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Detection of shock structure around Mach disk in axisymmetric plasma jet

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ABSTRACT

Plasma jets have been used widely in various fields such as materials and aerospace engineering. The understanding of the shock structure is important to control a supersonic jet using a magnetic field. An experiment of axisymmetric argon plasma jet under strong magnetic field was carried out to detect the shock structure around the Mach disk precisely. A magnetic field was applied to the jet using a pair of identical superconducting coils. The jet images in a vacuum chamber were taken by a digital single-lens reflex camera with high spatial and color resolution through a viewing window. The distribution of light intensity from photographic data was converted to the radial intensity, relevant to plasma density, using Abel-inversion. The radial shock structure, that is not apparent on the ordinary photos, can be detected from the converted distributions. The software for the analysis was developed to detect the shock structure in the plasma jet. The method of shock detection was also detailed. The hidden shock characteristics such as triple point were found using the radial intensity obtained from the data with high color resolution. The shock lines upstream of the Mach disk under the magnetic field were indicated in detail. The reflected shock location could be determined. The intensity distribution downstream of the Mach disk was significantly changed by applying the magnetic field. The interaction between plasma density and magnetic field clearly occurs at higher density region downstream of the Mach disk.

1. Introduction

Plasma jets have useful characteristics and have been used widely in engineering fields [1–3]. For example, several investigations in aerospace engineering have been carried out to develop a new type space vehicle that is controlled with MHD interaction [4–6]. When the vehicle flies beyond the speed of sound, shock-waves are formed. It is important to clarify the shock structure for supersonic jet control using a magnetic field [7]. Experimental studies of plasma jets have previously been conducted to examine the influence of the magnetic field [8], although it is necessary to make further efforts. The deformation mechanism of shock structure under strong magnetic fields has not been completely obtained [9]. The discussion of the magnetic effect has been restricted to the overall behavior of the jet. It is necessary to address the jet area, which is subject to the application of the field. In particular, the analysis of flow characteristics around the Mach disk under the field becomes important for under-expanded plasma jet. To clarify the shock structure around the Mach disk, it is essential to find the shock-wave triple point where three shocks, that is, barrel, normal and reflected shock, intersect. Emission spectroscopy measurement as the experimental study is very suitable for the various plasma analyses and has been used in the numerous plasma investigations [10]. However, the measurement region is restricted due to limitation of moving area of the optical probe. It also takes several minutes to measure over the observing region. Instead, the analysis of an image taken by a camera is the most convenient to detect the structure because the visible flow can be directly observed for the luminosity of plasma. Although the flow profile can be approximately obtained by using the photograph, the radial feature remains hidden in the case of an axisymmetric plasma jet. In such a case, the introduction of Abel-inversion [11], frequently used to determine the radial temperature distribution with spectroscopic analysis, is useful for applying the color intensity in the image data. The color intensity from photo-data can be converted to the radial intensity, relevant to the plasma density, using the inversion. The distribution of the converted radial intensity can be directly compared with the density profile obtained from the numerical analysis. High spatial and color

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resolution are required to obtain the appropriate data from the image analysis.

On the other hand, a numerical analysis has frequently been employed as a useful shock-detecting tool for the ordinal compressible flow [12]. Although the numerical solution of the plasma jet has been obtained partially [13], it is still difficult to simulate exactly the behavior under a strong magnetic field. In particular, the prediction of interaction between the plasma flow and the field is not sufficient due to the extremely complex phenomenon. Thus, the image analysis is an effective means to observe plasma jet structure from experiments under a strong magnetic field.

From these points of view, an experiment of an axisymmetric plasma jet under strong magnetic field was carried out to detect the shock structure around the Mach disk. The images of an argon plasma jet in a vacuum chamber were taken by a Digital Single-Lens Reflex (DSLR) camera with high color resolution through a viewing window. The camera was focused on the area around the Mach disk, and its color (light) intensity was set to have the suitable high value for the analysis. The distribution of light intensity from photo-data was converted to the radial intensity, relevant to plasma density, using Abel-inversion. The software for the analysis was developed to detect the shock structure in the plasma jet. The results with a magnetic field were compared to those without the field. The radial shock structure, which is not apparent on the ordinary photos, can be revealed from the converted distributions. The jet area, which is subject to the magnetic field, was clearly identified from the present analysis.

