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Suppression of reflected oblique shock wave by multi-filamentary plasma

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Abstract. This paper describes the results of experimental study of stripwise near-surface plasma effect on oblique shock wave (SW) reflection from a solid wall in a $M = 2$ duct-driven shock-dominated airflow. Methods applied include schlieren visualization, plasma characterization with electric probes and optical emission spectroscopy, wall pressure measurements along the test section. The transient filamentary plasma is generated by means of a Quasi-DC electric discharge between flush mounted surface electrodes in a spanwise array. Test arrangement includes a shock wave (SW) generator installed on the bottom wall of the test section and the plasma generator installed on the upper wall. The SW generated from the bottom wall impinges the significantly disturbed boundary layer (BL) generated by the plasma array. The effect of reflected SW mitigation is demonstrated due to the interaction with the plasma-modified BL. The model of interaction is discussed and supported by the results of numerical simulation.

1. Introduction

The control of shock wave interaction with a boundary layer (SWBLI), other SWs, and separated flows in a supersonic/hypersonic airflow is of fundamental and technological interest for aerospace science and industry. Currently airflow conditioning in supersonic inlets is one of the major issues of high-speed airbreathing propulsion [1, 2, 3]. The flow structure in the duct (isolator), at the entrance to the combustor, at the compression surfaces of the inlet, and over other control surfaces is sensitive to the geometrical configuration and main flow parameters, including the state of the boundary layer and the presence of compression/expansion waves previously impinging the BL. In most cases, the control schemes include stationary / movable mechanical elements or gas wall jets. The issue here is in a lack of flexibility, a total pressure loss, and frequently in a long response time, orders of magnitude longer than a characteristic gasdynamic time. Intensive studies of the physical processes at SWBLI are motivated by the need of precise control of shock-dominated flows in ducts, over compression surfaces, or other conditions where BL and shear layers are present. Electrical discharges of different types and in different geometries were tested for such a purpose [4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

The importance of plasma non-uniformity and its transient behavior for SW and BL control has been considered in numerous publications [14, 15, 16, 17, 18, 19, 20, 21, 22]. A filamentary plasmas, to some extent equivalent to heated zones with much higher sonic velocity, significantly changes the SW structure and velocity [21, 22, 20]. The localized heating generated by the plasma produces “hot spots” operating similar to solid obstacles, although this interpretation may be too simplistic. The flow interaction with the hot spots may result in the generation of new flow structures, such as streamwise
vortices and wavelets travelling with the flow, while a rapid modulation of discharge energy coupling / body force may lead to effectively tripping the boundary layer. The main premise of this approach was forcing the flow with a high amplitude perturbation. A significant localized heating in the near-surface discharge filaments and repetitive compression wave formation by the plasma were demonstrated, for example in Refs [23, 24, 5]. In addition to this, localized plasma actuators also excite flow instabilities, generate large-scale coherent structures in the flow [7, 6], and result in significant mixing enhancement and modification of shear layers [25, 26, 27].

This work explores the Quasi-Direct-Current (Q-DC) electrical discharge impact on the shock-wave structure and wall pressure distribution in a supersonic duct-driven airflow. A major focus is the effect of a streamwise filamentary plasma array on the reflection pattern of the impinging shock wave at the interaction with the boundary layer.

2. Test setup and instrumentation

The experiments were performed in the supersonic blow-down wind tunnel SBR-50 at the University of Notre Dame. The test section is arranged inline with a Mach 2 Laval nozzle. The cross section at the exit of the nozzle ($x = 0$) is $Y \times Z = 76.2$ mm (width) $\times$ 76.2 mm (height), with a $1^\circ$ expansion angle on the top and bottom walls and a total length of $x = 610$ mm measured to the diffuser, as it is shown in figure 1. The electrode array is flush-mounted on a plane wall as a single unit, indicated in figure 1 as “Electrodes”. The test section of the SBR-50 high-speed facility is equipped with 2 pairs of quartz windows placed as the side walls of the duct for optical access. In the current experimental series, the conditions were as follows: initial Mach number $M = 2$; total pressure $P_0 = 1 - 3$ bar; stagnation temperature $T_0 = 300$ K; duration of steady-state aerodynamic operation $t = 1 - 2$ s. At unit Reynolds number $Re_L = 1.3 - 4 \cdot 10^7$ m$^{-1}$, a turbulent boundary layer was developed at the plasma location with an initial thickness $\delta = 2 - 3$ mm. A trail of reflecting shock waves, related to the plasma generation, is indicated by straight lines. More details are available in [20].

