MAKER: Volumetric Flow Visualization System Using CW Laser & Scanning Mirrors

Mr. Waqas Latif  
Richa Bagalkotkar - Khokhar  
Dr. Shouling He, Vaughn College of Aeronautics & Technology

Dr. Shouling He is an associate professor of Engineering and Technology at Vaughn College of Aeronautics and Technology, where she is teaching the courses in Mechatronics Engineering and Electrical Engineering Technology. Her research interests include modeling and simulation, microprocessors and PLCs, control system designs and Robotics. She has published more than 45 journal and conference papers in these research areas.

Dr. Amir Elzawawy

Dr. Amir Elzawawy is an assistant professor at Vaughn College of Aeronautics and Technology. Dr. Elzawawy teaches courses in Mechanical and Mechatronic Engineering programs. His research background is in the area of experimental fluid mechanics and currently active on the area of CFD (Computational Fluid Dynamics) and heat transfer simulations.

Milana A. Natanova

Graduated form Vaughn College with BS degree in Mechatronics Engineering. Will Be working at Cyeint Inc. as an Engineer.

Dr. Hugh Jack P.E., Western Carolina University

Not an author.
ABSTRACT

In this project, a new and improved volumetric flow visualization system using continuous wave laser and scanning mirrors has been designed. This system is economical, has a uniform light intensity with the capability of producing multi-layer laser sheets to create a 3D image of the flow that is spread over a large volume. Compared to the existing devices used in the aviation and space technology industries, such as the Particle Image Velocimeter and the NFAC Long–Range Laser Velocimeter (LRLV), the light intensity of each sheet produced by the Volumetric Flow Visualization System is uniformly distributed and the strength of the intensity remains unchanged. This project was partially sponsored by Maxon Precision Motors, Inc, a leading company in building micro-motors used in humanoid robots, commercial aircrafts, camera lenses, race cars, cardiac pumps and other high precision industrial applications.

Keywords: Flow Visualization, Laser, Scanning Mirrors

1. INTRODUCTION

In the aviation and aerospace industry, work in the area of Fluid Flow Visualization is conducted in wind tunnels using various flow visualization systems which replicate the actual environment the object will face in the real world. The current best flow visualizer uses concave lenses to create a fan like projection of the laser to create a plain over the fluid flow which lacks in uniformity of the light intensity. These kind of systems are used to visualize the fluid flow in 2-Dimension only. Therefore, it does not give an accurate result and can be perfected by this design. This system design is not only economical but most importantly creates a volumetric picture of the flow around an object with uniform high intensity resolution which can benefit the aerospace and aviation industry immensely.
The objective of this project is to develop a user friendly, economical and effective volumetric airflow visualizer over 3-Dimensional physical objects by utilizing optics and a high speed camera. The camera is used to capture the images of the flow frame by frame to create a 3D pictorial result. The concept used in this project is to utilize a single laser beam which is reflected from a set of mirrors placed on an octagonal disc. The disc is rotated at a high speed with the help of a motor and controller, which creates multiple laser planes parallel to each other with an increment of 5mm. These laser planes illuminate the smoke produced by a smoke machine. The camera is then used to capture the image of each plain which, when combined together, gives us a volumetric visual of the smoke flow.

Various techniques of flow visualization are used in the field of flow metrics in industries to study the flow through valves, pumps, flow meters, and other devices. It helps to optimize the design of the device based on the flow factors such as the speed variations in different areas, flow separation, recirculation and turbulent and laminar zones. Wind tunnels are used in most of the flow visualization methods to simulate the required environment around the object design [1]. Figure 1 shows flow visualization technique for the large wind tunnels of the National Full-Scale Aerodynamics Complex (NFAC) that uses a laser sheet produced by the NFAC Long-Range Laser Velocimeter (LRLV) to illuminate a smoke airflow.

As seen in the Particle Image Velocimeter (PIV) in Figure 2, the laser sheet is generated by using an incident laser beam and one or more cylinder-shaped optical lenses. These lenses cause the laser beam to be spread out to form a fan shaped laser sheet which is then reflected onto the object in testing inside the wind tunnel with the help of a mirror placed in a 45° angle. As the single laser beam energy is distributed over a larger area, the light intensity is also distributed non-uniformly. This results in a variation in the intensity of the laser sheet in Gaussian
distribution. Therefore, the intensity is inversely proportional to the area of the laser sheet produced.

