Article

Journal Renewable Energy

June, 2023 Vol.7 No.18 9-18

Low-cost Schlieren system for flow visualization in transparent media in the wind sector

Sistema Schlieren de bajo costo para visualización de flujos en medios transparentes en el sector eólico

URIBE-CASTILLO, Citlali† & RICO-ESPINO, José Guadalupe*

Universidad Tecnológica de Querétaro, División Ambiental, Área de Energías Renovables

ID 1st Author: *Citlali, Uribe-Castillo /* **ORC ID:** 0009-0009-3832-8654, **CVU CONAHCYT ID:** 1292854

ID 1st Co-author: *José Guadalupe, Rico-Espino* / **ORC ID:** 0000-0001-9371-0885**, CONAHCYT ID:** 208880

DOI: 10.35429/JRE.2023.18.7.9.18

Received March 30, 2023; Accepted June 30, 2023

Abstract

The Schlieren technique is frequently used for qualitative visualization of flow around an object. Temperature and density change can also be obtained with this technique. In this project, the aim was to develop a low-cost Schlieren system starting from easily available materials and commercial equipment. Cell phone holders were used as supports to position the concave mirrors. A light-emitting diode (LED) lamp was used as the illumination source, while a knife, a condenser lens, and printed parts in PLA (polylactic acid) plastic were key to the prototype development. Preliminary results showed an effect with limited visual perception due to the low temperature change in the objects under examination. In later experiments, qualitative visualization with a better degree of visual perception was observed due to the higher temperature range reached in the test. The images that were obtained were satisfactory and they allowed validation of the prototype development. Its main application points to the visualization of transparent flows that are formed in the airfoil of a wind turbine blade.

Schlieren, Flow, Blade, Aerodynamic airfoil

Resumen

La técnica Schlieren se utiliza con frecuencia para la visualización cualitativa del flujo que envuelve un objeto. Los cambios de temperatura y densidad pueden ser obtenidos también con esta técnica. En este proyecto el objetivo es el desarrollado de un sistema Schlieren de bajo costo, a partir de materiales y equipos comerciales de fácil acceso. Para posicionar los espejos cóncavos se usaron soportes del tipo para teléfono celular. Una lámpara con un diodo emisor de luz (LED) como fuente de iluminación, una navaja, una lente condensadora y piezas impresas en plástico PLA(ácido poliláctico), fueron la clave en el desarrollo del prototipo. Los primeros resultados mostraron un efecto con escasa percepción visual debido a la baja variación de temperatura en los objetos de prueba. En los resultados finales se realizaron visualizaciones cualitativas con mejor grado de percepción visual debido al rango de temperatura más elevado alcanzado en las pruebas. Las imágenes obtenidas fueron adecuadas y permitieron validar el prototipo desarrollado. Su aplicación principal se orienta en la visualización de los flujos transparentes que se forman en el perfil aerodinámico de un alabe de un aerogenerador.

Schlieren, Flujo, Alabe, Perfil aerodinámico

Citation: URIBE-CASTILLO, Citlali & RICO-ESPINO, José Guadalupe. Low-cost Schlieren system for flow visualization in transparent media in the wind sector. Journal Renewable Energy. 2023. 7-18: 9-18

*Correspondence to Author (e-mail: jose.rico@ciateq.mx)

† Researcher contributing as first author.

I. Introduction

Wind turbines use the force of the wind to produce electrical energy by converting kinetic energy into mechanical energy. In Mexico, there are only nine wind energy-producing states. Oaxaca is the main generator and in 2021 it provided 2,749 MW, which is equivalent to 10% of the country's total production. The states of Tamaulipas, Jalisco, Nuevo León, Chiapas, Baja California, San Luis Potosí, Sonora, and Quintana Roo also have wind power plants with a lower production percentage. (Fernández, 2023)

The blades of a wind turbine are one of its main components. They are designed to have a life cycle of approximately 20 years, during which time they will be subjected to extreme loads and fatigue due to the action of the wind and therefore they will become increasingly susceptible to instabilities caused by these phenomena. These loads cause vibrations in the wind turbine, and premature failures or wear appear in its components, causing low efficiency in energy production, costs, and lifetime of the system.(Vicente Ramírez, 2021)

The trend for wind turbine development and innovation is to search for more adaptable structures and materials, due to the need to reduce mass. However, by doing so, turbines are exposed to more vibrations and, therefore, to the generation of failures in their components. As a result, there are inevitable losses in energy production.

