Shock wave modulation
due to discharged plasma using a shock tube

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Abstract
The interaction phenomenon between shock waves and the DC-discharged plasma was experimentally investigated to aid future supersonic aerodynamic performance improvements. A shock tube was used to generate the shock wave. For the discharged plasma generation, a wedge type test model with electrodes (anode and cathode) connected to the power supply system was installed into the shock tube measurement section. The nominal shock wave Mach number in the experiment was 2.0. The plasma input power range was from 0 W to 35.7 W, where 0 W corresponded to the no discharge case.Schlieren photography was used for visualization, and the pressure histories were measured. From the visualization, due to the interaction with the discharged plasma, shock wave modulation with curvature was observed. However, from the pressure measurement, pressure histories in a plane parallel to the shock wave were nearly identical between the side-wall and the top-wall, despite the shock wave modulation. From these results—obtained from visualization and pressure measurement, the shock wave modulation observed in this study had a three-dimensional (3D) structure. In order to comprehend this phenomenon, a 3D simulation with a simple modulated temperature field was conducted. The simulation results also indicated 3D shock wave modulation. Therefore, experiment and simulation both support the 3D structure of the modulated shock wave due to the interaction with the discharged plasma.

Key words: Shock wave, Shock tube, Discharged plasma, CFD, Shock wave modulation

1. Introduction

Recently, there has been a resurgence of interest in supersonic transportation (Aronston and Schueler, 2005, Henne, 2005). However, to make this a reality, the problems related to the wave drag and sonic boom due to the shock wave ahead of the cruiser must be solved (Conway, 2005).

Until now, sharp front configurations have been developed as an aero-spike system for reducing wave drag (Reding et al., 1977). Recently, the quiet spike was proposed as an upgraded version of the aero-spike system (Cowart and Grindle, 2008). However, owing to the sharpness of the aero-spike, the strength of the system structure is of concern. Additionally, for the quiet spike, there has been anxiety about the complexity of the system.

Lately, the energy deposition technique has attracted attention as a novel method for improving aerodynamic performance for the future of supersonic transportation systems (Tret’yakov et al., 1996, Adelgren et al., 2005, Knight, 2008). Sasoh et al., further emphasized its significance by demonstrating its merits; the gain of both flight power and drag reduction (Sasoh et al., 2010, Kim et al., 2011).

The baroclinic effect plays a key role in this energy deposition method (Knight, 2008). Therefore, for the application of this method to the development of actual supersonic transportation, the fundamental mechanics of the
effect should be elucidated.

Categorizing energy deposition methods, three primary methods are possible; laser irradiation (e.g., Tret’yakov et al., 1996), AC discharge (e.g., Znamenskaya et al., 2008), and DC discharge (e.g., Marcheret et al., 2001). Of all the methods, the DC discharge method is expected to be most suitable for fundamental comprehension because parametric study of its input power—indeed of the Mach number—can be easily conducted using a shock tube.

There have been many studies on the interaction phenomena between shock waves and DC discharged plasma (Ganguly et al., 1997, Adamovich et al., 1998, Marcheret et al., 1999, Kuo et al., 2001, Marcheret et al., 2001, Blezinger et al., 2005, Sato et al., 2005a). Specifically, many researchers have discussed the configurations of the modulated shock wave due to the interaction with the DC discharge (e.g., Ganguly et al., 1997). For example, Marcheret et al., (Marcheret et al., 2001) discussed the structure of the modulated shock wave configuration, however, the discussion was mainly based on computational fluid dynamics (CFD) simulation and was not directly shown by the experimentation.

Additionally, most including Marcheret et al., used discharge tubes. Their experiments utilized the shock waves generated by the spark electrodes; thus, for their discharge tube experiments, the strength of the generated shock wave varied with the shock wave propagation. Therefore, it was difficult for them to keep the shock Mach number constant during the propagation of the shock wave in the discharged field. Furthermore, there was a possibility that some kind of disturbance would emerge from the discharge electrode to the propagating shock wave because of the configuration of the experimental facility. This could disturb the Mach number of the propagation shock wave. Therefore, it was difficult to comprehend the phenomena from the viewpoint of the plasma input power effect, which are completely independent of the Mach number effect, by using conventional discharge tube facilities.

