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IMPROVEMENT OF SMOKE RAKES AND THE IMAGE PROCESSING FOR THE FLOW VISUALIZATION EXPERIMENTS

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ABSTRACT

Flow visualization is a commonly used technique to examine aerodynamic characteristics of a body. In this brief study, an improvement made to the smoke rake system of a commercial open-circuit vertical wind tunnel is presented. The improved smoke rake system decreases smoke line thickness from its nominal value of 3 mm to 1.5 mm and increases the number of smoke lines from its nominal value of 25 up to 91. Flow patterns around a 3D-printed NACA 4412 airfoil model are photographed, and the digital images are processed using filters. The results demonstrate a clear enhancement of the streak line visualization compared to that of the original smoke rake system.

INTRODUCTION

The aerodynamic characteristic of the flow around an object is visualized with streak lines [Kuraan and Savaş, 2020]. Methods such as oil, tuft, water and smoke are used to visualize streak lines in experimental aerodynamic studies [Ristić, 2007]. Smoke generators and rakes, the main elements of smoke experiment setups, form a fluid (smoke) that is suitable for visualization, and convey this smoke to the experiment room in filamentary form. Generation of the smoke in color and form suitable for conducting the experiment is important to make scientific investigations [Trinder and Jabbal, 2013]. Certain defects (vibration and interruption) formed in the smoke lines during the test may affect the experiment outcomes. In order to minimize experimental errors and interpret the obtained results correctly, image processing techniques are generally applied to the flow visualization by smoke experiment studies. Specifications of an image are based on the position of the camera and the test object in relation to each other, the mobility of the object, and ambient conditions. Images based on above conditions may not be of the desired quality and for this reason, image processing can be used for enhancing the experimental results.

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Kuraan et al. analyzed the flow over the spinning cone by the smoke test method. They used a smoke-wire system to produce the streaks. Droplets form at the lee side thanks to the heater in the system. 60% glycerin-water solution is used to obtain denser smoke. Experimental results are enhanced by applying background subtraction to the images obtained at the tests [Kuraan and Savaş, 2020]. Gao et al. improved the flow visualization technique with smoke-wire in order to capture better result images. A capacitor is used to obtain a higher current. Besides, they succeeded at obtaining images simultaneous with the discharge of electric current by means of the micro-controller [N. Gao and Liu, 2018]. Trinder et al. have done studies to enhance the experimental setup in order to improve the results of flow visualization by smoke test. As the setup was going to be used for educational purposes, they ensured smoke generation by using water-based fluid and fog machines. In addition, they designed exit tubes at the test section and a smoke rake with holes at the opposite side in order to produce smoke lines [Trinder and Jabbal, 2013].

The aim of this study was to improve the smoke rake of a commercial wind tunnel in order to can capture more information on the flow field. This study comprises design and testing of 3D-printed smoke rakes to enable flow pattern visualization in more detail and image processing applied to the smoke lines to make the streak lines around the aerodynamic body more visible.

METHOD

The experiments were performed in the TecQuipment AF17 open-circuit vertical wind tunnel, available at Aerodynamics Research Laboratory at University of Samsun. The wind tunnel is capable of performing between the speed range of 0.8-35 m/s which has a test section measured at 26 x 26 x 4 cm (width x height x depth). The wind tunnel is equipped with ViCount Compact Smoke Generator. Non-toxic oil is heated up above 300 °C, turns into oil vapor and is ejected from the smoke generator to the test section of the wind tunnel by utilizing compressed carbon dioxide. The oil vapor turns into smoke by condensation as it enters the test section. A smoke rake (named SR-1) at the entrance of the test section is used to inject the smoke into filaments.