The purpose of this research is to apply a qualitative technique that allows visualizing the flows formed around the blade of a wind turbine. In order to observe this phenomenon, the Schlieren technique will be applied. This is an optical technique to visualize flow with density changes, from which information is obtained about flow variables, such as the different densities along a section. A light source, two parabolic mirrors, a blade, and a screen or image sensor are needed to assemble the system. The system has a "Z" configuration, with the test area in the center.

In this study, a low-cost system is proposed, which allows the visualization of flows in transparent media in the blade of a wind turbine by means of qualitative analysis that allows its implementation and academic use.

II. Resources used

For the development of the prototype, several resources were used. The total assembly cost was approximately US$1,000. Including direct costs (tools and materials) and indirect costs (services and special equipment).

III. Development

This section describes the methodology that was applied to develop the prototype of the Schlieren System. Firstly, the state of the art of the Schlieren technique is presented to introduce background information on previous works. Secondly, the design of the components by a CAD software is shown, which was used to make the necessary parts for the system structure. Finally, the development and assembly of the system is reported.

Background

The Schlieren effect is the set of non-homogeneities of a transparent material, not visible to the human eye. The study of this effect began when the need arose to develop high-quality lenses that did not present these inhomogeneities. The father of inhomogeneous media optics was the scientist Robert Hooke. He observed the Schlieren effect in 1665 with a system consisting of a large convex lens and two candles, as shown in Figure 1. One candle served as the light source, and the other produced the rising hot air, which he observed with his system. He was probably the first scientist to use a Schlieren-type setup, aiming to visualize the different densities produced by combustion. Unfortunately, his method was not precise enough to obtain optimal results. (Settles, 2001)

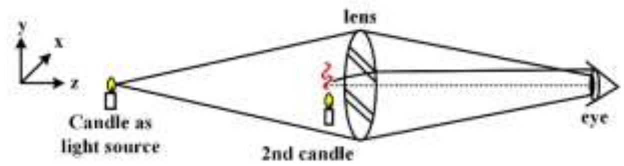


Figure 1 Hooke's optical configuration, with two candles, a lens, and a human eye
Source: Own Elaboration

ISSN 2523-2881

The Dutch astronomer Christiaan Huygens also designed a Schlieren system for the detection of irregularities in lenses, which consisted of a distant light source focused on the lens to be studied resulting in an image of varying brightness, which indicates the original irregularities of the lens.

August Toepler adapted the Schlieren for flow visualization, developed from the Foucault knife configuration, which resulted in improved quality, contrast, and sensitivity of Schlieren images compared to images obtained with previous arrangements.

Propagation of light in a homogeneous medium

The Schlieren technique is used to determine flow density gradients in fluids by observing refraction as light goes through these gradients, so it is necessary to find a relationship between the refractive index of the medium and the density of the medium. The following equation can be used:

$$n - 1 = k \cdot \rho \quad (1)$$

where n and ρ are the refractive index and density of the medium, respectively, and k is the Gladstone-Dale Constant, which is a function of the particular gas and the wavelength of light used in the optical system.

The refractivity $(n - 1)$ of a gas depends on gas composition, temperature, density, and wavelength of illumination. In many cases, the temperature, density, and pressure of gases not far from normal atmospheric conditions are more closely related to the simple equation of state of the perfect gas:

$$\frac{p}{\rho} = R \cdot T \quad (2)$$

where R is the specific gas constant, T is temperature, ρ is density and p is pressure. Gases flowing with varying density are called compressible flows and they may arise due to temperature differences or high gas velocities. All these conditions may lead to perturbations of gases that refract light, which can be visualized by refraction changes.

