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Design and Construction of a cost-efficient Laminar Flow Wind Tunnel for Aerodynamic Testing

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***Abstract*:** The intention of this project is to design and build a cost-efficient laminar flow wind tunnel to test airfoil performance characteristics. While there are cost-efficient wind tunnels available for learning purposes, they are usually only designed to show the visual representation of airflow over the airfoil. This project will create accurate and repeatable measurements of performance characteristics, making it a budget friendly solution for college level research labs. The wind tunnel will be designed using CAD and scientifically tested for laminar and uninterrupted flow. The main measurement of lift/drag will come from load cells with an Arduino microcontroller measuring the amount of force exerted on the airfoil. When placed in the wind tunnel, the load cells situated on the airfoil will sense real-time pressure exerted on it, which can be measured in real-time as a measurement of static pressure deviation. Furthermore, this wind tunnel will serve as an enhancement for analyzing angle of attack relative to airfoil efficiency. Results will be analyzed relative to the angle of attack and flow separation, which are two of the most important factors for accurate airfoil comprehension in the aerospace industry.

***Index Terms*:** Aerodynamic testing, Airfoil performance, Arduino-based measurement, Laminar flow wind tunnel, Lift and drag analysis.

I. INTRODUCTION

A wind tunnel is a system that allows one to study the effects of moving air on stationary solid bodies. By generating a controlled airflow, one can determine what air would do on a smaller version of an airplane, car, or any other configuration. Wind tunnels are essential to the study of aerodynamics. However, the ease of operation of industrial-grade wind tunnels is often far too expensive for school/college lab settings and independent experiments. Therefore, this experiment aims to create an inexpensive alternative that operates with the same efficient output required for simple studies of aerodynamics.

The means of construction is derived from the wind tunnels of prior research with modifications for cost efficiency while still meeting all necessary performance requirements [1]-[6].

II. LITERATURE REVIEW

There is research on different aspects of wind tunnel construction which could result in a cost-effective wind tunnel. Towles-Moore [1] studies the scale of high-speed subsonic wind tunnels. De la Cruz and Luzzatto-Fegiz [2] create a wind tunnel apparatus the size of a pocketbook that can be kept on a desk, considerate of cost and material. Shamsuddin and Kamaruddin [4] study small wind tunnels as compared to flow visualization, which relates to the anticipated purpose of this project. Barlow, Rae, and Pope [3] supplied information regarding contraction ratios, the necessity to reduce turbulence, and diffuser efficiency for wind tunnel applications. The NASA paper [6] about wind tunnel components assessed settling chamber and honeycomb components and how much their necessity for laminar flow. The component configuration article by Baydono and Sleiman [5] assessed different configurations for various experiments, including one for a portable wind tunnel, which revealed that lower cost could still equate to efficiency.

III. METHODOLOGY

1) Breakdown of the parts of a wind tunnel: A simple laminar flow wind tunnel is a system that requires many components. The primary components of this configuration are the drive section, settling chamber, contraction cone, test section, and diffuser [7].

Drive Section: The drive section provides the necessary flow for operation within the tunnel by either extracting air from the test section or exuding it from the contraction cone. This is especially important for supersonic and high-speed tunnels which require pressurized air or gas to help with the necessary flow composition. However, for this design, an electrically operated fan or pneumatic pump is sufficient [6].

Settling Chamber: The purpose of the settling chamber is to minimize turbulent airflow. Air becomes turbulent when it has eddies in the airstream from colliding particles during transit or deviation of direction. Therefore, the settling chamber is formed of wire mesh and a honeycomb structure to assist in as much straightened airflow before it enters the contraction cone [6].

Contraction Cone: The functionality of the contraction is to minimize the space for air travel so that air velocity is increased before reaching the test section. It also aids in laminar flow since a confined entry encourages entry flow to remain as it should within the apparatus. A contraction cone facilitates this arrangement by simply allowing air to enter the test section more easily [6].

Test Chamber: This is the section of the wind tunnel devoted to aerodynamic testing as this part of the tunnel possesses the most laminar flow and average velocity. This means that, in controlled settings, adjustments for drag, lift, and yaw are more accurately assessed. In addition, if the experimenter has adequate access, the flow can be assessed visually with the introduction of air or smoke [6].

Diffuser Section: Once the air passes through the test section, it needs to slow down before it rejoins the system. Thus, the diffuser section increases in cross-sectional area and, concomitantly, decreases in velocity. However, this is not immediate; if it were, there would be too much pressure change instantaneously and, in reality, too much energy would have to be spent to keep air going. Furthermore, the diffuser section is longer than the contraction section because it needs to sustain this velocity reduction for a longer amount of time [6].

2) Design Methodology: The major components of a wind tunnel consist of the following:

- Test section
- Settling chamber
- Contraction
- Honeycomb
- Diffuser
- Fan section

The first step is to define the purpose of the wind tunnel and determine the required dimensions [1]. For example, the honeycomb is designed after the contraction since its design depends on the cross-sectional area of the contraction [4]. Similarly, the diffuser must be designed before the fan section, as the fan section is integrated within the diffuser [3]. The design of the test section is determined by its intended purpose, and all other components are designed to fit around it [5]. Thus, the order of design completion for the wind tunnel will be as follows:

Test section → Settling chamber → Contraction → Honeycomb → Diffuser → Fan section

Project materials and tools will include CAD software for design and visualization, such as AutoCAD and Google SketchUp, for model development [6].

