This article presents the method of analyzing a mach 2 flow of air through a scramjet and over a cavity using hydroxyl tagging velocimetry (HTV). This method is of particular use in supersonic engines, where fuel is ignited by a flame protected from airflow by a cavity. Emphasis of the experiment discussed is placed on the image analysis portion of the HTV experiments. The current software used to analyze laser intersections, created by Michigan State University, is user-intensive and inefficient because of the large number of inputs needed to produce a result. The conceptual method behind this imaging software is explained along with the mathematical algorithms related to the spatial correlation technique. The spatial correlation technique offers a way to determine the distance that an object has moved from one photograph to another. This work focuses on improvements to the dynamic analysis of images to expand the applicability of current software tools. The failures and successes of each method are explained.

Hydroxyl tagging velocimetry (HTV) is the process of extracting the velocity vectors of an air flow by splitting apart water molecules in air and tagging the OH atom. The OH atom is tagged by taking a photograph of the molecule at an initial position and a final position over some time interval. The velocity vector of the molecule and airflow is determined by dividing the change in position by the finite time interval.

Using the HTV process, Dr. Robert Pitz, Michael D. Lahr, and Zach W. Douglas determine how air flow, traveling at mach 2 in a scramjet nozzle, reacts when it encounters a small rectangular cavity of height 17 mm, width 153 mm, and length 66 mm. This cavity may be used in future systems to act as a place where a flame pilot may be used to ignite fuel. In a typical mach 2 flow, the flame would not ignite the fuel because it had no air-flow resistance. The cavity will be used to provide protection for the flame (Pitz et al. 2005, 6693).

The experimental setup is as follows. Humid air is pushed through a two-dimensional nozzle at mach 2, with a flow rate of 1.4 kg/s, with isentropic conditions of a pressure of 22 kPa, and a temperature of 290 K. As the humid air flows into the testing section, an ArF excimer laser of approximately 193 nm photo-dissociates water molecules into OH and H atoms. The lasers used in the experiment consist of two sets of eleven split lasers intersecting at 121 points, positioned by using a beam splitter, mirror, 300 mm focal length cylindrical lens, and 300 mm focal length cylindrical lenslets. The OH tags may
last only a few microseconds, therefore a yttrium aluminum garnet pumped dye laser with a frequency doubler at approximately 282 nm is pumped into the region containing the tagged flow. This causes the excitation of the OH, which is imaged by an intensified charged-coupled camera at 308 nm. The camera takes a picture as the flow is tagged and 2μs after it is tagged. These images are used to determine the displacement of the tagged flow. This displacement is used to calculate the speed and direction of the flow. This experiment is run at various places within the scramjet and at varying positions inside of the cavity. The experimental setup can be viewed in Figure 1 while the cavity schematic is shown in Figure 2 (Pitz et al. 2005, 6694-6696).
The flow in the cavity varies widely depending on its depth in the x-direction and its height in the y-direction. It also changes with respect to low back pressure and high back pressure. Therefore, the images of the tagged molecules vary widely. Figure 3 shows an image of an analyzed flow field using the HTV method (Pitz et al. 2005, 6697-6699).

The Hydroxyl tagging velocimetry method is useful in high speed flow and can be accurately used to calculate the velocity of air flow through a scramjet. Because of the camera positioning, however, flow can only be seen in the x and z-directions and cannot be calculated in the y-direction.

**Spatial Correlation Technique**

The software currently used to find the displacement of the air flow in the scramjet nozzle is based on the idea of spatial correlation. The location of a tagged region in an undelayed image is identified and a source window, a small square surrounding the image pixel of the tagged region, is created. A larger roam window is created on a second, delayed image, centered about the same region where the source window was defined. The source window is moved to differing locations in the roam window to determine the spatial correlation coefficient. Gendrich and Koochesfahani (1996, 68) give Equation 1,

\[
R(r,s) = \frac{I_1 \cdot I_2 - I_1 \cdot I_2}{\sigma_{I_1} \cdot \sigma_{I_2}},
\]

as the mathematical relationship of this process. The variables of these equations are defined by the following equations, where I represents the matrix of an image's intensity, N and M are the height and width of the source window respectively, and \( \sigma \) is the standard deviation:
If the spatial correlation coefficient, $R_{(r,s)}$, is at or near 0, then the location of the tagged region has been found. The $(r,s)$ coordinates are analyzed with the original coordinates of the tagged region on the undelayed image to find the displacement of the OH. This displacement is divided by 2 $\mu$s, the time elapsed between images, to determine the velocity of the flow. This data also allows for the direction of the flow to be found (Gendrich and Koochesfahani 1996, 68).

The program currently used contains sub-pixel accuracy by using a best fit polynomial to determine the intersection of the two lasers. This polynomial curve is defined in Equation 2 by Gendrich and Koochesfahani (1996, 71) as:

$$F(x,y) = \sum_{i=0}^{p} (c_{i,0}x^{i}y^{0} + c_{i,1}x^{i-1}y^{1} + \ldots + c_{i,i}x^{0}y^{i})$$

(2)

Many factors affect the accuracy of the displacement vectors. As the window size to laser line width ratio (L/W) increases, the error increases. Also, as the signal to noise ratio (S/N) increases, the error in the calculated displacement decreases. As the grid intersection angle increases, the error also increases. Taking into account the variables that affect the accuracy of the resulting spatial correlation, the displacement is accurate to within $\pm 0.1$ pixels (Gendrich and Koochesfahani 1996, 70-72).