Definition of the Schlieren System

The optical system or Schlieren photography is an optical technique in which the variation of the density gradient of a transparent, inhomogeneous medium is observed. This technique can be applied both to liquids and solids. Changes in density, or refractive index, can be due to different factors such as temperature change, exposure to high-velocity flows, and the presence of particles that do not belong to the material under study.

This technique is used to visualize aerodynamic flows and in quality control systems for crystals, glasses, and optical elements. (Gómez González, 2006)

Conceptual design of Z-array

Z-type Schlieren mirror array: Its name refers to its geometry which consists of two parabolic mirrors in series and the test zone between the two mirrors, as shown in Figure 2. The light source located at the focal distance of the first mirror projects the light over the entire surface of the mirror, it reflects and collimates it in the direction of the second mirror, and then it concentrates it on the knife, located at the focal distance of the second mirror. Finally, the camera is placed behind the knife. (Balduzzi & Balduzzi, 2020)

Z-type 2-mirror Schlieren system: Spherical, parabolic, and concave off-axis mirrors are often used as Schlieren equipment. However, the most popular arrangement is by far the Herschellian Z-type system that uses two parabolic mirrors on oppositely tilted axes. The combination of a diverging light beam, and an opposing converging analyzer beam, and a parallel beam between the two mirrors forms the letter Z, hence the name.

This system is currently the most widely used due to the large space created for testing and the optimal results achieved. However, it requires precise calibration, and its design must minimize optical aberrations arising from non-alignment of all components.

ISSN 2523-2881

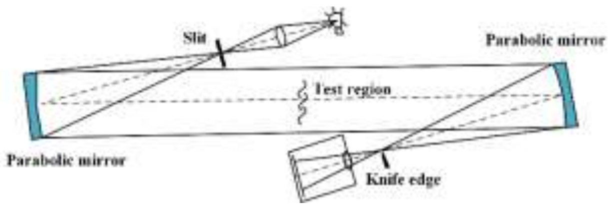


Figure 2 Schlieren Z-type system
Source: Own Elaboration

Distribution

The structuring of each part of the Type Z system, as shown in Figure 3, should be focused on decreasing optical aberrations (coma and astigmatism) and establishing sufficient space for object localization.

– The light source should be placed at the focal length (f_1) of the Mirror 1, to collimate the light beam with an angle of incidence equal to twice the compensation angle (θ_1) of Mirror 1. The compensation angle is the angle of rotation of the mirror in the XZ-Plane with respect to the vertical, or Y-Axis.

Compensation angle $= \theta_1 = \theta_2 = \theta$;

Angle of incidence $= 2\theta_1 = 2\theta_2 = 2\theta$;

The two parabolic mirrors used must be equal, so:

– Mirror 1 focal length (f_1) = Mirror 2 focal length (f_2) $= f$;

– The light beam is reflected and collimated by Mirror 1 towards Mirror 2, which must be placed in alignment with the optical axis and at a minimum of twice the focal length 2*f*, to have enough space for testing.

– Mirror 2, which has an angle of compensation equal to Mirror 1 but in the opposite direction, reflects the beam towards the knife, which is placed at a distance equal to the focal length, f.

– Finally, the camera is positioned after the knife at a distance depending on the used set of lenses, trying not to exceed 10 cm between the knife and the camera sensor. (Rosas Bonilla, 2018)

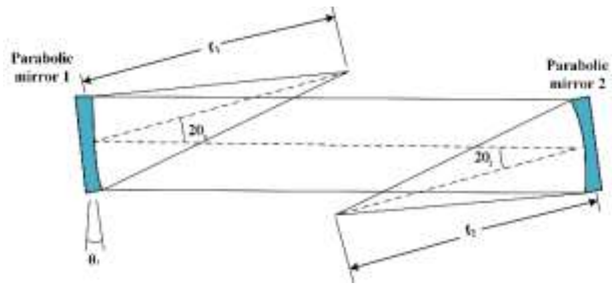


Figure 3 Schlieren system assembly: type Z distribution
Source: Own Elaboration

Sensitivity

The sensitivity of a measuring instrument is one of its basic characteristics, relating the output of the instrument to the received input. This technique is very sensitive to deviations of the incident light beam, allowing changes in density or refractive index to be visualized.

