International Journal Software Engineering and Computer Science (IJSECS)
4 (1), 2024, 184-195
Published Online April 2024 in IJSECS (http://www.journal.lembagakita.org/index.php/ijsecs)
P-ISSN : 2776-4869, E-ISSN : 2776-3242. DOI: https://doi.org/10.35870/ijsecs.v4i1.2190.

RESEARCH ARTICLE | Open Access

Arduino IoT Controller for Angle of Attack Measurement with Force Balance

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Received: January 30, 2024; Accepted: March 25, 2024; Published: April 20, 2024.

Abstract: The force balance system uses the whitestone bridge concept to read the airfoil aerodynamic lift and drag forces while also having a function to control the airfoil angle of attack. It is designed for low subsonic wind tunnels, especially for educational purposes. The system uses Arduino as the microcontroller to read the force data from the load cell sensors and gives commands to the rotary motor stepper to change the airfoil angle of attack. Arduino is combined with a novel mechanical linkage system designed and studied to ensure the sensors can read the correct airfoil lift and drag forces. The angle of attack is controlled with a smartphone to decide the degree of airfoil. The reading of the system is validated using spring balance that pulls the system with magnitudes of 1,1.5, 2, 2.5, and 3 kgF in some pulling force angle. The results show that the reading of the system is accurate compared to the theoretical results, with an average error of 2 %. The force measuring tool on the airfoil is the first step in a series of steps to produce the final project, namely the wind turbine. Research suggests that the load cell must be positioned correctly so that the sensor reading error can be increased again. The stepper motor must be turned off the bottom shaft to prevent the airfoil from rotating.

Keywords: Arduino; Force Balance; Drag Lift; Angle of Attack; Aerodynamics.

1. Introduction

Wind Tunnel is a tool used to study the effect of airflow on the aerodynamic forces acting on the model. For aeronautical applications, wind tunnels are an essential tool for designing and developing any aircraft [1]. This reaction force will give the plane a certain flying speed [2]. Some parameters become the object of interest to be measured, such as lift force, drag force, pitching moment, air pressure distribution, and boundary layer around the airfoil. The cross-sectional shape of the wing is referred to as airfoil. An airfoil-shaped body moved through a fluid produces aerodynamic forces. The component of aerodynamic forces perpendicular to the airflow is called lift, while the component parallel to the airflow is called drag [3]. Predicting the magnitude of airfoil aerodynamic forces is essential, especially in the development stages of various technological products, such as aircraft, drones, wind turbines, bridges, and land vehicles. Fernandez Lopez *et al.* used a wind tunnel to experiment with measuring the lift and drag coefficients concerning the angle of attack. They also observed the boundary layer separation around the airfoil [4]. If the angle of attack is less than 20º, the increase of the angle of attack will increase the drag [5]. The wing section used in the experiment is symmetric with 30 cm of span and 15 cm of chord. Chord sensitivity studies showed that the airfoil chord-to-test section length ratio plays a vital role in the accuracy of the measurements [6]. The lift coefficient curve is linear dependent for $-10^{\circ} < \alpha < 10^{\circ}$. One of the geometric parameters that determines the result of airfoil lift is the location of its maximum thickness [7]. This study shows wind tunnel capabilities to obtain a body's aerodynamic characteristics.

