Imaging Flames using a Rubens Tube

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1. Introduction

The goal of the experiment was to try to build a Rubens tube and capture an image with flames corresponding to standing waves. The Rubens tube was built by the team comprising of Aaron Zetley, Byron Pullutasig et all. The tube had an inner diameter of 3 in. and a length of 5 ft. A piece of elastic material was attached to one end of the tube and a speaker (provided by Robert Drevno) was placed on the end with the elastic.

2. Flow Phenomena

A Rubens tube is a convenient tool to effectively visualize standing wave acoustics, developed by German physicist Heinrich Rubens and Otto Krigar–Menzel in 1905 (Gardner and Gee, 2008)(Maciel, 2015). The actual functioning and science behind resonances, nodes/ antinodes, and standing waves is covered in previous team reports (Team First assignment on Flowvis.org). The flames coming out of the pressure nodes will be yellow, and the flames over the pressure antinodes will be blue (Kent L. Gee, 2009). One full wave can be observed in Figure 3, where the pressure nodes can be seen where the flames over them are yellow (right) and the pressure antinodes are towards the left.

Recalling the speed of light equation, as illustrated below, we can find the frequency of the sound wave (pitch) if we know the wavelength. This equation can be applied for the speed of sound as well. The speed of sound in propane is ~260 m/s.

$$f = v_{sound-propane} \big/ \lambda$$

Using what we already know about the dimensions of the tube, we can estimate that the wavelength (λ) is about 0.9 meters, which is a rather large wavelength. Now applying this information and calculating the frequency of the sound wave, we get,

$$f = 260 \big/ 0.9 = \ \sim 290 Hz$$

This is why the wave as seen in Figure 3 is fairly large. This enables us to observe and image the multiple flames over the pressure nodes and antinodes.

3. Flow Visualization Technique

The flame itself is the tracer for this experiment. The dark background contrasts nicely and allows the flow to be visible with clear edges. The tube was attached to a standard propane tank used for outdoor grilling purposes. The experiment was conducted during nighttime. Figure 2 provides further insight on the photography and lighting technique. The angle of the picture taken was 45º to the tube, length–wise.

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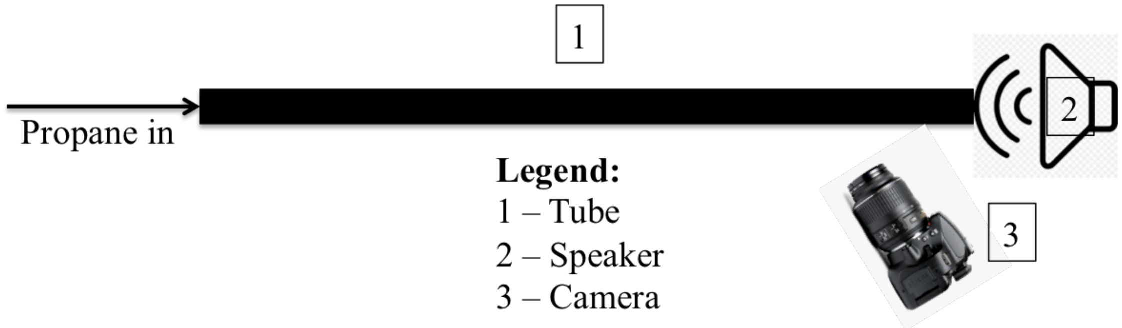

Figure 1: Setup used for imaging flow

4. Photography Technique

The Camera used was a Nikon D3200 with an 18–55 lens (DSLR digital camera). As shown in Figure 1, the camera was hand–held, and kept orthogonal to the lighting source. The required parameters are listed and calculated as follows:

1. *Lens Specs* – Focal length: 29 mm, F number (f/): 6.3
2. *Exposure specifications* – Shutter Speed: 1/50 sec, ISO: 3200, Aperture size = 4.6 mm(1)
3. *Camera and Image* – Nikon 3200 DSLR (digital), Original (w x h) = 6016 x 4000 pixels, Final (w x h) = 4950×2586 pixels
4. *Distance of object (to lens)*: 2.76 in(2)
5. *Field of View*: 16.75 in^2(3).
6. *Final cut processing (Photoshop)*: The self-explanatory Figure 2 summarizes the adjustments made in Photoshop of the original image, and Figure 3 shows the image before and after processing. Some editing was done using light curves to bring out a "Predator/ heat vision" feel to the picture, as the individual flames themselves look like people crossing a bridge.

   Reasons for choosing the mentioned settings: Medium–high ISO for better image saturation in the dark, but also to accommodate saturation by the flames.

Calculations:

[1]**Aperture size:** $D = F/f\# = 29 \text{ mm} / 6.3 = \underline{4.6 \text{ mm}}$

[2]**Distance to lens:** a non-conventional formula was used:

$$Ob = \frac{F(\text{mm}) \times \text{Real Height (mm)} \times \text{Image Height (Pixels)}}{\text{Object Height (Pixels)} \times \text{Sensor Height (mm)}} = \frac{29 \times 25.4 \times 6016}{4092 \times 15.4} = 70.32 \text{ mm} = \underline{2.76 \text{ in}}$$

Angle of view (degrees) for length:

$$2 \times \left(\arctan\left[\frac{\text{Sensor Width (mm)}}{2 \times F(\text{mm})} \right] \right) = 2 \times \left(\arctan\left[\frac{23.2}{2 \times 29} \right] \right) = 43.6^{\circ}$$