Previous work

In this project, research was conducted on some articles that served as a reference for the design of a low-cost Schlieren system.

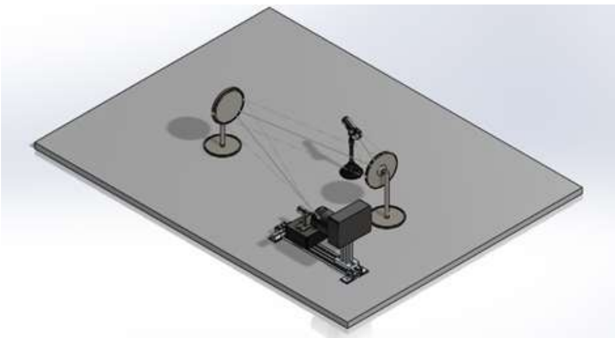
Kinsman (Kinsman, 2020) developed a design for a system that any student could build, align, and experiment with. This simple design uses a plastic Fresnel lens found in projectors.

Similarly, Stein (Stein, 2022) presented a system based on a single-mirror configuration, with a smartphone as the light source and the smartphone camera as the detector. The construction of the Schlieren Imaging System for smartphones is simple and affordable, and all parts used are 3D printable.

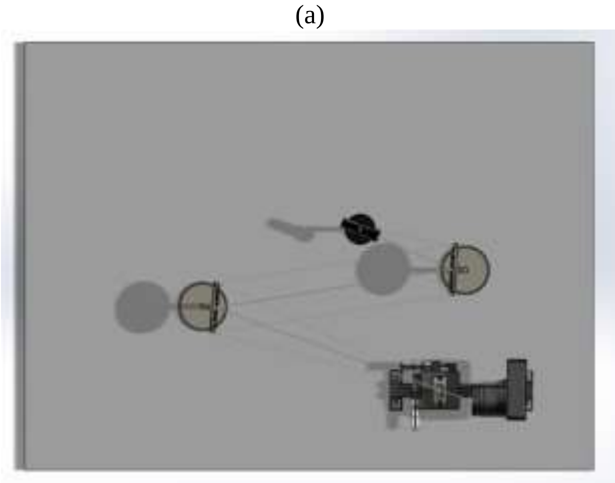
Additionally, research that used Schlieren images is presented in the work by Zhang (Zhang *et al.*, 2023) , focused on supersonic viewing tunnels, and Doroshchenko (Doroshchenko, 2023) , about processing and analysis of Schlieren images. Other Schlieren visualization techniques, such as the Synthetic type, were developed by Li and Xu (Li & Xu, 2023).

Mechanical Design

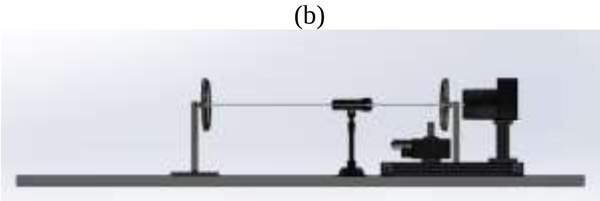
The first step to building the Schlieren System was to design it in the SolidWorks© program (Dassault Systèmes, 2023). The objective of the mechanical design is that the system should be as aligned as possible because the focal point must coincide with the two mirrors, the camera, and the lamp; the result is an image of flow visualization. The Schlieren System that was developed had a Z-arrangement, as shown in Figure 4.



