Steganalysis of a pulsed plasma jet ICCD camera image using LabVIEW

Victor J Law and Denis P Dowling
School of Mechanical and Materials Engineering
University College Dublin, Belfield,
Dublin, Ireland
e-mail viclaw66@gmail.com

Abstract—A LabVIEW computer program is presented as a steganographic tool to analyze and manipulate, intensified charge-coupled device images of atmospheric pressure plasma jet. The program deselects the red and green color planes and only uses the blue color plane that holds the imperceptible (to the human eye) fluid structure information beyond the visible distal-point of the plasma plume. Low pass pixel filtering of the spatial image followed by Fast Fourier transformation of the image into the complex image is used to access and truncate bit depth information. An inverse Fast Fourier Transformation is then used to convert the complex image back in to the spatial plane where image thresholding after applied to form a binary image of the fluid structure beyond the visible distal-point. Both conceptual and technical programming issues are discussed.

Keywords—Plasma; fluid structure; image; spatial-domain; frequency-domain; thresholding

I. INTRODUCTION

Today’s atmospheric pressure plasmas jet (APPJs) applications range from polymer and composite surface cleaning to medical and dental treatments. To understand and control these plasma applications modern plasma diagnostics embrace an array of electrical, thermal, acoustic, optical and imaging sensors. Associated to these sensors are analytical software tools that are designed to explore the specific signal of the sensor. A specific aspect of interest in these APPJs is the local turbulent flows or instabilities that are aligned with the central gas flow and decaying heat path of the plasma jet. From the early 2000s studies of thermal flame and plasma jets instabilities have used Schlieren imaging [1, 2]; and more recently high-speed Schlieren imaging [3] and direct capture by intensified charge-coupled device (ICCD) camera followed by manipulation of the complete spatial-domain information (red green blue (RGB) colour planes) [4] have been employed. In the latter case, RGB ICCD images have proved to be very successful in identifying and codifying the linear propagation velocities of built-like structures [5], and the non-linear propagation of Snake-like [6] and Kink and Wrinkles structures within a pulsed plasma jet [7, 8]. In this body of work, the majority of the luminous spatial and temporal plasma jet information is contained within the red and green planes while the blue plane that relates to fluid structure beyond the visible distal-point is imperceptible to the human eye. Accessing the hidden information within the blue plane has been recently reported [7, 8]. In these two bodies of work a purpose built National Instruments LabVIEW software program used to deliberately deselect the red and green colour planes and only manipulate the spatial-domain and frequency-domain information of the blue colour plane. The deselection of the base red and green colour planes may be considered to be the digital steganographic (from ancient Greek for ‘covered writing’) equivalent of the role played by the knife blade edge within the Schlieren imaging process.

Due to the diagrammatic nature of LabVIEW programming it is the aim of this paper to present the design concepts, including panel and block-diagrams of the LabVIEW programs used in [7, 8]. LabVIEW program was chosen for this application because the basic programs have been established in the field of high temperature plasma physics since the 1990s [9] and with continuing software updates [10]. LabVIEW 2011 incorporating vision and motion image acquisition (IMAQ) virtual instruments (VIs) are used in this work and are deployed within a Windows 7 environment. Information on the use of IMAQ VIs within a LabVIEW 7.1 for plasma spraying can be found in reference [11]. It is noted. that similar software, such as MATLAB or Java may be used for this purpose. As regards to the computer used, all LabVIEW programs are installed in a Dell Inspiron laptop computer.

II. PLASMA JET

The plasma jet studied in this work is the kINPen med® it is operated with a square wave pulsed frequency of 2.5 kHz and uses argon as the carrier gas at a flow rate of 5 standard litres per minute. The plasma physics of the plasma jet itself is not discussed here, but can be found in references [1 to 8].

III. ICCD CAMERA

The Andor iStar 334T ICCD camera is used to capture images of the pulse-on period (200µs) of the plasma plume. A 14 cm focal length glass lens focused the region from between 2 mm upstream to 30 mm downstream of the exit nozzle. Using this combination the overall optical chain (between camera and plasma-plume) is of the order of 2 m and the camera spectral range is restricted to 300 to 850 nm by the glass lens. The camera is triggered, via a delay generator, from the rising edge of the photo-diode signal. Within the camera the images are...
processed using a false-colour scale from blue (low intensity) to yellow (high intensity). For maximum visual differentiation the gain was set to 2817 out of a maximum of 4095, where the final digital images are formatted as a 24-bit depth (8-bit red; 8-bit green; 8-bit blue) Joint Photographic Experts Group (JPEG) image. The colour image is formed as a 2(dimensional array of \(N\times N\) pixels, where \(N = 1024\). The RGB image is formed from three overlaying colour filters where the value of each colour pixel location \((x, y)\) has an 8-bit \((0\text{ to }256)\) intensity level value of \(R(x, y)\), \(G(x, y)\) and \(B(x, y)\), respectively. The intensity value \((Z)\) of each pixel forms the frequency domain location (i.e. \(Z_R(x, y), Z_G(x, y)\) and \(Z_B(x, y)\)). The final value used depends upon the final colour and intensity at each pixel within the spatial-domain image array. Fig. 1 shows the orthogonal relationship of the spatial-domain pixel array and the 8-bit depth frequency-domain for one of the three base colours. In this figure, bit information is placed abruptly in the depth axis, only as an example.