![Figure 1 Geometric configuration of the SBR-50 test section with air jet based SW generator.](image)

In this test series a controlled SW generator was installed on the bottom wall: a crossflow array of 5 sonic air jets supplied with a pulsed valve (impulse ratio is approximately $J = 1$). In this scheme a wall cavity was arranged on the bottom wall simulating a cavity-based flameholder. Instrumentation available for the current test include:
- pressure distribution, 48 pressure ports over the top and bottom walls, 16 channels PSI 9116 scanner, response time 2.5 ms;
- set of P02 pressure sensors – Pitot probes, installed in a downstream zone between the test section and diffuser;
- fast camera imaging Photron FastCam (black / white);
- high-definition schlieren system, details are described in [20];
- optical emission spectrograph;
- set of electrical probes.

For the plasma generation, the custom-made power supply used in the present experiments is designed to operate with a steep falling voltage-current characteristic and individual control of each output channel [20]. The electrodes were powered by a constant-voltage, $U_{ps} = 5$ kV. The power supply
has been connected to the electrodes with the help of a solid-state Behlke™ switch. Typical time sequences of plasma voltage and the discharge power are shown in figure 2 measured at a total pressure $P_0 = 3$ bar; a total plasma power release was $W_{pl} \approx 20.2$ kW in this case. A strong coupling of the plasma to the flowing gas causes fast oscillations of the plasma shape, and consequently, of the plasma voltage and power, as shown in figure 2b. The saw-tooth waveform of the plasma voltage is a result of the movement of individual plasma filaments with the airflow.

![Figure 2](image1.png)  
**Figure 2** Typical voltage-power record: (a) voltage on electrode gap $U_{pl}$; (b) discharge power $W_{pl}$.

![Figure 3](image2.png)  
**Figure 3** Image of the Q-DC plasma at $P_{st} = 270$ mbar, 7 electrode configurations. Exposure 10µs.

The morphology of the Q-DC electric discharge appears in the form of a loop of a constricted (filamentary) plasma connecting the neighboring electrodes, as shown in the camera image in figure 3. The dominant frequency of plasma oscillations is $F = 8 - 15$ kHz, depending on the inter-electrode gap and the gas density / velocity, which govern the length of the plasma loops. Two basic electrode configurations were used (7 and 11 electrodes): the plasma filaments are shorter for the 11 electrode discharge than for the 7 electrode case. At lower pressures the 11 electrode discharge oscillates at a higher frequency, as it is illustrated in figure 4a. As the pressure increases the dominant frequency of the 11 electrode array approaches that of the 7 electrode array. The plasma power is typically in the range of 5-20 kW for the parameters used for this work. Figure 4b shows the nearly linear dependence of the power on the static pressure when the circuit parameters/geometry are held constant. It is important to note that at the same average current the power release for the 11 electrode configuration is significantly lower than for the 7 electrode pattern. The gas temperature in the plasma filaments was measured by optical emission spectroscopy to be as high as $T_g = 3800 - 6000$K depending on conditions [20]. With a high local gas temperature, the multi-filamentary plasma zone presents an array of longitudinal subsonic jets surrounded by a supersonic flow. The volumetrically expanded zone produces a long cone of subsonic flow, where the physical velocity may be close to the gas speed in the supersonic core flow. Such an uncommon gasdynamic structure produces a near-surface stratified zone, which enables a significant redistribution of the gas pressure.
The effect of the Q-DC plasma generated near the plane wall consists of gas heating in the airflow zone downstream of the electrode system, which causes an increase of the gas pressure and the subsequent propagation of a compression wave. In supersonic airflow, an oblique shock wave (SW) is observed originating from the root part of the plasma filaments [24, 20]. The SW impinges on the opposite (bottom) wall increasing the pressure in the zone of interaction. Then, a series of SW reflections is observed in the test section downstream of the plasma generator, see figure 1. An important feature of the Q-DC generated shock wave should be noted: despite the filamentary and transient nature of the discharge the generated shockwave is nearly planar in the region away from the electrodes [28].