Additionally, Arduino technology will be used for integrating load cells and measuring lift and drag forces [2].

Google Sheets may be used for result visualization and data analysis [3].

Theoretical components will include practical engineering principles regarding aerodynamics to increase the proper air flow through a wind tunnel and achieve desired results [4].

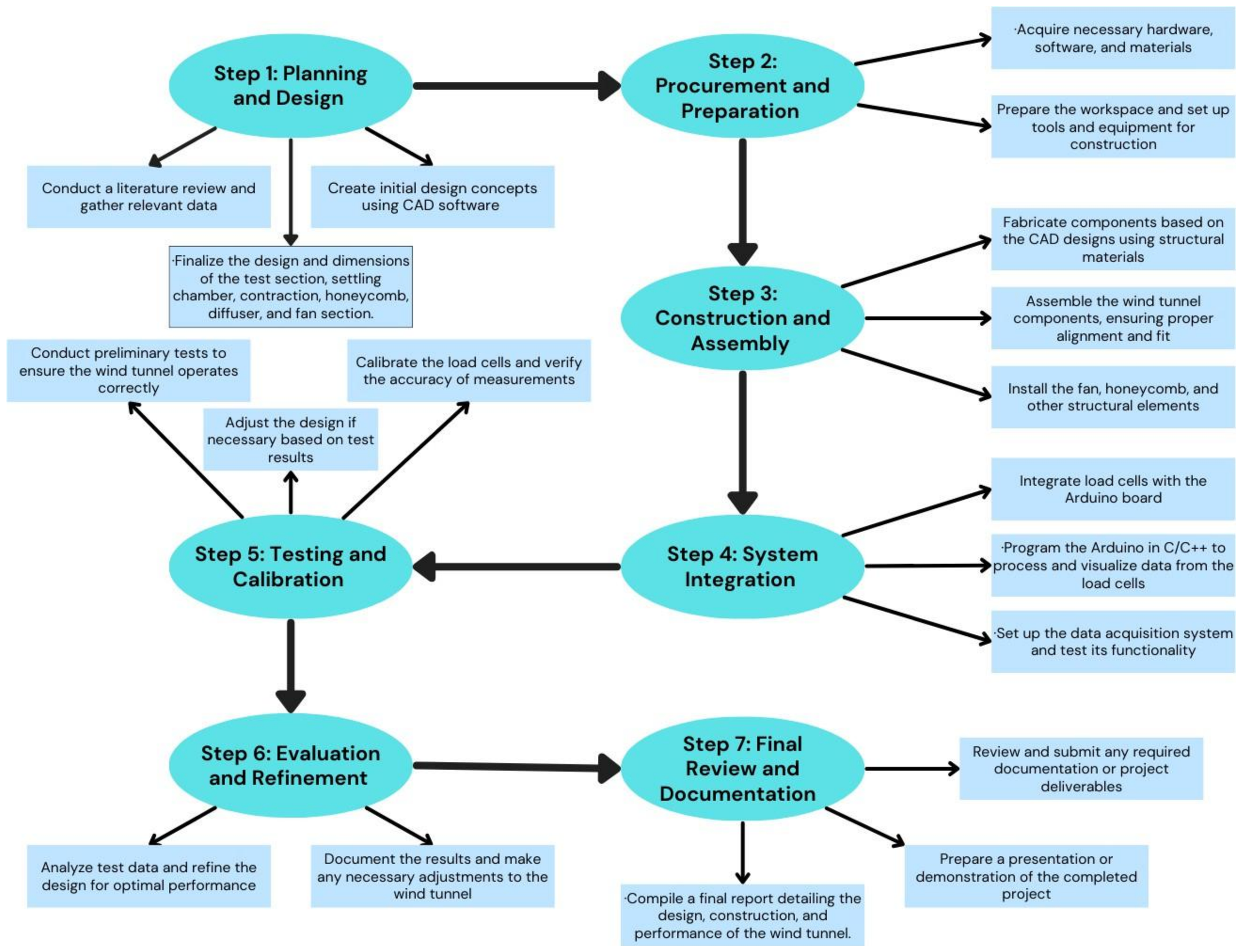
The use of electronic components such as sensors and Arduino measuring devices for increased measurement accuracy [1].

Theoretical components are boundary layer and fluid dynamics referred form [5]. Software and hardware components will include extensive iterative prototyping, testing, and computational simulations to obtain proper laminar flow and accurate wind tunnel readings [2].

The theoretical principles of aerodynamic forces such as Bernoulli's principle and boundary layer theory, will be used to guide the construction and design [4].

The Arduino coding will utilize C/C++, various electronic components will be used to allow for compatibility with load cells, in order to receive accurate measurement for aerodynamic testing [6].