Figure 2: Particle Image Velocimetry

These techniques are modified using a new concept in this project to overcome the drawbacks, i.e. the lenses in the system shown in Figure 2 is replaced by an octagonal disc mounted with mirrors which creates laser sheets with uniform intensity throughout the area of the sheet. The laser beam is not distributed across the sheet area. Therefore, the sheet has the same energy as the laser beam used. This project also focuses on creating a volumetric result instead of a 2-dimensional flow visualization system mentioned in the reference [2].

2. HARDWARE DESIGN

2.1. Frame Design

There were two options on constructing the frame design. One option was to design a skeleton based frame to mount the disc on. The other one was to have an enclosed Plexiglas frame where the disc is mounted on the inside of the frame. It was decided to design the frame using the enclosed Plexiglas frame option to increase the safety component of the system. The enclosed frame option helps in avoiding any injuries in case of mirror detachment from the disc due to centrifugal force while in the operation mode.

The design of the frame is based on the dimensions of the college wind tunnel opening 19” x 7”. Therefore, the frame dimensions were chosen to be 24” x 7.5” x 12”. After the material required to construct the frame for the project was researched, it was decided to build the frame using the aluminum t-slot beams which are light weight, strong and easy to assemble, as shown in Figure 3. Once completing the frame in which the final assembly of the project was to be mounted, there was an issue pertaining to the frame assembly because incorrect screws were purchased.
Correct screw size was required in order to attach the frame together with 90-degree angle brackets, as shown in Figure 4.

![Figure 3: T-Slot Concept and Slotted Aluminum Extrusion](image)

![Figure 4: Parts Needed to Install the Frame Together](image)

In order to correct the error, new screws with the length of 8mm were ordered. The Plexiglas was cut according to the dimensions measured directly from the top of the wind tunnel as 12” x 12” x 24” (Figure 5A) and the motor was installed onto the frame by drilling into the Plexiglas along with the universal hub attachment. After everything was set up, it was realized that the laser reflection would not be able to hit the center of the wind tunnel. Therefore, both frame and the Plexiglas was re-cut according to the new dimensions of 7.5” x 12” x 24” (Figures 5B&5C).

![Figure 5: Development of the Frame](image)
2.2. Disc with Mirrors
Calculation of Mirror Dimension

In order to find out the required dimensions for the mirrors, some calculations were conducted as shown below. The factors considered during the calculation were the radius of the disc, $r$, and the distance, $h$, between the bottom mirror and the base of the wind tunnel. Different lengths of the mirror, $L_m$, were considered to see how the length of the laser sheet, $L$, reacted and the best fit mirror length was chosen.

Based on the trigonometric figure 6, the value of $\alpha$ can be found as follows:

$$\tan \alpha = \frac{r}{L_m} = \frac{2r}{L_m} \quad (1a)$$
$$\alpha = \tan^{-1} \left( \frac{2r}{L_m} \right) \quad (1b)$$

Furthermore, the relationship among $\beta$, $\theta$, and $\gamma$ in terms of $\alpha$ can be explained as follows:

$$\beta = 90 - \alpha \quad (2)$$
$$\gamma = 90 - \frac{\alpha}{2} \quad (3)$$
$$\theta = \gamma - \frac{\alpha}{2} \quad (4)$$

By putting (3) into (4) and (1b) into (5), we have:

$$\theta = 90 - \frac{\alpha}{2} - \frac{\alpha}{2} = 90 - \alpha \quad (5)$$
$$\theta = \beta$$
$$\theta = 90 - \tan^{-1} \left( \frac{2r}{L_m} \right) \quad (6)$$

Figure 6: Trigonometric Relationship between Angles

From Figure 6 we can also derive the following:

$$\frac{L}{2} = h \tan \theta \quad (7a)$$
$$L = 2h \tan \theta \quad (7b)$$

By putting (6) into (7b), we have:

$$L = 2h \tan \left( 90 - \tan^{-1} \left( \frac{2r}{L_m} \right) \right) \quad (8)$$