2. Experimental setup and procedures

2.1. Experimental setup

The axisymmetric plasma jet was generated in a vacuum pumped chamber [10]. Argon was employed as the working gas. The base pressure in the chamber was kept below 1 Pa by using a mechanical booster pump assisted with an oil-sealed rotary pump before the jet was exhausted. The experimental conditions are indicated in Table 1. A magnetic field was applied to the plasma jet using a pair of identical superconducting coils capable of generating a field in excess of 3 T. The applied magnetic field is set up with the magnetic flux density at the midpoint between the coils, B_c. The relation between persistent current i_c and B_c is presented in Table 2. The schematic of an under-expanded jet including Mach disk and the corresponding magnetic field distribution are shown with coordinate system in Fig. 1 on the left. The origin is located at the intersection of the nozzle exit and center axis. The flow direction is defined as x-coordinate, and the radial (r-) coordinate is perpendicular to the x-coordinate. All distances in the following figures are normalized by the nozzle exit diameter d_e ($d_e = 7.5$ mm). The distance along the center axis between the torch exit plane and the middle plane of both coils, L, was specified to be 350 mm. The magnetic flux density B_{MD} stands for the magnetic flux density at $x/d_e = 6$, corresponding approximately to the axial location of the Mach disk x_{MD}. The distribution of magnetic field near the nozzle exit has the moderate positive gradient to the flow direction. Moreover, the magnetic field distribution around the coils is illustrated in this figure on the right ($x/d_e = 46.66$ corresponds to $L = 350$ mm).

Table 1
Experimental condition.

Background chamber pressure p_b, Pa	412 ± 7
Mass flow rate $\dot{m}$, g/s	1.19 ± 0.01
Supplied current to a plasma torch i_s, A	150
Distance from origin to midpoint of coils L, m	350

Table 2
Relation between persistent current and magnetic flux density.

i_c, A	0	35.72	71.44	107.16
B_c, T	0	0.5	1.0	1.5
B_{MD}, T	0	0.131	0.263	0.394

2.2. Image analysis procedure

Photographic images of the plasma jet were taken by the DSLR camera (Nikon D3X, 24.5 megapixels) with high color resolution (14 bit) through the viewing window. The camera was set to be far enough away from the focal point, located in the central plane of the jet, to reduce aberration effects. The validity of light intensity distribution obtained here was confirmed by comparison with spectroscopic measurement data [14]. The focused area in the flow direction was selected around the Mach disk. The light intensity on the analysis was set to record as high as possible. Thus, higher digital color intensity approached the full-scale value. Unfortunately, the highest value of light intensity just downstream of the nozzle exit saturated and could not be used. The image format employed on the analysis is 'RAW data format', which records signals directly from the image sensor in the camera. The RGB color intensities were extracted from the RAW data. The relative intensity distribution of each RGB color in the present plasma is almost the same because the saturation of the color is low (The color is near white). The maximum value of color intensity at each pixel was selected as the light intensity and was the green intensity, which is the most sensitive color [14] almost the case for the present camera. The intensities for the analysis were obtained by averaging over those for 10 RAW data sets to improve the signal-noise ratio. A spatial resolution of about 0.034 mm/pixel could be obtained in the present work. The vertical distribution of the light intensity was converted to the radial one using the Abel-inversion that is frequently used to determine the radial temperature distribution with spectroscopic analysis. The expression for Abel-inversion is as follows

$$I_R(r) = -\frac{1}{\pi}\int_r^R \frac{\frac{dI(z)}{dz}}{\sqrt{z^2 - r^2}} dz \tag{1}$$

where, I and I_R denote the light and radial intensity, respectively, and R is the radius of the jet. The radial intensity I_R becomes a function of radial distance from center axis. Then, z means the vertical coordinate, which is perpendicular to the viewing direction. In other words, the integration of radial intensity $I_R(r)$ over the viewing direction is the light intensity I (z). The computational software for the present work was newly developed to reveal the shock structure in the plasma jet and can process the various image analyses. An example of the distribution of radial intensity without a magnetic field is also indicated in Fig. 1 as a background of shock characteristics.

3. Results and discussion

3.1. Detection of shock structures

An example of gray-scaled maps of radial intensity distribution ($x/d_e = 0$–12, $r/d_e = 0$–2.5) is demonstrated in Fig. 2, in which the color in the higher intensity region is brighter. The image above presents the case without a magnetic field and the one below is the