Fig. 1. Orthogonal relationship between the spatial-domain \((N \times N\) array) and frequency-domain bit depth information.

IV. SOFTWARE DESIGN CONCEPT

The basic design of the processing and analysis of the 24-bit JPEG image processing software follows two distinct data flow pathways. The first pathway has six processing steps. These are: steps 1 and 2 create and read the image; steps 3 and 4 are a user defined line intensity profile that compares the pixel intensities along a chosen line in the \(N \times N\) array of the image. The function of this step in conjunction with step 4 (RGB colour plane separation) allows the operator to visually evaluate (step 5) which colour plane is to be transformed into the frequency-domain; finally step 6 is the automatic save and archive of the line profiles data for later analysis.

This second data flow pathway begins at step 4 of the first data flow pathway. The function of this step is to perform conversion between the spatial-domain and frequency-domain and associated low pass filtering and finally thresholding in to the final binary image. This second pathway has six process steps and three temporary image displays that allow the user to make decisions while manipulating the data flow. Step 1 is a user defined colour plane selection; step 2 is an automatic conversion to grey scale for preconditioning for the next step 3; Step 3 is the Fast Fourier Transform (FFT) that generates a complex image in which high frequencies are grouped at the centre, while low frequencies are located at the edges; step 4 is the low-pass filter stage truncation stage; step 5 converts the filtered complex image back in to the spatial-domain using an inverse FFT, and; step 6 is the local threshold algorithm that converts the spatial image into a binary (black and white) image [12]. Finally, the spatial image save option is proved for historical analysis. Shown in Fig. 2 is a simple schematic of the steps of the dual parallel data flow pathways (solid lines) including user-interface (dotted line). The data flow moves from top to bottom.

Fig. 2. Schematic of data design showing initial read and dual parallel data flow pathways (solid lines) and user decision making (dashed lines).

V. LABVIEW PROGRAMING

The LabVIEW software packages form a complete programming language based entirely on graphical user interface. The sub-program VIs create graphical constructs equivalent to a while-loop, case-structures and IMAQs and other VIs). These components are placed on a panel (block diagram) which is ultimately hidden from the operator. The data flow through the VIs is controlled by connecting ‘wires’ between objects, somewhat like constructing an electrical circuit. The graphical user interface (front panel) is created from a flexible set of
predefined graphical displays and controls. The image read and display IMAQ VIs are located outside of the while-loop so when the program is operated the image opens and stays open to allow interactive processing of the image within the while-loop. The two data flow pathways are placed within the while-loop. Fig. 3 depicts the complete LabVIEW block diagram. Note it is rotated through 90 degrees and enlarged over 1 column for clarity. The data flow therefore reads from the bottom of the page to the top of the page.

B. Data flow path 2

This section details the construction of the data flow pathway 2 within the while-loop and the single reference VI outside the while-loop. The pathway starts by sampling the information generated at the colour extraction VI in pathway 1. From here, a case structure containing the red, green and blue planes is used to select the base colour. The user control dialog box is set to default on blue plane.

The next processing sequence requires spatial-domain gray scale and border size control and pixel averaging to clean the noise within the base colour image. This IMAQ VI is not held in the vision VI library, but rather in an external library. Therefore Vision Assistant software is used to both gray scale and perform the pixel average process prior to the conversion into the temporary complex image for frequency filtering, truncation and conversion back into the spatial domain using an inverse FFT sequence. Once this code section was completed the code was inserted into pathway 2, from where the IMAQ NIblack threshold VI is used to make the final binary image.

VI. DISCUSSION

This section presents examples of the software in use. Example ‘A’ shows the original plasma jet image. Example ‘B’ shows the colour extraction and cross-sectional line profile of the plasma plume. Finally, ‘C’ shows pixel averaging and binary image of the frequency-domain truncation.

A. Original plasma jet image

The original ICCD camera image (JPEG 24 bit depth) of the plasma jet is shown in Fig. 4. In this image a user yellow cursor (x, y coordinates: 840, 0 to 840, 1025) bisects the plasma plume at 90 degrees. The line thus defines the cross-sectional intensity profile in each base colour plane.
Consider now that the colour changes along the cursor line: starting from the plume intersection region to the outer region blue regions. Here we note white-yellow represent the hottest part of the plasma jet which rapidly cools through red and green, then through a faint light-blue halo and beyond into imperceptible changes (to the human eye) in the blue background.