In contrast, shock tubes can generate shock waves with nearly constant propagation velocities; thus, it is possible to conduct the experiment and independently control the shock Mach number and the discharge power. Sato et al., conducted experiments and CFD simulations using the shock tube and the DC discharge facility, and discussed the configuration of the modulated shock wave caused by the interaction with the discharged plasma (Sato et al., 2005a). Even though their research for an investigation of the interaction between the shock wave and the DC-discharged field was one of the pioneering work from the viewpoint of using a shock tube and a DC discharge power supply system, only the discharge current was reported for the discharge state, and the discharge power was not mentioned (Sato, et.al., 2005a). Therefore, analyzing the effect of the discharge input power was quite difficult based on their results. Additionally, their discussion about the modulated shock wave configuration was mainly based on the CFD simulation, not on the direct pressure history measurement. Direct experimental measurements, such as the pressure history, are desirable for comprehension of the phenomena of the modulated shock wave configuration.

Based on the above background, our research group began to study the interaction phenomena between shock waves and DC-discharged plasmas using a shock tube and a DC discharge system. In this paper, the shock wave modulation phenomena are discussed based on experiments (e.g., visualization, measurement of the pressure histories in a plane parallel to the shock wave) and three-dimensional (3D) CFD simulation for comprehension of the experimental results.

2. Experimental facilities

2.1 Shock tube

For shock wave generation, a non-diaphragm type shock tube that was developed by our group and installed in Meijo University was used. This facility was designed based on the MO-Tube (Oguchi et al., 1976, Maeno 1979), and the quick action valve was rather simplified. This facility can generate shock waves with nominal propagation Mach numbers between 1.6 and 2.0 in the interval between 50 and 150 of the initial pressure ratio. In this experiment, the pressure ratio was set to 150. The high-pressure chamber was filled with air up to 0.3 MPa. The initial pressure in the low-pressure tube was set to 2 kPa. Air was used as the test gas.

Figure 1 shows the measurement system of the test section of the shock tube. A Schlieren visualization system was employed at the measurement section as shown in Fig. 1. A xenon flash lamp (SA-200F, Nisshin Electronic Co. LTD.) was used as the light source. The effective field of view for the visualization had a 50-mm diameter. Images were acquired with a high-speed camera (HX-1, 10⁶ FPS, NAC Inc.). For the trigger signal of the camera, a pressure sensor (located at position 1 in Fig. 1) was installed on the top wall 50 mm upstream from the measurement section.
At the measurement section, a 15-degree wedge type model with electrodes was installed for the discharge. This type of model is useful for the shock tube experiment of which the main scope is the incident shock wave configuration. This is because the incident shock wave propagates on the model top surface without suffering from the shock waves reflected at the bottom part of the model, and these reflected shock waves arrive at the top surface of the model after the passage of the incident shock wave. Figure 2 shows a schematic side view of the test section with the test model, which was made of insulated ceramics. On the top surface of the model, two cupper electrodes (anode and cathode) with 10-mm diameters were mounted flush. The center-to-center distance between the two electrodes was 25 mm, as shown in Fig. 3. The two electrodes were mounted in the direction perpendicular to the shock wave propagation direction.

For the pressure measurement, three pressure sensors (PCB 113B28, 14.5 mV/kPa, PCB Inc.) were used. Figure 3 shows a cross section view of the measurement section. As shown in Fig. 3, the sensors at positions 2 and 2’ were in the same plane, parallel to the shock wave. The sensors at positions 1 and 2 were installed on the top wall of the shock tube, as shown in Figs. 1 and 2. Contrastingly, the sensor at the position 2’ was installed on the side window. For the pressure measurements in the plane parallel to the shock wave, the visualization window was converted to a dummy window with the pressure sensor at position 2’.
2.2 DC discharge system

