse power and pulse duration vs repetition frequency](image)

**Figure 4.** Discharge a) pulse power and b) pulse duration vs repetition frequency (average power was approximately 11 W)

The PIV data obtained for pulse energy of \( E_{\text{dis}} = 0.7 \text{ mJ} \) (\( f = 18.2 \text{ kHz} \)), \( \beta = 4^\circ \) are shown in Fig. 5. High average frequency of the discharge means that the flow disturbances produced by the sparks travel downstream with small distance between them (≈15-20 mm). Since the high voltage system is self-regulated the breakdowns are not perfectly periodical. In the experiments PIV system was triggered by a discharge and the traces of the preceding discharges present in each single velocity distribution. However in the averaged data shown in Fig. 5 we can see only trace of the triggering breakdown since the delay between the sparks is not perfectly constant.
Figure 5. Mean velocity fields at different time lag ($E_{dis} = 0.7$ mJ, $\beta = 4^\circ$). Top to bottom: reference, discharge 100-220 µs with $\Delta t = 60$ µs.

At the moment $\Delta t = 100$ µs the disturbance generated by the discharge passes the interaction. It can be seen that the compression waves upstream of the interaction are concentrated close to the interaction and they are more intense in comparison with the reference laminar case. This is evidence of diminishing or disappearance of the laminar separation zone upstream of the interaction. This is similar to the turbulent test case but the reflected shock wave is weaker. Fullness of the velocity profiles increases in the interaction and downstream.

The disturbance is represented by the area of low velocity in the boundary layer due to the hot spot with low density and high temperature. Decrease of velocity in this spot is amplified when it goes through the shock wave because of changes of the shocks configuration induced by the spot.

RMS of velocity pulsations for this test case is presented in Fig. 6. We can see high level of pulsations in the hot spot region. The hot spot travels downstream and the level of velocity pulsations decreases. It is necessary to note that level of the pulsations in the wake is generally decreased in comparison with the reference case everywhere except the spot itself.

Figure 7 presents the comparison of laminar and turbulent (artificial turbulization, zig-zag trigger in position of $X=100$ mm) test cases and cases with discharge excitation with various power. It can be seen that discharge actuator allows to achieve less intensive shock wave and slow growth of the wake. The best result was obtained for the lower value of spark energy.

Variation of the momentum thickness for the case of $E_{dis} = 0.7$ mJ, $\beta = 4^\circ$ is presented in Fig. 8. It can be seen that the spark discharge is able to reduce the average momentum thickness in the wake by 30% in comparison with laminar case.
Figure 6. RMS of longitudinal velocity at different time lag ($E_{dis} = 0.7 \text{ mJ}, \beta = 4^\circ$). Top to bottom: reference, discharge 100-220 $\mu$s with $\Delta t = 60 \mu$s.

Figure 7. Mean velocity fields at $\beta = 4^\circ$. Top to bottom: laminar case, turbulent case, average discharge case $E_{dis} = 0.7 \text{ mJ}, E_{dis} = 1.3 \text{ mJ}$

Comparison of the averaged $\theta$ distribution with instantaneous ones presented in the same figure shows that in the region of the hot spot there is increase of losses. Therefore, the positive effect of the disturbances provided by the discharge may be eliminated by the hot spot.
The flow control efficiency may be estimated basing on $\theta$ value at the end of measurement region as $\eta_{dis} = 0.5 \rho U^3 (\theta_{lam} - \theta_{dis})/P_{dis}$. For $\beta = 4^\circ$ the maximum value of efficiency $\eta_{dis} = 225\%$ was obtained for minimum spark energy $E_{dis} = 0.7$ mJ. If the spark energy was increased up to $E_{dis} = 1.3$ mJ the efficiency dropped to 167%. Increase of spark energy up to 3 mJ resulted in negative efficiency -55%. This means that the disturbance generated by the spark is sufficient but there in negative effect provided by the hot spot increasing with the power. This conclusion agrees with results of computational study [8] where some optimum of pulse energy was found for the flow turbulization by a discharge. In the case of exceed of energy the effect diminishes due to heat spot formation. Since the flow parameters of study [8] and the presented experiments are close it can be assumed that decrease of energy by 10 will allow to keep positive effect and increase the control efficiency.

4. Conclusion
Spark discharge actuators were tested and found to be effective to excite powerful periodic disturbances and control the interaction region. Basing on the quantitative analysis it may be concluded that spark discharge actuator improves the average flow in the interaction region. It was found that all investigated values of pulse energy are sufficient for the generation of a turbulent spot and the suppression of the separation zone. But an increase the discharge power leads to an increase the effect of the heat spot which increases the losses in the boundary layer. The analysis shows that active flow control may be more effective in comparison with passive control by the roughness.

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