Assume $h = 0.45m, r = 0.05m, Lm = 0.03m$, we can have $L = 0.27m$ by using Equation (8).
Design of Disc#1

One major factor to be considered during designing the disc to hold the mirrors was to create parallel lines on the wind tunnel testing base by reflecting the laser beam from the mirrors while the disc rotated at a high speed. Many design approaches were discussed. The first idea was to make a cone shaped spiral disc. However, this particular idea fell apart due to the difficulty of accurately placing the mirrors on the disc. The second one was to design a cylindrical disc with mirrors attached to it in a spiral at a 45° angle. It was also decided to incorporate eight mirrors surrounding the disc. Since each mirror uniformly takes an angle of 45° of the round disc, it would be easier to design and implement it as well as calculate the required torque value for the rotating motor. Furthermore, it would be much easier to identify errors if any.

The first disc prototype was designed in an octagonal shape and the disc dimensions were measured in mm as shown in Figure 7. However, the design had a problem. The mirror attachment area was too small and impractical. Therefore, it was used for primary testing only to see whether the parallel plane theory works by attaching the mirrors with dimensions of $1 \times 1$ cm$^2$. This experiment was successful and helped in implementing the second design of the disc.

![Figure 7: CATIA Part Design for Disc #1 (mm)](image)

Design of Disc#2

In this design, the mirror attachment area was increased to facilitate the appropriate size of the mirrors. It was decided to implement grooves into the disc to hold the mirrors from breaking loose due to the generated centrifugal force during the high-speed rotation of the motor for safety reasons. This resulted in an increase in the distance between the mirrors which increased the distance between each parallel laser sheet. In order to keep the distance between mirrors as per the engineering requirement, it was decided to replace the grooves with screwing the mirrors onto the disc. Three screws per mirror were diagonally placed to hold it in place (Figure 8). Once the disc was printed using a 3D printer, it was found that the part was too bulky for the motor [3] and it was nearly impossible to make holes in the mirrors without cracking them or drilling the holes in an accurate place without the drill bit slipping to an incorrect spot.

![Figure 8: CATIA Part Design for Disc #2 (mm)](image)
Design of Disc#3

The final design of the disc was in a smaller size (See Figure 9) compared to the previous designs. The mirrors were secured using a strong adhesive material, i.e. gorilla glue. As safety was an important factor, it was decided to design an enclosed Plexiglas frame to hold the disc inside of the frame to increase the safety of the system. Several experiments were conducted with various rotational speeds of the motor to test the strength of the glue. The testing results were very satisfactory.

Figure 9: CATIA Part Design for Disc #3 (mm)

Centrifugal Force Calculation

The centrifugal force on the mirrors was calculated to ensure that none of the mirrors detach whenever the disc is rotated at a high speed. The centrifugal force was calculated in the following process.

The angular to linear velocity formula is

\[ v_t = r \times \omega, \]  

(9a)

where

\( v_t \) = Linear velocity in m/s
\( r \) = Radius in meter
\( \omega \) = Angular velocity in rad/s.

The revolution per minute (RPM) to Equation (9a) is

\[ v_t = r \times \text{RPM} \times \frac{2\pi}{60} \]  

(9b)

Equation (9b) was used to calculate for \( r = 0.05\)m and \( \omega = 6110\) RMP (maximum speed produced by the motor).

\[ v_t = 0.05m \times 6110\text{RPM} \times \frac{2\pi}{60} \]

\[ v_t = 31.99196 \text{ m/s} \]

For the centrifugal force, we have the following equation [7],

\[ f = \frac{mv^2}{r} \]  

(10)

where \( m_{glass} = \rho LH \frac{A+B}{2} \) and \( \rho \) = the density of glass, L, H, A, and B can be seen in Figure 11.