Some wind tunnels use manual mechanisms to measure the aerodynamic forces and moments of the airfoil and set the airfoil angle of attack position. A novel force balance is developed to measure low-magnitude mean aerodynamic forces [8]. The force balance is one standard instrument that can directly measure aerodynamic forces and moments in the wind tunnel. The force balance can be a bar placed on top of a fulcrum, with one end connected to the airfoil and the other to the weight. Before the wind tunnel is turned on, the airfoil model is placed at the end of the bar, and the weight at the other end is adjusted to balance the airfoil. The airfoil generates lift force when airflow is inside the tunnel, which causes the bar to be unbalanced. Additional weight needs to be added to rebalance the bar. This extra weight is equal to the lift force generated by the airfoil, so the lift force on the airfoil is obtained by integrating the measured pressure distribution over the airfoil surface [9]. The lift force gets higher when the relative angle between the airfoil and the airflow, so-called the angle of attack, is higher. To measure the change of lift force due to the angle of attack, the airfoil should be rotated manually, step by step. In each step, the weight is added to rebalance the bar and measure the lift generated by the airfoil for the current angle of attack. The accuracy of using manual setting in the wind tunnel test depends on the operator's ability to rebalance the force balance bar and set the angle of attack for each step. The airfoil type significantly affects the flying quality of an aircraft because it has a different geometric shape of each kind, producing different lift and drag [10]. Other operators may lead to varying levels of accuracy. Manual setting and data collection cause the time required for wind tunnel testing is getting longer. The data collection can be carried out when the airflow inside the wind tunnel is stable. Rebalancing the force balance, reading, and recording data also requires a certain amount of time. This process is carried out repeatedly for various values of angle of attack, and it needs a long time to obtain one aerodynamic lift curve. In addition, automated and commercial wind tunnels are generally expensive and specific to particular agencies or institutions [11].

Some research has been conducted on measuring the airfoil aerodynamic forces. Milan Tomin *et al.* (2020) researched and researched designing the force balance to obtain the airfoil's aerodynamic lift, drag, and pitching moment [12]. The system uses three load cells and electronics hosted under the test section to minimize interference with the airflow. The system can collect the lift, drag, and pitching moment coefficients for some angles of attack. Asutosh Boro (2017) designed the lift and drag measurement system tested at various velocities and angles of attack. The experimental lift and drag coefficients are compared with literature values [13]. The system accurately predicts lift forces, but there is still a considerable error in measuring the drag forces.

Further, the same design could be experimented with different sensors for better accuracy and cost reduction. Wind tunnels can also be used as a teaching aid to increase students' understanding of aerodynamic phenomena. Morris *et al.* (2010) designed a force balance for educational wind tunnels. The system uses two load cells, one to measure lift and the other to measure drag [14]. A linear actuator is implemented in the system to change the angle of attack. The design is suitable for education because it is low-cost and gives sufficient accuracy. Instead of manual setting and data acquisition, the system consists of load cell sensors to read the forces and electrical actuators to change the airfoil angle of attack, which are studied in this research. Arduino is the microcontroller that reads the force data from the sensor and commands the actuator to change the angle of attack. Arduino is a standard microcontroller that researchers use either for wind tunnel force balance purposes [13][12][15], or to measure the airspeed inside the wind tunnel [16]. In this research, Arduino is combined with a novel mechanical linkage system that is designed and studied to ensure the sensors can read correct airfoil lift and drag forces.

2. Research Method

Using a load cell sensor, the force measuring tool uses a free mechanism to measure drag and lift. Drag and lift measurements on the airfoil experience movement in the mechanism in the direction of the applied pressure. This pressure will be read by a load cell sensor that has been connected to the airfoil testing frame. Four load cell sensors are installed, two for lift and two for drag measurements. Drag and lift readings use equations related to the influence of the angle of attack with the adjusted magnitude. The drag and lift results will be compared theoretically and with experiments to determine the error tolerance below 5%.

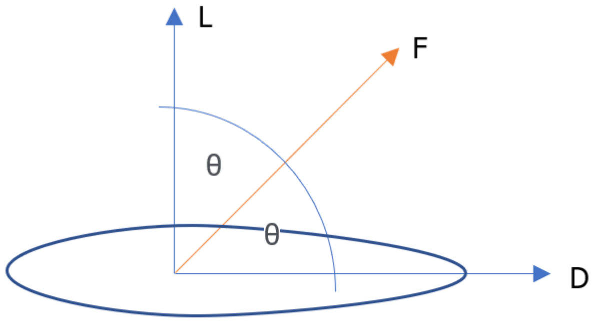

Figure 1. Drag and Lift Vector

Shown Figure 1. Drag and lift measurements are calculated with the equation:

$$D = F \cdot \cos\theta \quad (1)$$
$$L = F \cdot \sin\theta \quad (2)$$

Where:
D = Drag (N)
L = Lift (N)
F = Force (Kg)
θ = Angle (Degree)

The control system adjusts the angle of attack when the airfoil is tested. Developed an attack angle gauge based on modern devices that increases accuracy and reliability [17]. Angle settings can be done with four functions, namely: Counter Clockwise (CCW), Clockwise (CW), Reset (R), and Range Angle. The angle of attack has been determined at -24o to 24o with an angle range of 2o. The settings are processed with an Arduino microcontroller, which has been programmed to carry out the four functions above.