(a)



(b)



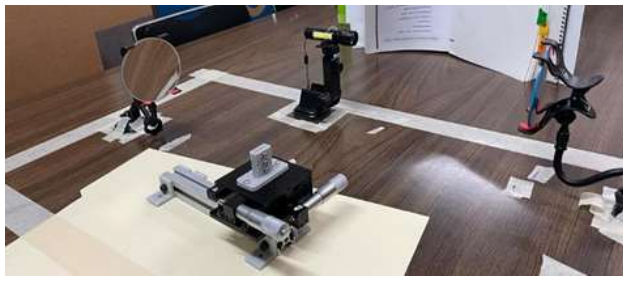
(c)

Figure 4 Schematic of Schlieren System Z-array: (a) isometric view, (b) top view, (c) front view
Source: Own Elaboration

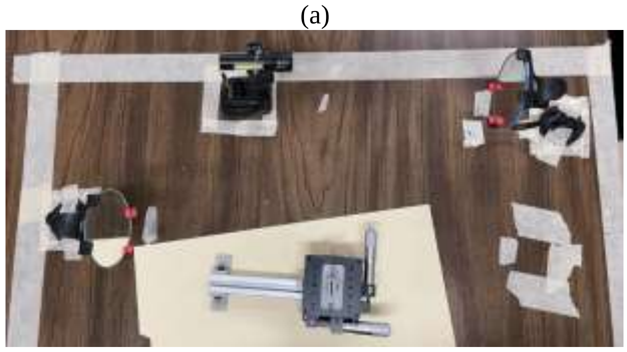
The mechanical design and distribution of the components in a virtual environment allow validating their position and the quantity of materials to be used.

Physical assembly of the Schlieren System

The whole system was assembled with the designed components, as shown in Figure 5. At this stage, the alignment of the main elements was adjusted.



(a)

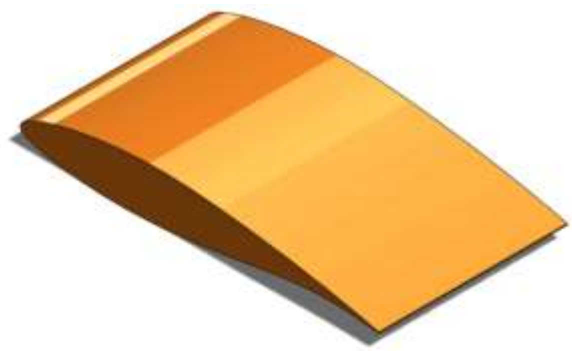


(b)

Figure 5 Assembly of the Schlieren System: (a) lateral view, (b) top view
Source: Own Elaboration

Blade segment of a wind turbine

A blade segment of the wind turbine was 3D-printed with PLA material. The design was created with the SolidWorks© program and it is shown in Figure 6 (Dassault Systèmes, 2023).



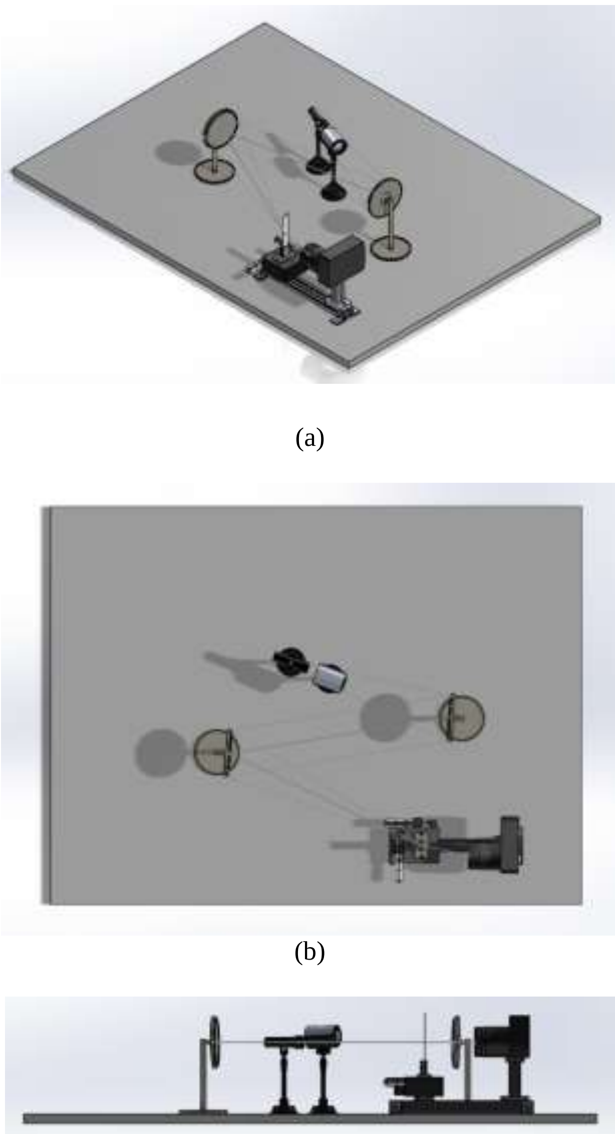
(a)