Figure 10: Linear Velocity

Figure 11: Trapezoid
By the given $L = 0.00254$, $H = 0.025m$, $\frac{A+B}{2} = 0.03m$, and $\rho_{\text{glass}} = 2500\text{kg/m}^3$, the mass of the glass mirror can be calculated as follows,

$$m_{\text{glass}} = \frac{2500\text{kg}}{m^3} \times 0.00254 \times 0.025 \times 0.03 = 0.00476\text{kg}$$

Put the value of $m_{\text{glass}}$ obtained from (11) into (10), we have the following result,

$$f = (0.00476\text{kg}) \left(\frac{(31.99196\text{m/s})^2}{0.05\text{m}}\right) = 97.436 \text{N} \approx 21.9 \text{ lbf}$$

For the required disc radius and motor RMP value, $r = 0.05m$ and $\omega = 400 \text{ RMP}$, the motor linear velocity and centrifugal force are,

$$v_t = 0.05\text{m} \times 400 \text{RPM} \times \frac{2\pi}{60} = 2.0944 \text{ m/s}$$

$$f = m \frac{v^2}{r} = \frac{0.00476\text{kg} \left(\frac{(2.0944\text{m/s})^2}{0.05\text{m}}\right)}{r} = 0.417 \text{ N} \approx 0.09 \text{ lbf}$$

Motor Selection

Several factors to be addressed before the motor was chosen are as follows:

1. Brush vs. Brushless

Brush-type motors are generally used below 5,000 RPM. The factors that limit brush motor life include commutator bar-to-bar voltage, brush current density, and power at the brush-commutator interface which can produce excessive arcing. Arcing erodes brushes wear accelerates once erosion begins. On the other hand, brushless DC motors have no brushes so there is no arching to reduce the life of the motor and brushless DC motors are better suited for applications needing a wide speed range. A DC brushless motor which is suitable for different speeds for testing and future use was selected for this application.

2. Size of Motor

Size of the motor was a necessary requirement for this application. Bulk motors could possibly topple over the frame due to their weight. Therefore, a lightweight motor was considered instead of a bulky motor to lessen the possibility of damage to the motor occurring during moving, testing or storing the system.

3. Speed of Motor

Speed was one of the most important requirements for this project because the rotational speed of the motor was required to be at-least 450 RPM. The minimum speed required was necessary to be able to spin the disc to obtain a continuous laser sheet on the base floor of the wind tunnel.

4. Torque Requirement

The torque required for this application was approximately 0.009 Nm.

5. Controllability of Motor
The speed feedback signal was required by this application to be able to see the speed of the motor as the input of the speed was changed. Brushless DC motor controllers require a position feedback signal from a sensor inside the motor which can be used to obtain the actual speed of the motor.

The EC Flat 45 motor (See Figure 13) by Maxon Precision Motors was selected to satisfy all of above mentioned parameters required for the motor. The specification of the motor with the cable specifications can be referred to [4][5]. This particular motor is brushless so that there will be no arcing in the motor during high speeds thus increasing the life of the motor. The size of the motor is compact so that it can fit even in tight spots but most importantly it is lightweight motor. The speed requirement for the motor is satisfied as this motor has the capability of producing the speed above 6,000 RPM. The EC Flat 45 is capable of producing the torque of 128m Nm, which is above the torque requirement for this application. Lastly, the speed signal can be required via the use of the controller in conjunction with the motor.

![Selected MAXOM Motor](image)

**Figure 13: Selected MAXOM Motor**

**Calculating Torques for the Rotating Motor**

Torque calculation of the rotating motor was a critical step for the design process which was directly related to the selection of the motor to drive the disc. We derived the torque value using the calculated inertia, $I$, multiplied the angular acceleration, $\alpha$. [6][7][8]

As shown in Figure 14, we consider the radius, the volume and mass of the disc as $r$, $V$, $m$, respectively, and the area of the top ring is $A$ ($A = \pi r^2$). Then we have

\[
dI = r^2 dm
\]

\[
dm = \rho dV
\]

\[
dV = LdA
\]

\[
da = 2\pi r dr
\]

By putting (15) into (14), we have:

\[
dV = 2\pi r L dr
\]

By putting (16) into (13), we have:

\[
dm = 2\rho \pi r L dr
\]