2.1 System Design

The measurement of lift and drag in the low subsonic wind tunnel can be done utilizing a load cell instead of a manual balance. The main focus of this research is the design and development of a system to measure lift and drag forces, which consists of a force balance mechanism and electrical components. Arduino Uno is used as the main microcontroller in the control system. The control system is a tool (part of tools) to control and adjust a system [18]. Arduino R4 Wi-Fi uses a controller and integration system for smartphones via Wi-Fi. Four load cell sensors are used to measure the lift and drag forces, and the sensor read uses HX711. The system also has an angle of attack controller to set the desired airfoil angle of attack without manually changing the airfoil setting. The system is then validated using spring balance to ensure that the reading is correct.

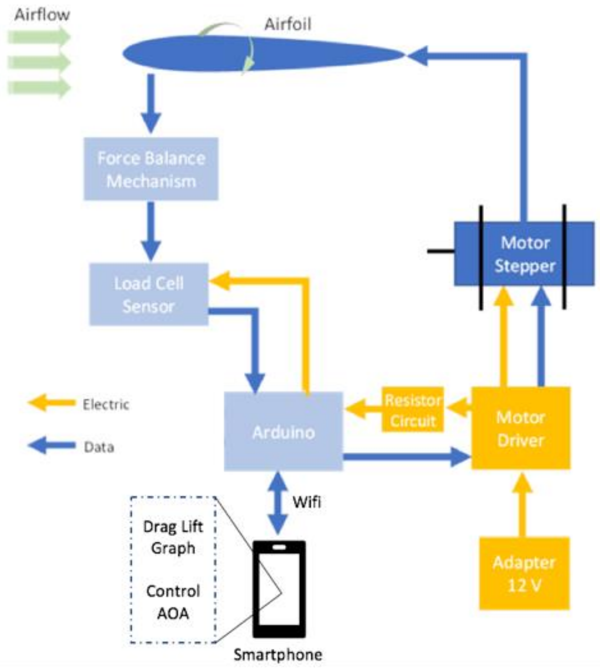

Figure 2. Block Diagram

The block diagram of the Arduino-based wind tunnel force balance system is shown in Figure 2. The load cell sensor measures the lift and drag forces from the airfoil. The sensor sends the measurement data to the Arduino to be processed and then sent to the IOT cloud Arduino and integrated into the smartphone to show graphs of measured lift and drag forces in N. The number of factors that affect the weight difference between digital scales and scales is very significant conventional [19]. Users can set the airfoil angle of attack using a smartphone control. Arduino reads the user input from the control smartphone and transfers it to the motor driver TB6600. The motor driver then actuates the motor stepper NEMA 17 to rotate the airfoil according to the angle of attack set by the user. Changes in lift and drag forces due to the angle of attack change are automatically sensed by the load cell and directly shown in the smartphone.