![Figure 4](image1)

**Figure 4** Data for discharge oscillation frequency (a) and plasma power (b) as a function of discharge arrangement, electric current, and static pressure.

![Figure 5](image2)

**Figure 5** (a) - pressure distributions over the wall opposite the electrodes; (b) - amplitude of relative pressure increase as a function of plasma power.

The 16 channel pressure scanner provides the dataset of pressure distribution throughout the test section. The pressure distribution for the wall opposite the electrodes is presented in figure 5(a) for the 7 electrode discharge. There are two large pressure increases which occur at approximately 140 mm and 400 mm downstream of the electrodes. These pressure peaks are a result of the shock wave-boundary layer interaction between the plasma generated shock wave and the opposite wall. The relative pressure increase (maximum pressure increase normalized by the static pressure at that point) without the discharge for 7 and 11 electrode arrays is shown in figure 5(b). The pressure increase as a function of plasma power follow the linear trend. Note that the 11 electrode system targets a smaller area of influence while achieving the same relative pressure increase.
3. Test results
The dynamics of the reflected SW was explored when unsteady SW generator was installed on the bottom wall of the test section. The multiple jet configuration allows for a nearly plane SW impinging the upper wall downstream of the electrodes installation, as shown in figure 1. Typically, the plasma was turned on first followed with the impinging SW. The air jets continued operation after the plasma was turned off. During each run of the facility, the data was collected on a baseline, SW structure at the air jets operation, SW structure at plasma operation, and with SW and plasma both. Schlieren images for three cases are shown in figure 6 (a)-(c), correspondingly. The figure 6(c) demonstrates a significant mitigation of the reflected SW. This effect was observed in a wide range of flow parameters, $P_0 = 1 - 3\text{bar}$.

![Schlieren images of the SW-plasma interaction.](image1)

**Figure 6** Schlieren images of the SW-plasma interaction. (a) – jets on/plasma off; (b) – jets off/plasma on; (c) – jets on/plasma on.

![Schlieren image of the interaction with cavity.](image2)

**Figure 7.** Schlieren image of the interaction with cavity. (a) – plasma on/jets off; (b) – plasma on/jets on.

Presence of the impinging SW modifies the plasma morphology, as shown in figure 7: the filament length is observed to be shorter due to plasma termination in the zone of increased pressure. The zone of the pressure elevation penetrates upstream along with the hot plasma filaments, presenting local subsonic areas. The pressure increases in the plasma zone which enhances the plasma-related SW strength. For the configuration with the cavity on the bottom wall, the plasma-related SW impinges the cavity, increases the cavity pressure, and promotes the SW originated from the cavity rim, as shown in figure 7(b).

The result of the pressure measurements is shown in figure 8 for $P_0 = 2.5\text{bar}$. Figure 8(a) demonstrates the result of the interaction in the vicinity of the electrodes. During air jet operation, the impinging SW interacts with the upper wall around $x = 40 - 60\text{mm}$ downstream of the electrodes that is represented by a significant pressure rise at the appropriate pressure tap. The reflected SW impinges
the cavity, leading to some pressure increase there, as shown in figure 8(b). During plasma generation, the pressure increases right behind the plasma zone and then drops down as fast as \( x < 30 \text{mm} \). The plasma-based SW affects the cavity flow similar to the air jet SW. In the case of plasma on /air jets on, the maximal pressure increase on the upper wall is less than the case of SW only. However, the length of the elevated pressure zone appears as long as \( x > 60 \text{mm} \). The pressure effect of the air jet related SW “propagates” forward to the plasma zone through the subsonic zone near the heated plasma filaments. The plasma related SW is amplified which then increases the pressure in the cavity. Note, in this case the pressure in the cavity is measured higher than upstream of the cavity, leading to an enhancement of the gas exchange between the cavity and the core flow and appearance of the SW originating from the cavity rim. Note that, based on the Pitot pressure sensors data, the described manipulation with the air jet and plasma slightly reducing the total pressure in the flow.

