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Abstract: The force balance system is used whitestone bridge concept to read the airfoil aerodynamic lift and drag forces while also have a function to control the airfoil angle of attack. It is designed to be used in low subsonic wind tunnel, especially for educational purposes. The system uses Arduino as the microcontroller to read the forces data from the load cell sensors and gives command to the rotary motor stepper to change the airfoil angle of attack. Arduino is combined with novel mechanical linkage system that is designed and studied to ensure the sensors be able to read correct airfoil lift and drag forces. Angle of attack controlled with smartphone to decide degress airfoil. The reading of the system is validated using spring balance that pulls the system with magnitude of 1,1.5, 2, 2.5, and 3 kgf in some angle of pulling forces. The results show that the reading of the system have good accuracy compared to the theoretical results with average error of 2 %.

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

1. Introduction

Wind Tunnel is a tool used to study the effect of the airflow on the aerodynamic forces acting on the model. For aeronautical applications, wind tunnel is important tool for the design and development of any aircraft (Renneboog, 2023). This reaction force will make the aircraft able to fly at a certain flying speed (Yopiandi et al., 2020). 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 (Soler Manuel, 2014). The ability to predict the magnitude of airfoil aerodynamic forces is very important, especially in the development stages of various technological products, such as aircraft, drones, wind turbines, bridge, and various land vehicles. Fernandez Lopez, et al use wind tunnel to perform an experiment in measuring the lift and drag coefficients with respect to the angle of attack, also observe the boundary layer separation around the airfoil (Lopez Fernandez & Morales, 2019). The angle-of-attack is less than 20^o, the increase of angle-of-attack will increase the drag(Ma et al., 2022). 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 an important role in the accuracy of the measurements (Oruganti & Narsipur, 2021). The curve of lift coefficient 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 (Akbar, 2020). This study shows some capabilities of wind tunnel to obtain the aerodynamic characteristics of a body.

Some wind tunnels use manual mechanism to measure the aerodynamic forces and moments of the airfoil as well as setting the airfoil angle of attack position. A novel force balance is developed for the measurement of low-magnitude mean aerodynamic forces (Feero et al., 2019). One common instrument that can directly measures aerodynamic forces and moments in wind tunnel is the force balance. The force balance can be in the form of a bar placed on top of a fulcrum with one end connected to the airfoil and the other end is connected 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 there is an airflow inside the tunnel and this causes the bar unbalance. Additional weight needs to be added to re-balance the bar. This additional weight is equal to the lift force generated by the airfoil, so lift force on the airfoil obtained by integration of the measured pressure distribution over the airfoil surface (Nandini et al., 2018). The lift force gets higher when the relative angle between airfoil and the airflow, so called the angle of attack, is higher. To measure the change of lift force due to 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 current angle of attack. The accuracy of using manual setting in the wind tunnel test is dependent on the operator ability to re-balance the force balance bar and to set the angle of attack for each step. The type of airfoil greatly affects the flying quality of an aircraft because it has a different geometric shape for each type so that it will produce different lift and drag (Wijaya & Adiwidodo, 2022). Different operator may lead to different level of accuracy. Manual setting and data collection cause the time required for wind tunnel testing are getting longer. The data collection can be carried out when the air flow 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 long time just to obtain one aerodynamic lift curve. In addition, automated and commercial wind tunnels are generally expensive and specific to certain agencies or institutions (Matsuo Yuichi, n.d.).

Some researches have been conducted in the area of measuring the airfoil aerodynamic forces. Milan Tomin (Tomin et al., 2020) conducts research about designing the force balance to obtain aerodynamic lift, drag, and pitching moment of the airfoil. The system uses three load cells and electronics that is hosted under the test section to minimize interference with the airflow. The system is able to collect the lift, drag, and pitching moment coefficients for some angle of attacks. Asutosh Boro (Boro, 2017) design the lift and drag measurement system that is tested at various velocities and angle of attacks. The experimental coefficients of lift and drag is compared with literature values. The system has good accuracy in predicting lift forces, but there 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 tunnel can also be used for educational purposes, as a teaching aid to increase student understanding of aerodynamic phenomena. Morris, et al (Morris, 2010) designs a force balance to be used in educational wind tunnels. The system uses two load cells, one to measure lift and the other is used to measure drag. A linear actuator is implemented in the system to change the angle of attack. The design is suitable for educational 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 actuator to change the airfoil angle of attack is studied in this research. Arduino is used as the microcontroller that reads the forces data from the sensor and commands the actuator to change the angle of attack. Arduino is common microcontroller to be used by researcher either for wind tunnel force balance purposes (Boro, 2017; Tintoré, n.d.; Tomin et al., 2020)or measuring the airspeed inside the wind tunnel (Junaidin et al., 2022). In this research, Arduino is combined with novel mechanical linkage system that is designed and studied to ensure the sensors be able to read correct airfoil lift and drag forces.