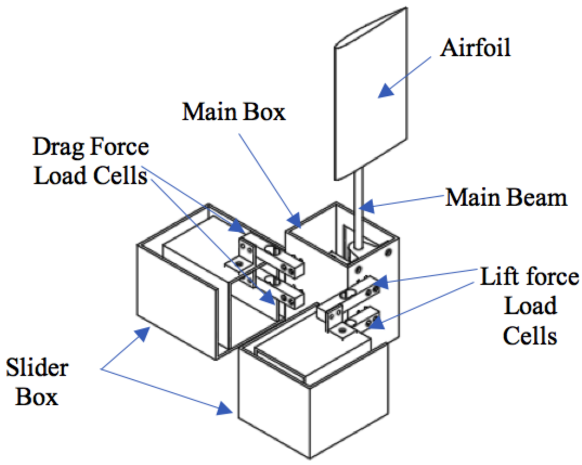

Figure 3. Force Balance Mechanism

The force balance mechanism is the central system that determines the reading of the lift and drag forces. Figure 3. shows the design of the force balance mechanism. The figure shows that the airfoil is mounted vertically on the top part of the force balance main beam. Installing an airfoil in a vertical position means that the lift and drag are measured in the horizontal plane. Thus, the weight of the system does not interfere with the load cell's reading of the lift and drag forces. The device detects the load, and the sensor will automatically read and send a signal. Then, the weight of the load will be displayed [20]. Several rollers are attached at the bottom of the main box, aiming to support the system's weight. A block bearing connects the main beam to the main box to freely rotate its axis. The rotation of the main beam determines the airfoil angle of attack. To control its rotation, a rubber belt connects the motor stepper to the main beam. Belts connect the wheel's gear to the reduction gear of the drive motor [21]. The motor rotation must use a belt to connect to the shaft to provide smooth rotation of the airfoil when controlled. The load cells are bolted to the main box and slider box. The slider box ensures the load cells react in only one direction of the force. Two parameters mainly describe a compliant structure: saltiness and admissible stroke. Stiness describes the force-to-displacement ratio. In the case of force sensing, it is related to the ultimate sensitivity of the load cell [22]. The load cell is a strain gauge that implements the "Jembatan Wheatstone" concept. Four resistors in "Jembatan Wheatstone "circuits with an excitation voltage applied across it [23]. One of the resistive components is the strain gauge, which has unknown resistance depending on the strain occurring in the indicator. If the resistive component is balanced, the output voltage is zero. When there is load, the strain gauge is deformed, leading to the gauge resistance change. Any shift in gauge resistance makes the bridge unstable, and the output voltage is not zero. One strain is found, it can be converted into the value of force applied to the sensor.

2.2 Electrical System Design

The electrical system is designed to read the airfoil lift and drag forces and control the airfoil angle of attack. The wiring diagram of the electrical system is presented in Figure 4. The chart shows that the load cell sensors are the primary sensors that read the lift and drag forces. This system uses four sensors, 2 sensors to measure lift force and two for drag force measurement. The rotary motor stepper is employed in the system to set the angle of attack. Users can set the angle of attack step by rotating the potentiometer, then press the left and right buttons to rotate the motor stepper. This stepper motor only produces rotational motion, whereas making a machining system requires rotational motion and translational motion [24]. There is a reset button to reset the airfoil position to zero without pressing the right or left button to rotate back the airfoil. The motor stepper can rotate the airfoil in the angle of attack range between -20° and +20°. The forces measurement and airfoil angle of attack are shown in the 12x6 cm LCD. The accuracy of the output voltage of the prototype power supply according to the setting voltage showed promising results, so all functions work [25].