Table 1: Specifications of the smoke rakes

Smoke Rake	Smoke Line Thickness	Number of Smoke Lines	Distance Between Smoke Lines
SR-1 (Original)	3.0 mm	25	9 mm
SR-2	1.5 mm	44	4.5 mm
SR-3	1.5 mm	91	2.5 mm

The smoke rake of the commercial wind tunnel (see Figure 1-a) is made of aluminum and produces 25 smoke lines of approximately 3 mm in diameter. The smoke lines are relatively thick and sparse, so several areas on the images cannot be interpreted well. In order to overcome this problem, new smoke rakes which can produce thinner and denser smoke lines were designed and tested. Specifications of the rakes are listed in Table 1. The smoke rake (named SR-2) can produce 44 smoke lines of approximately 1.5 mm in diameter (see Figure 1-b). The smoke rake (named SR-3) can produce 91 smoke lines of approximately 1.5 mm in diameter (see Figure 1-c). The main body of the designed smoke rakes are shaped like an airfoil and were manufactured using a 3D printer with PLA (Polylactic Acid) material.

(a)

(b)

(c)

Figure 1: The smoke rakes (a) SR-1 (b) SR-2 (c) SR-3

To ensure that defects can be diminished from flow visualization by smoke experiments, the image processing methods were applied to the photographed smoke lines around an aerodynamic body by a code written in MATLAB. The image processing steps are explained as follows (a diagram of the used image processing methods was given in Figure 2). Each pixel of an image has three intensity values, namely red-green-blue (RGB), and an image is defined by them. Conversion of the image into grayscale enables ease of operation as it reduces the work into single intensity [Kumar and Verma, 2010]. Median filtering is used to reduce the salt and pepper noise on the image. The median value of the nearby pixels is assigned to the pixel in order to remove unwanted noise from the image [Z. Gao, 2018]. The contrast of an image is increased with contrast stretching. The distribution of the intensity values of pixels within the range of maximum and minimum values is enabled with the histogram equalization method and thus the contrasts of the images are enhanced [Erwin and Ningsih, 2020]. Histogram equalization is an extensively used image enhancement method and plays a significant role in the enhancement of image quality [Xie et al., 2019]. Image sharpening method is used to increase the definition of the details in the image and remove the blur in the image that may occur due to image processing applications or due to image quality [Al-Ameen et al., 2019].