B. Color extraction and cross-sectional line profile

In this section three base colour planes (red green and blue) of the original JPEG image are separated and displayed along with the cross-sectional profiles of the plasma plume according to the yellow cursor line setting that was established in section V. A. Fig. 5 shows all three colour planes, alongside each profile is the cross-sectional line profile. The horizontal axis is in units of pixels of the spatial-domain and the vertical axis is calibrated in pixels: 0 to 256 pixels, or 8-bits, and represents the single colour plane image bit depth information.

Inspection of the red colour plane and its associated plume cross-sectional intensity profile reveals that the plasma plume information is concentrated within 50 pixels along the line of the central gas flow axis and around jet nozzle at bit depth value almost at 256 pixel level.

The green colour plane reveal a similar spatial and bit depth information, but with the addition of halo around the central gas flow axis.

C. Pixel averaging, truncation and binary image

We now consider the spatial-domain low pass average pixel filtering. The filter works by calculating the inter-pixel variation between the pixel under consideration and its neighbouring pixels. For a single pixel this means that 8 neighbouring pixels are compared. When the pixel under consideration has a variation greater than the user defined percentage (here we use 50%) it is set to the average value of neighbouring pixels. Fig. 6 schematically illustrates this process within a 10 x 10 pixel frame.

For comparative purposes, Fig. 7 compares the raw pixel line information with averaged line information along the cursor cross-sectional line as defined in Fig. 4 and Fig. 5.

It can be seen that the line noise in the raw data has been processed into a new line profile that yields a smoothed line containing a repeating periodic profile either side of the central plasma plume; where the bandwidth of the plume and
repeating structure is of the order of 40 pixels. Additionally, the depth of the periodicity is of the order of 10 pixels. This process is repeated of each pixel in the spatial-domain that starts at the initial x, y pixel coordinates of (0, 0) to yield an image that is ready for truncation (section V. D).

D. Truncation and binary image

Fig. 8A shows the spatial-domain image of the low pass averaging filtering processes. The image reveals three groups of light gray color striations against a more uniform and darker gray background: two groups either side of the plasma plume and one group to the front of the plume.

Typically, the parallel and frontal striations have a peak separation of the orders of 65 pixels with a pixel depth of 10 pixels.

A FFT is then applied to the image in Fig 8a to convert the spatial information into the frequency-domain. To smooth the noise a low-pass truncation process is used to remove any remaining high frequency component above a user defined cut-off point. An inverse FFT of the truncated information regains the spatial-domain image.

Fig 8.b shows the results of the local Nibblek thresholding segmentation algorithm when applied to Fig 8a. The operation produces a binary image where the background pixels are set to \( I = 0 \) (black) while setting the fluid structure pixel value to \( I = 1 \) (white). The result of this process produces a black-and-white binary image that represents the fluid structure within the original blue image.

In fig.8b the three sets of repeating striations (ripples) is again observed to radiate from plasma plume: one set from along the axis of the plasma plume and two sets extending from the point of plume in the direction of effluent flow. The 1 cm scale markers show that these ripples extend up to 4 cm from the nozzle with a local asymmetric complex structure between these ripples structures. This disturbance occurs at around 0.5 cm from the plume distal point. An important feature of notes here is that this break in the ripple continuity is revealed in this thresholding step and not and therefore hidden in the pixel averaging step. Lastly all the ripples, apart from the local disturbance, appear to have a periodic structure (between each white peak) typically of 1 to 2 mm.

VII. CONCLUSIONS

In this work, LabVIEW 2011 based software is used as a mean of steganalysis of ICCD camera image of the pulsed-on period (200 \( \mu \)s) of the KINPen med® atmospheric plasma jet. To reveal the hidden pixel information within beyond the visible plasma plume distal-point, RGB colour plane separation have been performed with the intention to investigate and reveal the imperceptible changes (to the human eye) in the blue colour plane.

The use of spatial-domain pixel averaging and frequency-domain pixel filtering has revealed hidden pixel information 2 to 3 cm beyond the visible distal-point of the plasma plume i.e. in the cool temperature reigns of the plasma effluent. This far-field fluid structure information may be used to support Schlieren imaging [1-3] investigations, and, or, in the understanding of what has been termed ‘spillover’ [13] and other surface interactions effects when plasma treating thermally sensitive polymers and their biomaterial counter parts. An important point that must be made here this the software is post treatment of ICCD and thus can be performed at any time on historical plasma images and thus extends experiments that did not have the availability of expensive Schlieren image equipment at that original time.
Flexibility in the colour plane choice (red, green or blue), not only allows both thermal and non-thermal plasma jets to be analysed, but also may extend the software use to other fields of image analysis.

ACKNOWLEDGMENT

This work is in part supported by the Irish Centre for Composites Research (IComp).

REFERENCES