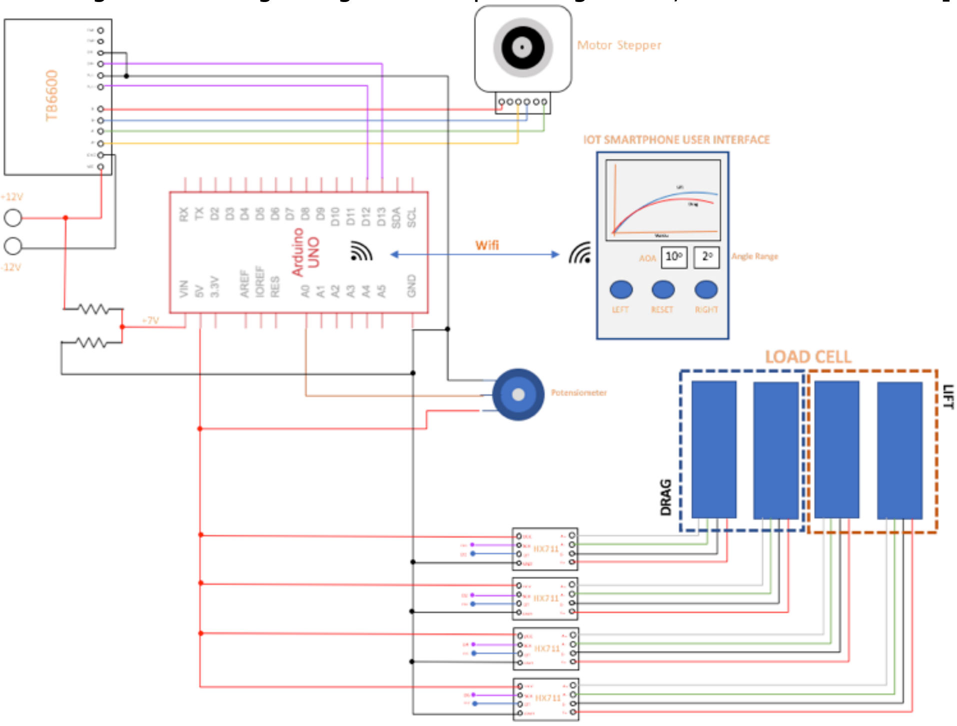

Figure 4. Wiring Diagram

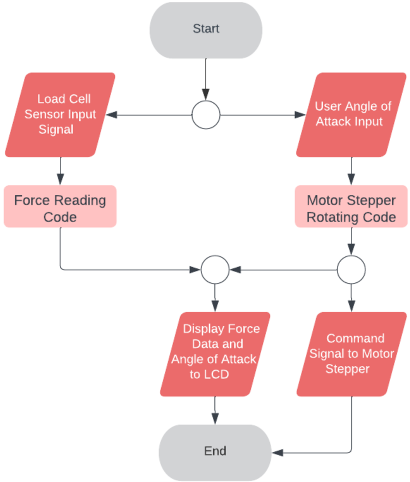

Figure 5. Arduino Program Design

The Arduino is programmed using a language similar to C++ language programming [16]. The general flowchart of the Arduino program for this force balance system is shown in Figure 5. The flowchart can be divided into two main parts: the first is to read the airfoil lift and drag forces, and the second is to set the airfoil angle of attack. Arduino receives signals from 4 load cell sensors. The signal is used as an input for force reading code. This code mainly processes the signal into the lift and drag forces in the N unit. The reading is displayed on the smartphone with a graph in real time. Users can input the desired angle of attack by pressing the available smartphone. Arduino processes the input signal and sends the command signal to the motor stepper. The motor stepper becomes the actuator to rotate the airfoil according to the specified angle of attack.

3. Result and Discussion

3.1 Results

Figure 6. shows the force balance mechanism that has been produced and assembled. The main bar is steel, while the glass fiber composite boxes are made. The motor stepper is positioned on the side of the main boxes. It is powered by 12V DC input [26]. The motor stepper mechanism adjusts the angle of the attack airfoil test because stepper motors are known for their precise control and accuracy. Motor steppers have 32 steps of micro-step control to produce smoother resonance and movement than smaller micro-steps. In addition, the current control of 1 A generates the best motor driver output with a lower-temperature motor [27].