Figure 4 shows the electrical circuit of the power supply system used to generate the DC-discharged plasma. For voltage and current measurement of the plasma, differential probes and an oscilloscope (DL1640, YOKOGAWA Inc.) were used. In Fig. 4, D.P. 1 is the differential probe (701926, Max 5kV, 1:1000, YOKOGAWA Inc.) that was used to measure the voltage applied between points A and B. The differential probe (700925, Max 500V, 1:10/1:100, YOKOGAWA Inc.) designated as D.P. 2 in Fig. 4 was used to measure the terminal voltage of the 10 Ω resistor. From the voltage measured by D.P. 2, the current through the plasma could be evaluated. Additionally, using the data from D.P. 1 and the plasma current, the plasma voltage could be determined. Figure 5 shows the voltage-current characteristics of the discharged plasma generated by this power supply system at an ambient pressure of 2 kPa, with air as a test gas. As shown, while the plasma current changed from 0 A to 0.1 A, the plasma voltage was nearly constant around 500 ± 50 V. Therefore, this generated plasma could be regarded as glow discharged plasma, and the maximum power consumed by the plasma (i.e., plasma input power) was estimated at 55 W.
3. Numerical Method

In order to qualitatively comprehend the experimental results, numerical simulations were also conducted. For the governing equation, the 3D Euler equation was employed.

$$\begin{align*}
\frac{\partial}{\partial t} \begin{bmatrix}
\rho \\
\rho u \\
\rho v \\
\rho w \\
e
\end{bmatrix} + \frac{\partial}{\partial x} \begin{bmatrix}
\rho u \\
\rho u^2 + p \\
\rho u v \\
\rho u w \\
(e+p)u
\end{bmatrix} + \frac{\partial}{\partial y} \begin{bmatrix}
\rho v \\
\rho v u \\
\rho v^2 + p \\
\rho v w \\
(e+p)v
\end{bmatrix} + \frac{\partial}{\partial z} \begin{bmatrix}
\rho w \\
\rho w u \\
\rho w v \\
\rho w^2 + p \\
(e+p)w
\end{bmatrix} &= 0 .
\end{align*} \tag{1}$$

In order to solve the governing equation, the AUSMDV scheme (Wada et al., 1994) with a 3rd-order MUSCL discretization method was applied. In order to save computational time, the 1st-order explicit method was applied to the time integration. The shock wave propagation analysis was conducted on a 0.05×0.05×0.034 m domain. In order to save computational time and memory, the computational domain was divided into 150×150×30 grid sections in the x-, y- and z-direction, respectively. The shock wave propagation direction in this simulation was along the x-direction. The propagation Mach number was set to 2.0. In this study, the simulation was used only for qualitative comparisons with the experiment and for confirmation of the interpretations of the experimentally observed phenomena. Therefore, even this coarse grid system was sufficient for discussing the related phenomena especially for the modulated shock wave configuration. From this simulation, the 3D shock wave modulation due to the modulated temperature field can be comprehended.

In order to simulate the interaction with the discharged plasma, the plasma was regarded as the heat source to induce the modulated temperature field, and the induced temperature field was assumed to be the steady state before the interaction with the shock wave. Therefore, in this study, the simple temperature modulated filed model shown in Fig. 6 was imposed as an initial condition, and the modulated temperature field was maintained until the shock wave arrival. The temperature modulation corresponded to the density modulation, since the initial pressure in this simulation was uniformly distributed at 2 kPa. The temperature modulation field was simply set as a semi-elliptical cylindrical distribution whose axis lay in the region between $y = 0.01$ m and $y = 0.04$ m (at $x = 0.025$ m, $z = 0$ m). The distribution was simply assumed a Gaussian function;

$$T = T_0 + T_p \exp \left[ - \left\{ \frac{(x-x_c)^2}{d^2} + \frac{(z-z_c)^2}{d^2} \right\}^\alpha \right] , \tag{2}$$

where $x_c = 0.025$ m, $z_c = 0.0$ m, $\alpha = 0.16$, $d = 0.005$ m, $T_0 = 300$ K, and $T_p = 900$ K. The maximum temperature was set at 1200 K. Figure 7 shows the temperature distributions along the x- and z-directions at $y = 0.025$ m. This temperature model was adapted from Sato’s experimental results (Sato, et.al., 2005b) and rather simply modeled for the present 3D simulation. It is reported that the simulation using this temperature modulated field model can reproduce the experimentally observed phenomena of the shock wave deformation, at least qualitatively (Sato, et.al., 2005b).
4. Experimental results
4.1 Visualization results

Figure 8 comprises images of the propagating shock wave in the case without the discharged plasma. The shock wave propagation Mach number was 2.11±0.06. In this case, a normal shock wave can be observed upstream and downstream of the electrode position.