(b)

Figure 6 Blade segment (a) isometric and (b) front view
Source: Own Elaboration

Modification and improvements to the Schlieren System

The first results obtained were not entirely satisfactory, because the Schlieren effect could not be observed in the performed tests. Therefore, it was decided to make various adjustments to the Schlieren system, such as adding a condenser lens, to concentrate the light of the lamp, and direct it towards the mirror. Additionally, the arrangement was modified, as shown in Figure 7. The adjusted distribution includes the condenser lens.



(a)

(b)

(c)

Figure 7 Schlieren system with condenser lens: (a) isometric view, (b) top view, (c) front view.
Source: Own Elaboration

Schlieren system

The final Schlieren System is shown in Figure 8. A sketch of the Schlieren system (Figure 9) as well as the measurements of its orientation angles and the distance at which each mirror should be placed (Figure 10) were also prepared as a reference for future installations so that it could be assembled anywhere. The next stage was testing the system behavior.

Figure 8 Final Schlieren system
Source: Own Elaboration

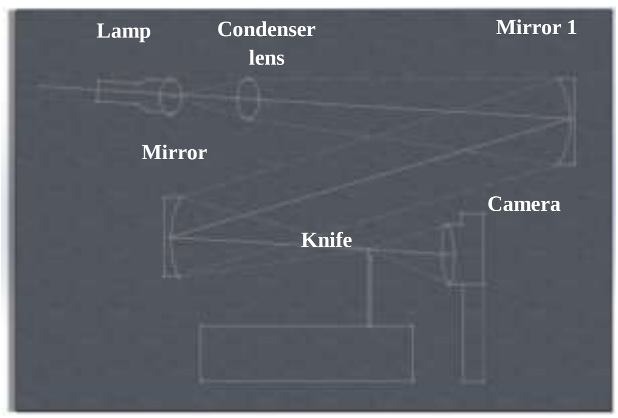


Figure 9 Schlieren system sketch
Source: Own Elaboration

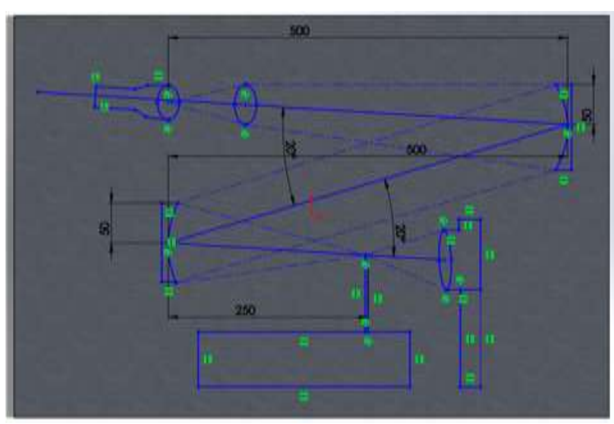


Figure 10 Schlieren system sketch with dimensions
Source: Own Elaboration

ISSN 2523-2881

IV. Experimentation

Preliminary tests were carried out with a hot air gun reaching a temperature of 60°C. These tests were not entirely satisfactory since the effect could not be appreciated because the variation of the refractive index with the temperature was not sufficient to be appreciated in the system.

Subsequently, other tests were carried out using an air gun with higher temperature and another one with solid alcohol. In this case, satisfactory results were obtained since the Schlieren effect could be observed, as shown by comparing Figure 11 and Figure 12.