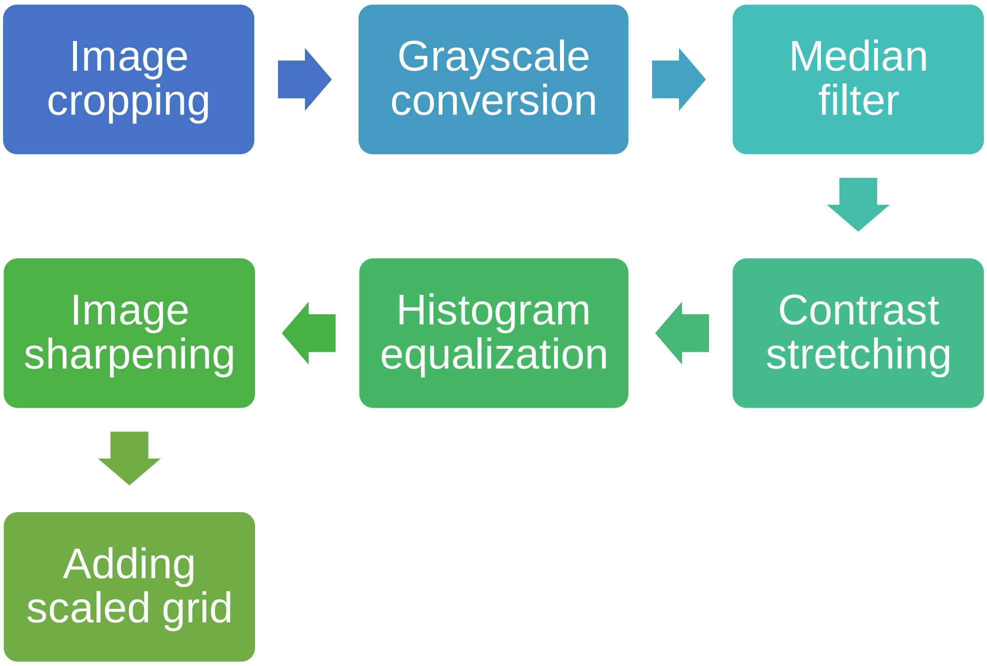


Figure 2: Applied image processing steps

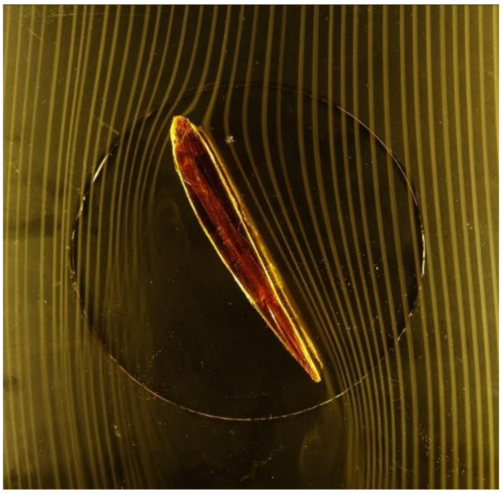
A 3D-printed NACA 4412 airfoil was mounted in the test section for flow visualization experiments. The image of the experiment was taken by the SONY RX10 III camera with F2,4-4 lens aperture and 24-600 mm zoom lens and by using 1/15 s shutter speed. The camera is placed opposed to the test section. Furthermore, a matt black coating was applied to the test section wall in order to prevent glowing and enable clear observation of smoke lines. To prevent glowing, a blackout blind system that envelops the camera and experiment setup was also used. Additionally, strip LED lights were placed inside the test section onto side walls to provide illumination to smoke lines.

RESULTS

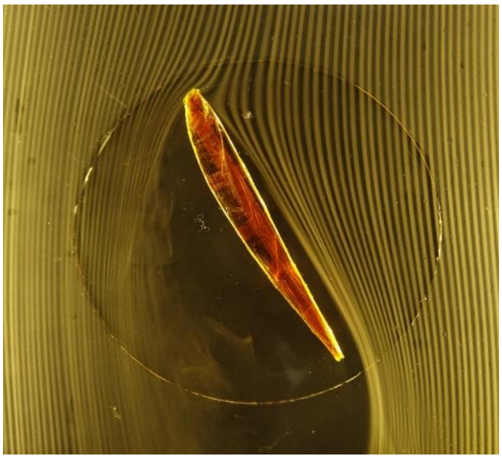
Improvement of the smoke rake

The smoke lines shaped by the rakes were given in Figure 3. It has been observed that SR-2 and SR-3 can produce denser and thinner smoke lines than SR-1 as expected. The images contain unclear parts when the experiments are conducted by SR-1. 3 mm injection holes result in more disturbed smoke lines followed by diffusion to the incoming flow. Nevertheless, these problems have been overcome by increasing the density and decreasing the thickness of smoke lines by using SR-2 and SR-3. SR-3 can shape denser smoke lines than SR-2, therefore it has been observed that SR-3 is the most ideal system for injecting the smoke into the test section.

(a)



(b)