Figure 9 shows images in the case with the discharged plasma. The shock Mach number was 2.05±0.06, and the plasma input power was 20.0 W. In this case, shock wave modulation can be clearly observed. Remarkably, the shock wave has two lines even upstream of the electrode position as if it were splitting, and the configuration has some kind of the curvature as shown in Fig. 9 (a). This is because even just upstream of the electrode position, the temperature is modulated due to the discharged plasma. This phenomena is consistent with the previous result (Sato et al., 2005a). In the region downstream of the electrode position, as shown in Fig. 9 (b), this tendency is exaggerated. The electrode position was the point at which the interaction effect from the discharged field was strongest. Therefore, shock wave modulation was enhanced while passing through this region. At a glance, the visualized shock wave in Fig. 9 (b) had dispersed relative to those observed in Fig. 8 and Fig. 9 (a). This was caused by the shock wave attenuation due to the interaction with the discharged plasma. This was consistent with the shock wave attenuation reported in the previous references (Gunguly et al., 1997, Marcheret et al., 2001, Sato et al., 2005a). From Figs. 8 and 9, owing to the interaction with the discharged plasma, the shock wave can be modulated to have curvature similar to two split lines. Details of the modulated configuration will be discussed in Section 5.

Fig. 8 Visualization results of a shock wave without the discharge; (a) upstream and (b) downstream of the electrodes position; shock Mach number $M = 2.11\pm 0.06$. 

![Temperature distribution along the x-direction (y = 0.025 m, z = 0m) , and the z-direction (x = 0.025 m, y = 0.025 m).](image)
4.2 Pressure measurement results

Figures 10 and 11 depict the pressure histories measured at the three positions (1, 2 and 2’) shown in Fig. 3. Sensors at positions 2 and 2’ were located in the same plane parallel to the shock wave.

Figure 10 shows the case without the discharged plasma, and the shock Mach number was $2.08 \pm 0.03$. In this case (corresponding to 0 W input power), the pressure signals located at positions 2 and 2’ (in the same plane, parallel to the shock wave) had jumps at the same moment. This corresponded to the fact that the shock wave without the discharged plasma had a normal plane configuration as visualized in Fig. 8.

Figure 11 shows the case with the discharged plasma. The discharge plasma input power was 35.7 W and the shock Mach number was $2.11 \pm 0.03$. Despite the interaction with the discharged plasma, we can observe only one jump due to the shock wave arrival at the sensor positions. Moreover, the signals at positions 2 and 2’ jumped simultaneously. Comparing to the visualization results, this pressure measurement seemed inconsistent. The pressure histories and cause of this phenomenon will be discussed in the next section from the viewpoint of the modulated shock wave configuration.
Fig. 11 Pressure histories in the case with the discharge; shock Mach number $M = 2.11 \pm 0.03$; plasma input power 35.7 W.

5. Discussion

5.1 Shock wave modulation

From the visualization results, owing to the interaction with the discharged plasma, the shock wave develops two surfaces. There are two possible explanations for this phenomenon. (Case I) the shock wave had the curvature across the shock tube horizontally (y-direction in Fig. 12) or (Case II) it split into two waves with no curvature in this direction. Figure 12 summarizes these possibilities, schematically showing the shock wave configurations and corresponding pressure histories expected at positions 1, 2 and 2’. The relation between the shock wave configuration and the pressure histories for each case is as follows.

In Case I, the shock wave has curvature across the shock tube both vertically (z-direction) and horizontally (y-direction). Therefore, in this case, the shock wave has a three dimensional structure. The shock wave near the top and side wall of the shock tube is mostly unaffected such that the pressure histories at positions 2 and 2’ rise simultaneously. As a result, sensors at positions 2 and 2’ produce nearly the same signal, and only one jump due to the shock wave arrival can be observed.

In Case II, the shock wave is split into two waves, and there is the curvature along the z-direction but not the y-direction. Therefore, in this case, the shock wave has a three dimensional structure. The shock wave near the top and side wall of the shock tube is mostly unaffected such that the pressure histories at positions 2 and 2’ rise simultaneously. As a result, sensors at positions 2 and 2’ produce nearly the same signal, and only one jump due to the shock wave arrival can be observed.