By putting (17) into (12), we have:
\[ dI = 2r^3 \rho \pi L \, dr \]

\[ I = 2 \rho \pi L \int_{r_i}^{r_o} r^3 \, dr = 2 \rho \pi L \left( \frac{r_o^4}{4} - \frac{r_i^4}{4} \right) \quad (18) \]

\[ \rho = \frac{m}{\pi (r_o^2 - r_i^2) L} \quad (19) \]

By putting (19) into (18), we have:

\[ I = \frac{1}{2} m \left( r_o^2 + r_i^2 \right) \quad (20) \]

\[ I = \frac{1}{2} mr^2 \quad (21) \]

When the disc has both inner and outer radius, the moment of inertia can be obtained using Equation (20). However, if the disc only has an outer radius, Equation (21) can be utilized to calculate the moment of inertia.

\[ I = \sum m_i r_i^2 = m_1 r_1^2 + m_2 r_2^2 + \cdots \quad (22a) \]

\[ I = \frac{1}{2} m \left( r_o^2 + r_i^2 \right) + \frac{1}{2} mr_o^2 \quad (22b) \]

The mass equation below is derived from Equation (19),

\[ m = \rho \pi L \left( r_o^2 - r_i^2 \right) \quad (23) \]

By putting (23) into (22b), we have:

\[ I = \frac{1}{2} \rho \pi L_1 \left( r_o^2 - r_i^2 \right) \left( r_o^2 + r_i^2 \right) + \frac{1}{2} \rho \pi L_2 \, r_o^2 \, r_0^2 \quad (24) \]

By plugging in the value of ABS plastic, \( \rho = 1040 \, \text{kg/m}^3 \), and other values we have into the Equation (24), we get:

\[ I = 0.5 \pi \left( \frac{1040 \, \text{kg}}{\text{m}^3} \right) \left( 0.052m \right) \left( 0.05^2 m^2 - 0.046^2 m^2 \right) \left( 0.05^2 m^2 + 0.046^2 m^2 \right) \]

\[ + 0.5 \pi \left( \frac{1040 \, \text{kg}}{\text{m}^3} \right) \left( 0.01 m \right) \left( 0.05^4 m^4 \right) \]

\[ I = 2.52677 \times 10^{-4} \, \text{Kg} \cdot \text{m}^2 \]

Consider the torque as \( T \), the testing air flow \( v \) is 10m/s, the distance from laser beam to testing area \( h \approx 0.25m \), then the angular acceleration, \( \alpha \), and the angular velocity, \( \omega \), can be obtained from the following expressions:

\[ \omega = \frac{v}{h} = \frac{10 \frac{m}{s}}{0.25m} = 40 \frac{\text{rad}}{s} \approx 400 \text{rpm} \]

\[ \alpha = \frac{d\omega}{dt} \approx \frac{\Delta \omega}{\Delta t} = \frac{40 \frac{\text{rad}}{s}}{5 s} = 8 \frac{\text{rad}}{s^2} \]

\[ T = I \alpha = 2.52677 \times 10^{-4} (\text{Kg} \cdot \text{m}^2) \times 8 \left( \frac{\text{rad}}{s^2} \right) = 0.0020214 \text{Nm} \]

where \( \Delta t = 5s \).

**Controller**

The ESCON 36/3 type controller was utilized for this application. It is a small-sized, powerful 4-quadrant PWM servo controller for the highly efficient control of permanent magnet-activated
brushless EC motors up to approximately 97 Watts. This controller hardware features include speed control open or closed loop, current control, speed ramp, analog set value, digital I/O, configurable potentiometers and I×R compensation factor for user to utilize according to their needs. This controller is designed to be configured via USB interface using the graphical user interface ESCON Studio for Windows PCs. This particular controller also has status indicators to notify the user for any potential problems which include the green LED meaning that the controller is operational and red LED meaning that the controller has an error. For the application in the project, the controller’s digital I/O’s mode was utilized to obtain the desired output from the controller. The controller uses 12V input source to produce different functionalities via analog or digital I/O’s. For the application, the motor was to operate at a constant speed of at-least 400 RPM, which can be easily accomplished by either setting the value or adjusting the desired value using the ESCON studio software.