![Figure 8](image)

**Figure 8** Wall pressure redistribution behind the plasma (a) on upper wall; and in vicinity of the wall cavity (b) on bottom wall.

4. Discussion and summary

In fact, the multi-filamentary plasma zone presents a set of longitudinal subsonic jets surrounded by a supersonic flow, as shown in figure 9(a) for a single plasma filament. The volumetrically expanded zone produces a cone of subsonic flow, where the physical velocity is close to the gas speed in the supersonic core flow. The pressure is increased due to the impact of the impinging SW and affects this cone, increasing the gas pressure in the subsonic zone. The gas expansion induces the conical SW attached to the plasma filament root (electrode). The shape of a “soft” plasma trail complies reducing the reflected SW strength.

![Figure 9](image)

**Figure 9** (a) - scheme of a single plasma filament interaction with supersonic flow and impinging SW; (b) plasma array and SW superposition.

In the case of a multi-filament plasma array, figure 9(b), the interference of the conical shock waves produces a combined compression wave attaining the form of a plane shock. A specific structure of the near-surface gas layer, consisting of the intermittent lengthwise zones of supersonic and subsonic flow, possesses a mitigating effect on an external impinging SW. The mechanism of interaction is considered
as follows: the pressure, increasing due to the impact of the impinging SW, affects the whole subsonic area, increasing the gas pressure in the upstream zone and reducing the pressure magnitude right after the SW.

The plasma-SW-flow interaction in configuration with a fixed SW generator (analogy of experimentally used jet-based SW generator) was simulated numerically using FlowVision CFD software. The simulation was based on the solution of the three-dimensional unsteady Reynolds averaged Navier–Stokes equations accompanied by the $k-\varepsilon$ turbulence model. The calculation domain includes only a thin layer, which is 4.5mm wide and contains half of one plasma filament located near a side plane of the calculation domain. The symmetry condition was set to both side planes of calculation domain. No-slip conditions and wall functions were used on top and bottom boundaries ($y+$ in range of 10-50). Geometry of the test section corresponds to the experimental one. Influence of the plasma filament produced by Q-DC discharge was simulated by 3D volumetric heat sources. This approach demonstrated good consistency of experimental results and simulation data for plasma flow control in a supersonic inlet [12]. The volumetric heat source was 80mm long and 1.8mm in diameter which approximate the experimental data obtained from image analysis. Power of a single plasma filament was varied in the range of $W_1 = 125 - 1000$ W. Artificial schlieren images (gas density gradient) are shown in figure 10 for two cases: (a) baseline - plasma off; (b) heat source power $W = 8$ kW that is close to one of experimental conditions.

![Figure 10 Result of CFD simulations: density gradients. (a) baseline, plasma off; (b) heat source power $W = 8$ kW.](image)

In figure 10(b), there is a significant reduction of the oblique shock caused by the solid wedge. Figure 11 shows the distribution of the Mach number in vicinity of a single heated filament. It is seen that the “plasma” filament produces an extensive subsonic zone of a semi-conical shape. These data support the hypothesis on a stripwise structure producing by the plasma array near the surface with alternating subsonic-supersonic airflow. It was also found that the attenuation of the shock reflection leads to a local increase of total pressure.

![Figure 11 Result of CFD simulations: flow Mach number in vicinity of heated filament, $W_1 = 500$W.](image)

The generation of surface localized discharges in a high-speed flow leads to a substantial change in the structure and parameters of the flow field. The Q-DC electrical discharge affects the flow similar to a soft wedge, whose angle depends on the electrical power deposition. The structure of the plasma-based displacement layer appears as an array of intermittent supersonic and subsonic lengthwise zones. The plasma-based configuration may be applied to mitigate the reflected SW due to the impinging SW interaction with the plasma-related displacement layer. It is beneficial for critical flow configurations
because the electrical discharge can be switched on/off electronically at any time and synchronized with all other processes, such as a trajectory change or engine thrust modulation. The active compliant structure may aim in shifting the reflected SW, the mitigation of reflected SW strength, or an elimination of the reflected SW for flow control purposes. This technique demonstrates feasible potential for the control of shock wave – boundary layer interaction.

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