From the experimental measurements shown in Fig. 11, the pressure histories of the sensors located at positions 2 and 2’ had nearly the same signal, and neither time lag nor a second jump can be observed. Thus, the shock wave modulation due to the discharged field matches Case I. Therefore, it appears that the shock wave experienced 3D modulation due to the interaction with the discharged plasma. This was likely caused by the fact that the shock wave was locally modulated only around the modulated temperature region (corresponding to the region around the discharge.)
Fig. 12 Diagrams of possible cases (Case I, Case II) for the shock wave configuration modulation: (a) top view, (b) side view, (c) expected pressure histories of the sensors at positions 1, 2 and 2’.

5.2 Comparison with numerical simulation

Figure 13 indicates pressure contour lines obtained from the numerical simulation. The dense lines correspond to the shock wave configurations propagating through the modulated temperature field which was simply modeled as the discharged field. In Fig. 13, \( t \) is the relative time which represents the time elapsed since the shock wave passed through \( x = 0.0 \) m. As shown in this figure, before the interaction with the modulated field (at \( t = 9.41 \mu\text{sec} \)), the normal plane shock wave can be observed. However, once the interaction occurred (at \( t = 40.9 \mu\text{sec} \)), the shock wave experienced 3D modulation.

Figure 14 depicts the view image of Fig. 13 observed from the plane parallel to the x-z plane in the direction of the line of sight along the y-direction. Figure 14 (a) is at \( t = 9.41 \mu\text{sec} \), and (b) is at \( t = 40.9 \mu\text{sec} \), respectively. This is the same direction of the line of sight as the experimental visualization results shown in Figs. 8 and 9. From this viewpoint, the plane shock wave is visible at \( t = 9.41\mu\text{sec} \); in addition, the modulated shock wave can be observed with a primary curved shock wave and a trailing plane-like shock wave at \( t = 40.9\mu\text{sec} \). The modulated configuration in Fig. 14(b) resembles the experimental result shown in Fig. 9, at least qualitatively.

Figure 15 shows the pressure histories obtained from the simulation. Point A, which was on the side wall of the shock tube (\( x = 0.025 \) m, \( y = 0.0 \) m and \( z = 0.017 \) m) as shown in Figs. 13 and 14, corresponds to the pressure sensor on the side wall in the experiment (position 2’ in Fig. 3). Point B, which was on the top wall of the shock tube (\( x = 0.025 \) m, \( y = 0.0 \) m and \( z = 0.016 \) m) as shown in Figs. 13 and 14, corresponds to the pressure sensor on the top wall in the experiment (position 1 in Fig. 3).
m, y = 0.025 m, and z = 0.034 m) as shown in Figs. 13 and 14, corresponds to the pressure sensor on the top wall in the experiment (position 2 shown in Fig. 3). These points were in the same plane, parallel to the initial normal plane shock wave. As shown in Fig. 15, the pressure histories at positions A and B have the same signal. In these pressure histories, a jump corresponding to the arrival of the shock wave at the measurement points can be observed, but no second jump can be observed. This result qualitatively agrees with the experimental result shown in Fig. 11.

Based on the comparison of the shock wave configuration and the pressure histories between the experiment and the simulation, qualitative agreement can be observed. Therefore, this simulation supported the observation that the shock wave modulation in the experiment had a three dimensional structure.

Fig. 13 Results from the 3D simulation showing the pressure contour lines; dense lines corresponding to shock wave configuration before and after the interaction with the modulated temperature field.

Fig. 14 View image of Fig.13 from the plane parallel to the x-z plane in the direction of the line of sight along the y-direction, (a) t = 9.41 µsec, (b) t = 40.9 µsec, respectively.
6. Summary

In order to investigate the interaction phenomena between shock waves and discharged plasma, an experiment using a shock tube and a DC discharge system was conducted. From the visualization results, shock wave modulation with curvature and two lines due to the interaction with the discharged plasma was observed. From pressure measurements in a plane parallel to the shock wave, the pressure histories at the top wall (position 2) and the side wall (position 2') had the same signals even in the case with the discharged plasma. These pressure histories suggest that the shock wave was curved in both the y- and the z-directions. Therefore, the shock wave modulation due to the interaction with the discharged plasma had a 3D structure. Results from the 3D simulation confirmed the comprehension of the experimental results.

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