Figure 11. Preliminary test with air gun
Source: Own Elaboration

Figure 12 Test with solid alcohol
Source: Own Elaboration

After obtaining the results of the tests performed on the Schlieren system for qualitative visualization of the phenomenon in transparent flows, in a subsequent stage, further application of both qualitative and quantitative visualization can be obtained from a blade segment. Quantitatively, the blade exit zone can be instrumented using strain gauges. In this area vibrations occur at the angles of attack where the wind flow changes from laminar to turbulent.

The process of gluing strain gauges is shown in Figure 13 and Figure 14. Four points were instrumented: two each in the low-pressure and high-pressure zone (top and bottom surface).

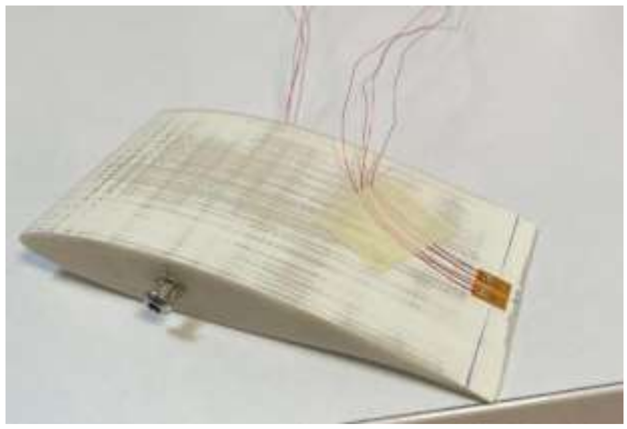


Figure 13 Strain gauges positioned on the top surface
Source: Own Elaboration

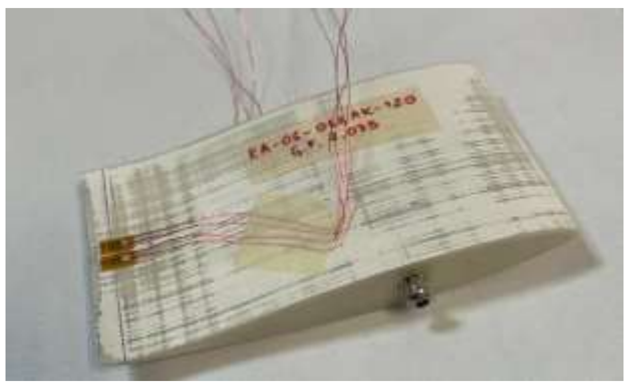


Figure 14 Strain gauges fixed at the bottom surface
Source: Own Elaboration

V. Analysis of results

The purpose of this section is the analysis and interpretation of the results obtained from the Schlieren system. The information is presented as a sequence of images.

In the images captured from the test performed with solid alcohol (Figure 15), it can be seen that flow visualization is clearer than with the hot air gun (Figure 16).

This is due to the solid alcohol reaching a higher temperature than the hot air gun, which reaches a maximum temperature of 60°C, and, therefore, the phenomenon can be better appreciated. On the other hand, it should also be mentioned that the system is not as sensitive as expected, since there should be no problem when performing tests, even at lower temperature. Preliminary analysis indicates that the increase in temperature between a hot air gun and the solid alcohol flame allows a significant change in air density. Therefore, the refractive index also undergoes a considerable change that is sufficient for the Schlieren System to be able to detect it.

Figure 15 Sequence of Schlieren images captured in the solid alcohol test
Source: Own Elaboration

Figure 16 Sequence of Schlieren images captured in the air gun test
Source: Own Elaboration

A promising improvement adopted after the preliminary tests was to modify the bases of mirrors and lamp. The bases were printed in PLA material so that the system could be installed and transported anywhere, in addition to increasing the aesthetics of the prototype. Figure 17 shows the new design of the bases supporting the concave mirrors that allowed better adjustment.

Figure 17 New bases for the Schlieren system
Source: Own Elaboration

VI. Conclusions

The objective of this project was to develop a prototype for flow observation in transparent media. Among the different Schlieren configurations available, the Schlieren Z-array technique was selected.