3) Implementation plan:



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IV. Construction and Assembly

The subsequent resources and materials required to build the wind tunnel in accordance with stability and measurement requirements:

- Load cells
- Data acquisition system (e.g., analog-to-digital converters)
- Fan and motor assembly
- Honeycomb structure
- Contraction and diffuser components
- Structural materials (e.g., aluminum, acrylic)
- Measurement tools (e.g., calipers, rulers)
- CAD software (AutoCAD or Google SketchUp)
- Arduino board
- Arduino IDE (for programming)
- Data visualization and analysis software (e.g., MATLAB or Python libraries)
- Construction materials for wind tunnel (e.g., aluminum, acrylic)
- Fasteners and adhesives
- Electrical wiring and connectors
- Technical references and aerodynamics textbooks
- Prototyping tools (e.g., 3D printer, laser cutter)

V. Potential Applications

The low-cost, portable laminar flow wind tunnel design project could be utilized for a variety of real-world applications. For instance, this would make a great instructional opportunity in university and technical school settings, as students would learn from the ground up with in-house resources, given that limited funding to support such a large endeavor often out of reach for them. Too frequently, students miss out on dynamic testing, as larger wind tunnels are project-based and located in large facility settings.

However, a project like this wind tunnel allows students to take projects from creation to testing using this inexpensive option. In addition, because the wind tunnel is portable and inexpensive, small workshops and community outreach projects can obtain it to improve testing opportunities. Furthermore, projects made with this design can be modified and revised as need, because fixed designs are typically meant for more specific endeavors.

VI. Expected Results

Ultimately, the completed project will yield a working budget-friendly, portable laminar flow wind tunnel coupled with testing capabilities for aero foils for aerodynamics. This wind tunnel will provide a proper determination of lift and drag force using a load cell and utilizing an Arduino to process findings which can be viewed in real-time. The project is justified by the learning experience because it creates a relatively inexpensive solution to otherwise extremely expensive wind tunnels, which allow experimentation at home relative to learned or unlearned classroom experiences in the realm of aerodynamics. Measurements of success will be: the wind tunnel is effective for aerodynamic testing (lifts and drag); laminar flows that are necessary for testing are successfully achieved within the boundaries of the testing section; the wind tunnel realizes all intended functionality in terms of operating the wind tunnel. Measurement of performance will be gauged through a performance assessment of how the wind tunnel operates versus what was designed as expectations since information obtained should be similar. Lastly, measurement of success via an external engagement with other scholars is an off-site measurement of success from an assessment of success from external assessments of potential future use and effectiveness from an educational standpoint.

VII. Limitations:

- **Size limitations:** The small wind tunnel is not suited for large models; it is only capable of testing small or scaled-down models.
- **Quality of flow:** Even though the wind tunnel is set up for laminar flow, it is possible that there is some turbulent flow due to construction tolerances and the lack of super fine adjustments to create perfect airflow uniformity.
- **Calibration of measurements:** The sensors and related data acquisition devices are cheap, which may create some error in finding true aerodynamic forces.
- **Materials:** The materials used are acrylic and aluminum, are cost-effective but lack durability. They also have rough surfaces, which may disturb the laminar flow.
- **Speed:** The wind tunnel is designed to test low-speed air flow and is therefore unable to test high-speed or supersonic airflow.

VIII. Future Scope

- **Greater automation:** Integration with AI and machine learning for complete automation of real-time data collection and data processing.
- **Improved sensor accuracy:** Additional onboard sensors and data collection systems could be added to minimize measurement discrepancies.
- **Changeable components:** Future versions could have interchangeable components to better facilitate testing of different drag profiles.
- **Ability to test airflow at in-between speeds:** Future versions can test airflow at in-between speeds with settings adjustments, potentially yielding results in transonic.
- **CFD Validation:** Employing computational fluid dynamics (CFD) to both validate and correlate experimental results with simulation results.

IX. Conclusion

This project conceived and constructed a low-cost laminar flow wind tunnel. Low-cost, yet high-quality materials were used, such as acrylic and aluminum for the frame, and inexpensive devices, such as Arduino-based sensors. With these materials, the project was able to achieve a balance between function and expense [2][5]. The testing procedure integrated all aspects necessary to this evaluation during each moment of construction, from the test section to the settling chamber, to the contraction cone, to the honeycomb, diffuser, and fan section, practically proving the design and construction sequence for achieving laminar flow and minimizing turbulence [3][4].

Relative to the findings from the tests, the wind tunnel proved to be effective for uniform air flow and improved performance needed for the aerodynamic tests. For instance, flow visualization showed laminar flow, and lift and drag measurements, taken post-testing, relative to expected measurements, validated the wind tunnel for small-scale experiments [3]. However, components concerned with calculating lift and drag involved slight discrepancies, thus recalibration for sensor precision seems necessary, which can be improved in the future.

To conclude, future potential enhancements involve a more sophisticated data collection process for precision, a more permanent arrangement to test various aerodynamic configurations, and CFD compatibility for more reliable validation of the experiments [1][6]. In addition, the ability to run at higher airflows would make this usable for even more aerodynamic research and educational applications. Nonetheless, this was a successful, cost-effective project for experimental aerodynamics and an opportunity for students and researchers to engage in wind tunnel testing.

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