Angle of view (degrees) for height:

$$2\times\left(\arctan\left[\frac{\text{Sensor Height (mm)}}{2\times F(\text{mm})}\right]\right)=2\times\left(\arctan\left[\frac{15.4}{2\times 29}\right]\right)=29.74^{\text{o}}$$

Angle of view (degrees) for diagonal:

$$2\times\left(\arctan\left[\frac{\text{Sensor Diagonal (mm)}}{2\times F(\text{mm})}\right]\right)=2\times\left(\arctan\left[\frac{27.85}{2\times 29}\right]\right)=51.3^{\text{o}}$$

[3]**Hence Field of View for length:**

$$2\times(\tan(\text{Angle of View})\times\text{Object Distance})=2\times(\tan(43.6)\times 70.32)=134\text{ mm}=\underline{5.3\text{ in}}$$

[3]**Hence Field of View for height:**

$$2\times(\tan(\text{Angle of View})\times\text{Object Distance})=2\times(\tan(29.74)\times 70.32)=80.35\text{ mm}=\underline{3.16\text{ in}}$$

Hence, the covered area was about ***5.3 in x 3.16 in = 16.75 in***^{2}, which is the field of view.

[4]**Time Resolution:** Flame streams were stationary, perturbed by the wind.

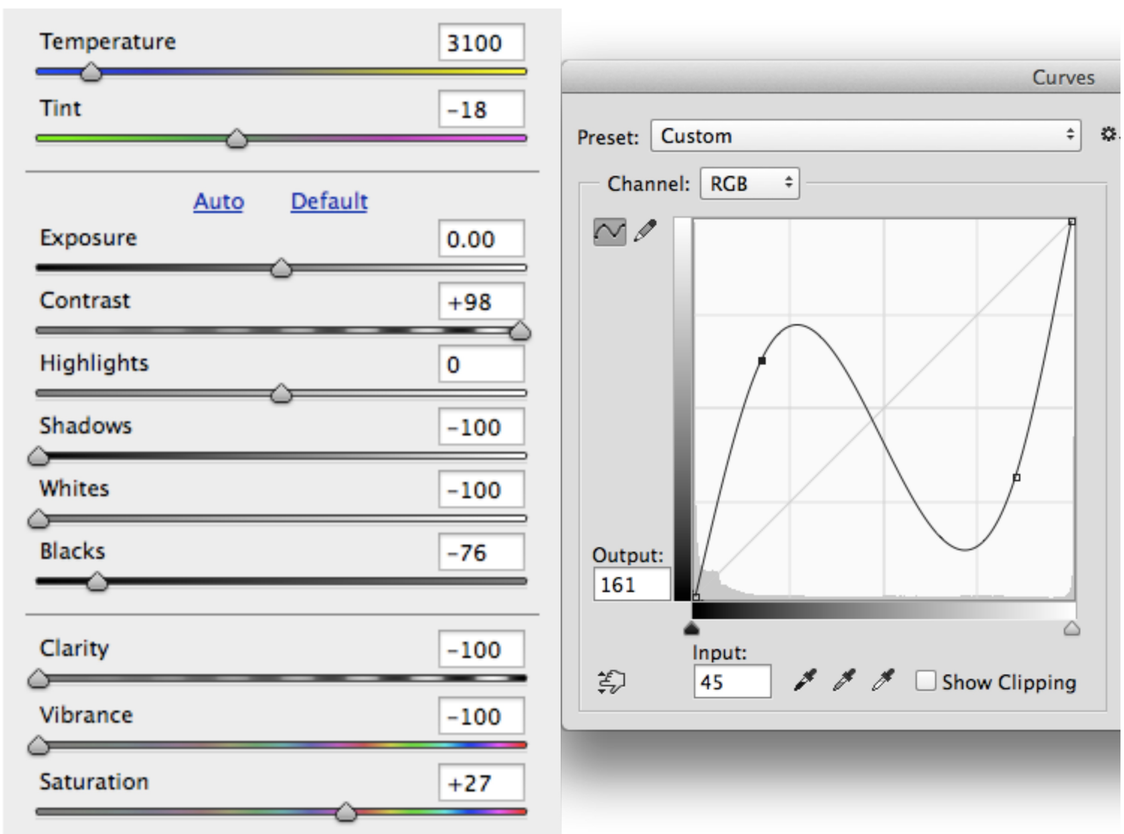

Figure 2: Basic menu on Photoshop was used to edit the image as seen on the left. The curves menu was edited as follows as shown on the right.

Figure 3: Unedited (top) and Edited (bottom) versions of Image

5. Image Characteristics

As seen in Figure 3, we can clearly see the flames emitted spaced equally apart. The wind creates patterns in the flames that resemble humanoid–like figures, crossing what seemingly looks like a bridge. On the left clear lines can be seen, as the radiation emitted by the soot formation is minimized by the wind. The opposite can be observed on the right. The highlights of the picture include the fact that the clear edges of the flames over the antinodes were captured.

References:

Gardner M., Gee L. K., (2008), "An investigation of Rubens tube resonances", *The Journal of the Acoustical Society of America* (2009), v125: p1285 – 1292.

Gee L. K., (2009), "The Rubens Tube", *Proceeding of Meetings on Acoustics* (2011), v8: p2294.

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Maciel T., (2015), "The Flaming Oscilloscope, The Physics of Rubens' Flame Tube", *Physocs Central*, *American Physical Society*.