This technique was the most efficient for the observation of the phenomenon since it has a wider space to perform the tests and, due to light refraction, it can reduce one of the optical aberrations that in this type of system, in this case, astigmatism.

In this project, special care was given to the design and assembly arrangement that were created in SolidWorks© (Dassault Systèmes, 2023). The manufacturing of the actual parts for the assembly was outsourced. It was necessary to economize by using materials and tools that were available, as well as by planning the design of each piece to reduce the amount to be used. Although the surface finish of the mirrors was not completely smooth, it was possible to meet the expectations and objective for which it was planned.

Improvements to the Schlieren System

Possible improvements and modifications to the system would be to utilize better quality mirrors since the ones that were used here caused some complications at the time of testing and produced blurry images.

VII. Funding

This work has been funded by CIATEQ, A.C. under project number: PQDG12002.

VIII. References

Balduzzi, N., & Balduzzi, N. (2020). *Diseño y construcción de un túnel de viento supersónico con sistema de visualización Schlieren.* [Universidad Nacional de La Plata]. https://repositoriosdigitales.mincyt.gob.ar/vufind/Record/SEDICI_1a1a5472d4057db6451753ca42224a62. oai:sedici.unlp.edu.ar:10915/137588

Dassault Systèmes. (2023). *SOLIDWORKS.* https://www.solidworks.com/es

Doroshchenko, I. A. (2023). Analysis of the experimental flow shadowgraph images by computer vision methods. *Numerical Methods and Programming (Vychislitel'nye Metody i Programmirovanie)*, *24*(2), 231–242. https://doi.org/10.26089/NUMMET.V24R217

Fernández, L. (2023, April 19). *Installed wind power capacity in Mexico 2011-2022.* https://www.statista.com/statistics/790712/installed-capacity-of-wind-power-generation-mexico/

Gómez González, E. (2006). *Guía básica de conceptos de óptica geométrica.* https://docplayer.es/6274832-Guia-basica-de-conceptos-de-optica-geometrica.html

Kinsman, T. (2020, January 18). *A Simple and Inexpensive Schlieren Optical System Using a Fresnel Lens | PetaPixel.* https://petapixel.com/2020/01/18/a-simple-and-inexpensive-schlieren-optical-system-using-a-fresnel-lens/

Li, H., & Xu, D. (2023). Extended-resolution of a single-camera synthetic Schlieren method for measurement of free liquid surfaces. *Experimental Thermal and Fluid Science, 149,* 110998. https://doi.org/10.1016/J.EXPTHERMFLUSCI.2023.110998

Rosas Bonilla, B. A. (2018). *Diseño y construcción de técnica de visualizacion de fluidos de alta velocidad Schlieren tipo-Z.* [Fundación Universitaria Los Libertadores]. https://repository.libertadores.edu.co/bitstream/handle/11371/1778/rosas_brayan_2018.pdf?sequence=1

Settles, G. S. (2001). *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media.* (Springer Science & Business Media, Ed.). https://books.google.com.mx/books/about/Schlieren_and_Shadowgraph_Techniques.html?id=HWtB2R0gWFgC&redir_esc=y

Stein, K. R. (2022, June 26). A Low-Cost, Portable, Smartphone Schlieren Imaging System. *Annual Conference Excellence Througn Diversity*.

Vicente Ramírez, J. C. (2021). *Análisis de las vibraciones mecánicas generadas debido al movimiento giroscópico del rotor de un aerogenerador de baja potencia.* [Universidad del Istmo]. http://www.unistmo.edu.mx/bibliotecas/tesis_posgrado/2018-2020/tesis%20Juan%20Carlos%20Vicente%20Ram%C3%ADrez.pdf

Zhang, X., Li, D., Zhang, Z., Huang, B., Wang, R., Pu, H., Huang, Z., & Chen, Z. (2023). Density field measurement deflectometry for supersonic wind tunnels. *Optics Letters*, *48*(7), 1714. https://doi.org/10.1364/OL.485063