**Dynamic Software Implementation**

Software created by M. M. Koochesfahni and C. Lum at Michigan State University, is used by R. W. Pitz and M. D. Lahr to analyze flow using the spatial correlation technique. However, the software is difficult to use because 242 sets of input are required before an image may be analyzed. The current
software approach forces the user to pinpoint all 121 intersecting points of the lasers on the undelayed images. Also, 121 source windows must be specified in the delayed image that will be spatially correlated with a roaming range in the image 2 μs later. This work shows software, in the MATLAB language, meant to automate these actions.

Many methods were explored to determine the most practical way of determining the intersections of the lasers. The contrast of the images and file types were investigated. Gray-scaled images are the most appropriate image type to use, because they are able to hold a large range of intensities, from 0 (black) to 255 (white). The average intensity of the cross peaks is about 210, while the range is from approximately 140 to 255. When the maximum intensity is large, the intensities along this line are also high and are confused as an intersection due to software error created by the large intensity range. To help alleviate this problem, the \texttt{imregionalmax()} function was used.\textsuperscript{1} This function searches through an image looking at a four by four box surrounding each pixel and determines if the pixel in question is a maximum by comparing it to these pixel intensities. The contrast of an undelayed image, Figure 4, is increased and the regional peaks of intensities above 100 are isolated and used to form a new image. The results from this function are found in Figure 5.

These images show that the \texttt{imregionalmax()} function does not pick up all of the cross-sections while the laser lines between peaks are often picked up.

A second approach taken was to model the lines of the laser. This method would work well in the free stream, because the lines are linear and do not vary much. In the cavity, where the flow is irregular, the laser paths are non-linear and this method is not accurate. The hue and saturation levels...
of the image are determined and large increases in intensity values are found. These values model the edges of the lines. If the points found are within a range of values and lie along the same side of the laser lines, then the points may be connected by a line. This is seen in Figure 6.

The green lines in the image are the lines created by the coded software. These lines follow the edges of the laser lines in most areas, but in some areas have incorrect slopes or cross over a laser line that they should not. The green lines may be analyzed because the relative points creating the lines are known; therefore, the slope and length of the line is known. If this method is further developed, the lines within a few pixels of each other that have a similar slope may be used to create a new line between the two lines. This created line would continue across the length of the image with an average slope of the lines used to create it. In this way the laser lines could be modeled. The modeled laser lines could be used to calculate the intersections of the created lines.

The third, and most effective, approach involves implementing software that looks into separate regions of the image. Each region’s properties are determined before finding local maximum intensities within each of the regions. The undelayed image is broken into a grid that is 16-by-16 as shown in Figure 7. The average intensity of each of the grid cells is calculated. Also, a regional maximum procedure was created to determine if a pixel has an intensity value that is greater than 80% of the pixels in an eight-by-eight pixel box surrounding the pixel in question. This pixel must also have an intensity greater than 90 to keep all black areas in the grid from obtaining a maximum value. The software then checks each cell in the grid to make sure that only one or no regional maximums exist. If more than one maximum exists, the pixel with the highest intensity is taken as the intersection point and the pixel of lower intensity is made to have an intensity of 0. This step prevents values that are on the
line but not absolute maximums from being considered a laser intersection. Because the grids are 16 pixels by 16 pixels, it is not possible for two laser intersections to fall into one grid. For each pixel that this not a maximum, the intensity value on the corresponding image is made 0 and turned black. For each pixel that is a maximum, the intensity value on the image is made 255 and turns white. The resulting image created using this custom regional maximum method on a free stream image is found in Figure 8.

As Figure 8 shows, all of the laser intersection points have been labeled as such. However, intensity values along the laser lines have been incorrectly added as intersection points. This occurs because the grid falls in an area that does not have an intersection point in it, but, because the grid contains a regional maximum, it considers this to fall on the intersection. This method creates the most accurate results but still needs improvement before it might supplement the current user-intensive interface.

An additional feature of the software may be included once laser intersection positions are found. The source window may be easily created dynamically based on the coordinates of the intersecting lasers. At these positions, boxes of fixed length could be centered, specifying a window in which to perform spatial correlation.

For hydroxyl tagging velocimetry in a supersonic flow over a cavity, spatial correlation works to within ±0.1 pixel accuracy using software developed at Michigan State University. Due to a large volume of input needed to analyze one HTV image, a more dynamic approach is needed to improve the user intensive program. The best method discovered to improve the efficiency of the software involves analyzing an image based on the properties of sub-sections of the image. By this process, a more ac-
curate representation of the intersection of the lasers may be made. However, the software must be improved before it can be implemented.

Notes

1. The imregionalmax function is a MATLAB defined function that cycles through a matrix checking each element to determine if its intensity value is greater than or equal to the values of the elements immediately surrounding it. A new matrix is created to show the location of each maximum point.

References


Jonathan Webb is a third-year student majoring in Mechanical Engineering in the School of Engineering with a minor in Mathematics from the College of Arts and Science. Born in Midland, Texas, Jonathan was an all-state tennis player and valedictorian of his high school. He is currently a member of Tau Beta Pi and serves as secretary of the Brothers Under Christ fraternity. Following his college graduation, he plans to continue his education studying business and product design.