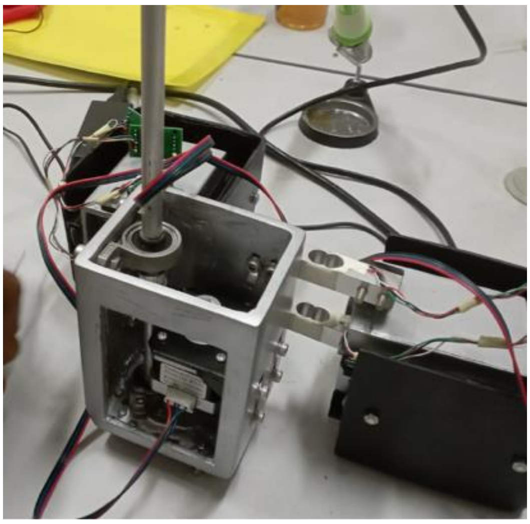

Figure 6. The Force Balance and Angle of Attack Control System Mechanism

To validate and check the reading of the overall system, the main bar is pulled with spring balance at five different angles. Figure 7. Shown user interface IOT in smartphone to controlled setting Attack of Angle Airfoil. Features in IOT smartphones are live graphs, kanan button, kiri button, reset button, angle, and step indicator. Live graph to see the lift and drag results received for the load cell sensor. The Kiri button controls the rotation of the left, and the Kanan button controls the rotation of the right airfoil. The reset button is airfoil rotation return to the starting point. The angle indicator shows the angle for airfoil rotation, and the step indicator shows the setting angle range for every step or rotation motor stepper.

Figure 7. User Interface IOT Smartphone

Figure 8. shows the diagram of the pulling force magnitudes and directions. In the figure, the spring forces are depicted with dotted arrow lines. Five directions of the forces are 0°, 30°, 45°, 60°, 90°, with the 0° coincides with lift direction and 90° coincides with drag direction. The magnitude of each force is the same, 1 kgF. If the reading is correct when the spring has pulled the system in a 0° direction, the lift reading is 1 kg, and the drag reading is 0 kg. Otherwise, when the pulling force is in the 90° direction, the lift should show 0 kgF, and the drag should show 1 kgF. The lift and drag readings in the other directions are the function of the cosine and sine of the angle. Determine the suitability of the angle set using a control system which is calibrated using an arc to determine the accuracy of the resulting angle.

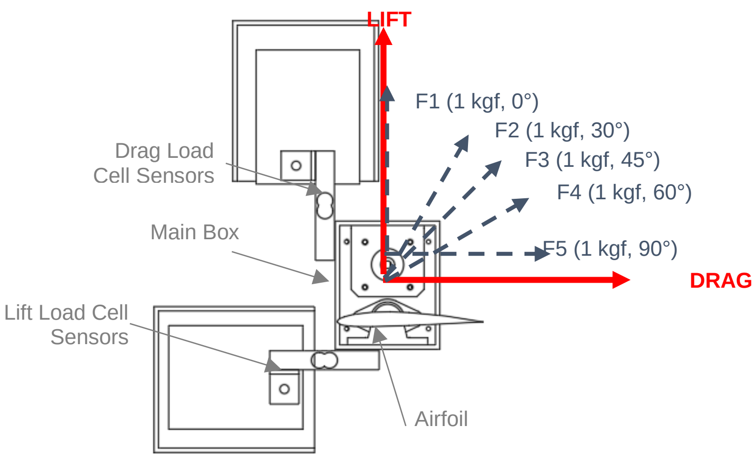

Figure 8. Spring Balance Pulling Force Angle (Top View)

Tests were carried out to determine the accuracy of the lift and drag values from sensor readings from 4 load cells with a slider box mechanism. The movement of the slider box given the load must be by the results of the lift and drag values of equations (1) and (2) by minimizing the error obtained. Table 1. shows the tolerance errors obtained when using the force measurement system obtained on airfoils given quantities of 1, 1.5, 2, 2.5, and 3.