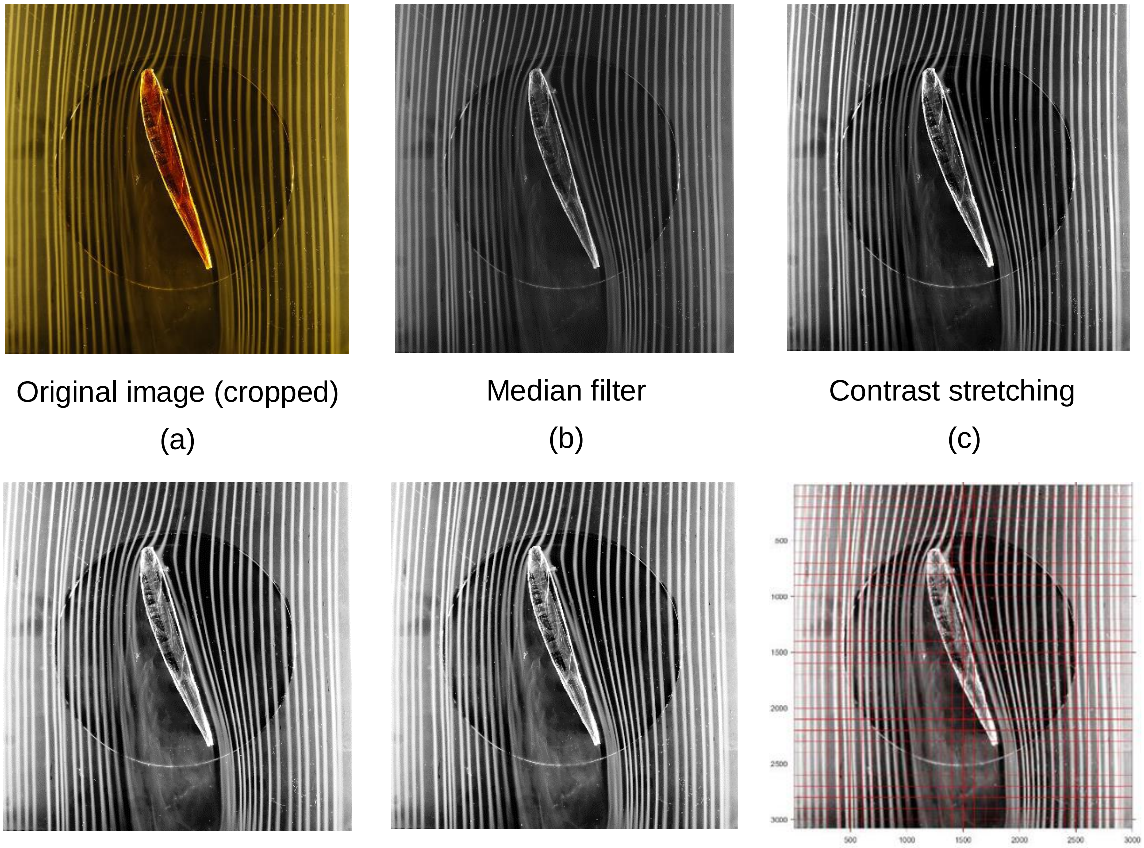


(c)

Figure 3: The smoke lines shaped by (a) SR-1 (b) SR-2 (c) SR-3

Image Processing

The results of the main steps of the applied image processing methods were given in Figure 4. To obtain images of the same size in the repeated experiments, cropping at a constant size is applied. (Cropped original image was given in Figure 4-a.) The image was then converted to grayscale. Image enhancement techniques were applied to observe smoke lines clearly. Median filter (given in Figure 4-b), contrast stretching (given in Figure 4-c), histogram equalization (given in Figure 4-d), and image sharpening (given in Figure 4-e) treatments were respectively applied during image enhancement. Finally, a grid with scale is placed on the images (given in Figure 4-f) to detect the position of the streak lines. It has been observed that the image processing methods make the flow-body interaction more understandable and more interpretable.



Original image (cropped) (a)
Median filter (b)
Contrast stretching (c)
Histogram equalization (d)
Image sharpening (e)
Final image with a scaled grid (f)

Figure 4: Main steps of image processing

CONCLUSION

Two smoke rakes (SR-2 and SR-3) for a commercial wind tunnel was designed and manufactured to produce thinner and denser smoke lines compared to the off-the-shelf rake (SR-1) of the wind tunnel capture more information on the flow field and enable better interpretation of the flow visualization experiments. The rakes were then tested with a 3D-printed NACA 4412 airfoil model. Images of flow patterns around the airfoil were processed using digital filtering techniques such as histogram equalization and median filter. The smoke lines visualized with the rake SR-1 had unclear parts and defects. Coupled with image processing, this problem has been overcome with the newly designed smoke rakes SR-2 and SR-3. It was found that the SR-3 was the most ideal design for injecting smoke into the test section and due to its larger number of smoke lines compared to the SR-2.

The defects within the images was diminished by applying the image processing methods to the smoke line images making the flow-body interaction more understandable and interpretable. Designing a graphical user interface (GUI) and improving the used image processing techniques (such as using background subtraction or the methods that makes the numerical calculations for the flow detachment analysis) are aimed for future studies.

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