![Controller](image)

**Figure 15: Controller**

Once the controller is supplied with 12V of DC source then the controller driver needs to be activated to run the motor. The ESCON 36/3 controller has four digital I/O’s ports that the user can implement. The digital I/O #2 was utilized to run our motor and the digital I/O needs to be activated with the use of 5V obtained from the controller itself. Once the digital I/O is supplied with 5V supply then the controller drive is activated and the motor starts to produce the uploaded speed set via the startup wizard in the ESCON studio software[9].

### 3. SOFTWARE DESIGN

**Studio Software**

The software utilized by the MAXON Precision Motors is called the ESCON Studio which is a user friendly servo controller program. This particular software has a wide range of functionalities with digital and analog inputs and outputs. The software provides the user with capabilities to have speed control, current control, commands by a set value, maximum efficiency, open or closed loop and provides circuit protection. The ESCON Studio software is required to operate the controller and the motor. Users can become familiar with the operation of the software to be able to operate the controller and the motor to produce the desired outcome by completing few exercises to become familiar with different control functionalities of the software itself.

The primary objective of our project was to understand the functions pertaining to the Digital I/O’s and speed control of the motor because the objective was to acquire the motor to run at-least 500 RPM so that the mirrored disc can produce a straight line sheet. This objective was accomplished by using a set value option to control the speed of the motor via the ESCON Studio. The software can be utilized in two different ways as far as obtaining the required speed
of the motor is concerned. One way is to go through the startup wizard to set all of the parameters required for the controller to operate the motor which is uploaded to the controller via the ESCON studio software. Once the file is uploaded to the controller, the motor connected to the controller can be used with the supplied input voltage of 12 Volts. The other way is to establish the communication among the motor, the controller and the ESCON studio software to set the parameters and utilize the different tools manually to adjust the speed of the motor to be able to observe the actual speed reading from the Hall sensors[4][9].

Phantom Camera Control (PCC)

The main software application for Phantom camera users is the Phantom Camera Control (PCC). Although many of the newer Phantom models have On-Camera control the V311 model that was used for this project did not. PCC is the only place that controls every camera function on every Phantom camera model. In order to control and fine-tune the cameras resolution, frame rate, exposure, memory segmentation, trigger modes, and automatic functions prior to recording the PCC was used. Also the PCC makes it easier to convert files to the format needed for the project. The PCC’s menu tool for images includes a histogram to monitor exposure, and other controls to adjust both advance and basic image parameters. Since Phantom Cine file are raw the parameter are applied as a metadata and only incorporated when the file is converted to a different format. Cine files can be edited and saved individually or by batch-functions. PCC has the ability to perform basic measurements for motion analysis. Such as analyzing distance, angel, velocity, and angular velocity[10][11].

Image J Program

ImageJ is a Java-based image processing program and it can be used to solve many image processing and analysis problems, from three-dimensional live-cell imaging to radiological image processing. ImageJ can display, edit, analyze, process, save, print 8-bit color and grayscale, 16-bit integer, and 32-bit floating point images. We used ImageJ to stack images together so that a single images shows result of multiple images. This was done in experiment 6 and 7 to find out the distance between each line that was created [12].

4. CONCLUSION

An innovative volumetric flow visualization system has been developed in the project. As we know, flow visualization is important to the aviation and aerospace industry. It allows engineers to better understand flow patterns over an object and optimize its design. In our project, we have designed the round disc which houses eight mirrors uniformly with 45 degree per mirror and 5 mm different level in depth between each mirror. The disc is mounted on a high-precision EC motor. When a laser beam hit mirrors rotated at a high speed, the flow in a wind tunnel can be clearly visualized.

In comparison with previous flow visualization designs, the design is cost efficient, and is able to produce multilayer laser sheets with uniform distribution of light intensity. The project will provide industries the opportunity to better understand fluid mechanic with visual aid. Rather than calculating thousands of points in a supercomputer which makes a number of assumptions, the 3D flow visualization system can be used to obtain actual information pertaining to the flow around it. This device can also be utilized in educational institutes to help students visualize and understand fluid flow behaviors.
REFERENCES