Table 1. Results Lift and Drag

			Theoretical		Force Measurement		Error	
Force	Magnitude (kgF)	Angle (deg)	Lift (kgF)	Drag (kgF)	Lift (kgF)	Drag (kgF)	Lift (%)	Drag (%)
F1	1	0	1.000	0	0.989	0	1	0
F2	1	30	0.154	-0.988	0.149	-0.958	3	3
F3	1	45	0.525	0.851	0.519	0.832	1	2
F4	1	60	-0.952	-0.305	-0.931	-0.298	2	2
F5	1	90	-0.448	0.894	-0.438	0.874	2	2
			Theoretical		Force Measurement		Error	
Force	Magnitude (kgF)	Angle (deg)	Lift (kgF)	Drag (kgF)	Lift (kgF)	Drag (kgF)	Lift (%)	Drag (%)
F1	1.5	0	1.500	0	1.477	0	2	0
F2	1.5	30	0.231	-1.482	0.231	-1.420	3	4
F3	1.5	45	0.788	1.276	0.762	1.245	3	2
F4	1.5	60	-1.429	-0.457	-1.395	-0.439	2	4
F5	1.5	90	-0,672	1.341	-0.653	1.296	3	3
			Theoretical		Force Measurement		Error	
Force	Magnitude (kgF)	Angle (deg)	Lift (kgF)	Drag (kgF)	Lift (kgF)	Drag (kgF)	Lift (%)	Drag (%)
F1	2	0	2.000	0	1.931	0	3	0
F2	2	30	0.309	-1.976	0.299	-1.923	3	3
F3	2	45	1.105	1.702	1.032	1.656	2	3
F4	2	60	-1.905	-0.601	-1.849	-0.588	3	4
F5	2	90	-0.896	1.788	-0.872	1.755	3	2
			Theoretical		Force Measurement		Error	
Force	Magnitude (kgF)	Angle (deg)	Lift (kgF)	Drag (kgF)	Lift (kgF)	Drag (kgF)	Lift (%)	Drag (%)
F1	2.5	0	2.500	0	2.455	0	2	0
F2	2.5	30	0.386	-2.470	0.378	-2.392	2	3
F3	2.5	45	1.313	2.127	1.292	2.046	2	4
F4	2.5	60	-2.381	-0.762	-2.300	-0.721	3	5
F5	2.5	90	-1.120	2.235	-1.093	2.148	2	4
			Theoretical		Force Measurement		Error	
Force	Magnitude (kgF)	Angle (deg)	Lift (kgF)	Drag (kgF)	Lift (kgF)	Drag (kgF)	Lift (%)	Drag (%)
F1	3	0	3.000	0	2.455	0	2	0
F2	3	30	0.463	-2.964	0.448	-2.892	3	2
F3	3	45	1.576	2.553	1.543	2.483	2	3
F4	3	60	-2.857	-0.914	-2.803	-0.880	2	4
F5	3	90	-1.344	2.682	-1.299	2.628	3	2

Show the reading of the t results by spring balance and ensure that the stepper shows a correct angle of attack. The reading of the system is validated using a spring balance that pulls the system with magnitudes of 1, 1.5, 2, 2.5, and 3 kgF in some pulling force angle. Testing is carried out to detect accuracy between theory and experimental results. Table 1 shows the percentage of error lift and drag tested. Force accuracies are not up to 5% for 15 testing test systems. They are shown in Figure 8. The result was drag and lift for 30 degrees with a magnitude of 1 kgF in IOT Cloud Arduino. Load cell adjustment to measure drag or lift in microseconds to result in balance.

Figure 9. Drag and Lift (30 Degrees).

3.2 Discussion

Implementing the force balance system with angle of attack control using Arduino iot technology represents a significant advancement in aerodynamic research and educational tool development. The system successfully measured lift and drag forces on the airfoil with reasonable accuracy, as indicated by the average error of 2% compared to theoretical values. This achievement highlights the system's reliability in capturing aerodynamic parameters crucial for aircraft design and engineering applications. One of the notable contributions of this study is the utilization of load cell sensors combined with Arduino microcontroller technology. This integration enhances the accuracy of force measurement and allows for real-time data processing and analysis. The ability to remotely control the angle of attack via a smartphone interface further demonstrates the system's versatility and accessibility, making it suitable for educational purposes and practical experimentation in low subsonic wind tunnel environments. The validation tests conducted using spring balance confirmed the system's reliability across different force magnitudes and angles, with errors consistently below 5%. These findings underscore the robustness of the force balance mechanism and its suitability for a wide range of experimental conditions. However, it is essential to note that minor adjustments, such as optimizing load cell positioning and motor stepper calibration, may further enhance measurement accuracy and system performance.

From an academic standpoint, this research contributes to the ongoing discourse on aerodynamic measurement techniques and instrumentation development. By addressing the limitations of manual force balance systems and traditional wind tunnel testing methods, the proposed system offers a more efficient and precise means of gathering aerodynamic data. Moreover, the open-source nature of Arduino-based platforms facilitates knowledge sharing and collaboration within the scientific community, fostering innovation and continuous improvement in experimental methodologies. In practical terms, the developed force balance system holds considerable promise for aerospace engineering research, aircraft design validation, and educational initiatives. Its affordability, ease of use, and customizable features make it an attractive option for academic institutions, research laboratories, and engineering enthusiasts seeking to explore aerodynamics in controlled experimental settings.

Furthermore, integrating IoT capabilities enables remote monitoring and data visualization, expanding opportunities for collaborative research and educational outreach activities. The force balance system presented in this study represents a valuable tool for aerodynamic experimentation and learning. By leveraging modern sensor technology and microcontroller platforms, researchers and educators can enhance their understanding of aerodynamic principles and inspire future generations of engineers and scientists in aerospace engineering. Further refinement and validation of the system in diverse experimental scenarios will contribute to its broader adoption and impact in academic and industrial settings alike.

4. Related Work

Wind tunnels are essential for studying airflow's impact on the aerodynamic forces acting on model aircraft, making them indispensable in aeronautical research and development [1]. Understanding these forces is crucial for achieving stable flight conditions, enabling aircraft to maintain altitude and maneuver effectively [2]. Parameters such as lift force, drag force, and pitching moment are exciting in aerodynamic analysis, with the airfoil's cross-sectional shape playing a central role in determining these forces [3]. Experimental studies by Fernandez Lopez and Morales (2019) underscore the importance of wind tunnel experiments in quantifying lift and drag coefficients across various angles of attack and observing boundary layer behaviors [4]. Such investigations contribute significantly to understanding aerodynamic characteristics and aid in the design optimization of aerospace vehicles.

Furthermore, studies by Ma *et al*. (2022) emphasize the influence of the angle of attack on drag, highlighting the need for precise measurement techniques to capture subtle aerodynamic effects [5]. In wind tunnel experiments, accurate measurement of aerodynamic forces relies on force balance systems, which have evolved from manual mechanisms to more sophisticated designs. Feero *et al*. (2019) present a novel force balance capable of measuring low-magnitude mean aerodynamic forces with high precision, offering an improvement over traditional methods [8]. This shift towards advanced instrumentation reflects the growing demand for enhanced measurement accuracy and efficiency in aerodynamic research.

Recent developments in force balance technology have also spurred innovations in educational wind tunnels, catering to the needs of engineering students and researchers alike [14]. By integrating load cell sensors and Arduino microcontrollers, educational wind tunnel setups offer a cost-effective solution for hands-on learning and experimental validation [12][13]. These systems provide real-time data acquisition capabilities and enable automated control of airflow parameters, enhancing the educational experience and fostering a deeper understanding of aerodynamic principles. Moreover, integrating Arduino microcontrollers with novel mechanical linkage systems demonstrates the potential for further advancements in force measurement accuracy and reliability [15]. By combining sophisticated sensing technologies with robust control mechanisms, researchers can overcome the limitations of manual data collection methods and accelerate the pace of aerodynamic research. While automated wind tunnels remain costly and institution-specific [11], ongoing research efforts aim to democratize access to aerodynamic testing facilities and promote interdisciplinary collaboration in aerospace engineering education and research. By harnessing the power of innovative technologies and collaborative partnerships, the aerospace community can continue to push the boundaries of aerodynamic knowledge and pave the way for future advancements in flight technology.

5. Conclusion

The low subsonic wind tunnel force balance system with angle of attack controller is designed and assembled to measure the aerodynamic lift and drag forces of the airfoil. The system uses 2 load cell sensors to measure lift force and another 2 load cell sensors to measure drag force. Arduino is used as microcontroller to process the sensors reading and give command signal to motor stepper in order to set the airfoil position according to the user input angle of attack. The system shows good lift and drag forces measurement with the average error of 2 %. Suggestion from research, the load cell must be positioned correctly so that the sensor reading error can be increased again. The stepper motor must be turned off the bottom shaft to prevent the airfoil from rotating.

Acknowledgments
Authors would like to thanks Indonesian Ministry of Education, Culture, Research and Technology for funding this research through *Penelitian Dosen Pemula* Program.

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