2. Research Method

The force measuring tool uses a free mechanism to measure drag and lift using a load cell sensor. 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. 4 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 magnitude having been adjusted. The drag and lift results will be compared theoretically and with experiments carried out to determine the error tolerance below 5%.

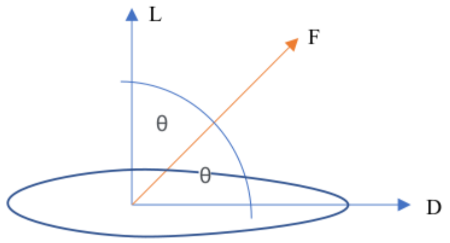

Figure 1. Drag and Lift Vector

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

$$D = F \cdot \cos\theta \tag{1}$$
$$L = F \cdot \sin\theta \tag{2}$$

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

The control system is used to adjust the angle of attack when the airfoil is tested. Developed an attack angle gauge based on modern devices that provides increased accuracy and reliability (Zadirienko et al., 2019). Angle settings can be done with 4 functions, namely: Counter Clockwise (CCW), Clockwise (CW), Reset (R), and Range Angle. The angle of attack has been determined at -24° to 24° with an angle range of 2°. The settings are processed with an Arduino microcontroller which has been programmed to carry out the 4 functions above.

2.1 System Design

The measurement of lift and drag in the low subsonic wind tunnel can be done utilizing load cell instead of using manual balance. The design and development of system to measure lift and drag forces that consists of force balance mechanism and electrical components become the main focus in this research. Arduino Uno is used as the main microcontroller in the control system. The control system is a tool (a parts of tools) to control and adjust of a system(Habib Patonra et al., 2020). Four load cell sensors are used to measure the lift and drag forces. The system also has angle of attack controller to set the desired airfoil angle of attack without manually change the airfoil setting. The system is then validated using spring balance to ensure that the reading is correct.

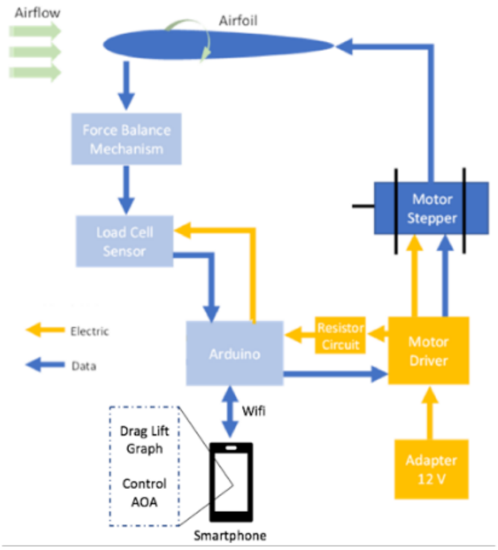

Figure 2. Block Diagram

The block diagram of Arduino-based wind tunnel force balance system is shown in Figure 2. The lift and drag forces from airfoil are measured by the load cell sensor. The sensor sends the measurement data to the Arduino to be processed and then send to the IOT cloud and integrated in smartphone to show graph measured lift and drag forces in N. The number of factors that affect the weight difference between digital scales and scales very significant conventional (Jawab et al., 2019). User can set the airfoil angle of attack using the control with smartphone. Arduino read the user input from control smartphone and transfer it to the motor driver. The motor driver then actuates the motor stepper to rotate the airfoil according to the angle of attack set by user. Change in lift and drag forces due to angle of attack change are automatically sensed by the load cell and directly shown in the smartphone.

2.2 Force Balance Mechanism

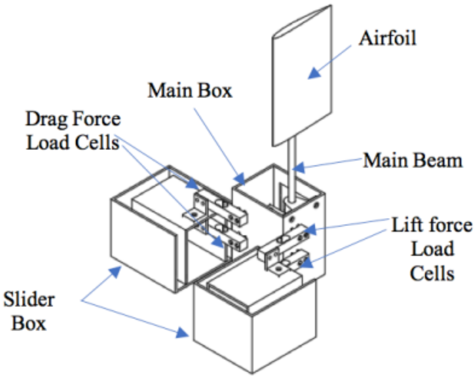

Figure 2. Force Balance Mechanism

The force balance mechanism is the main system that determines the reading of the lift and drag forces. Figure 3**.** shows the design of the force balance mechanism. As shown in the figure, the airfoil is mounted vertically on the top part of the force balance main beam. The installation of airfoil in vertical position means that the lift and drag is measured in horizontal plane, thus the weight of the system does not interfere the reading of the lift and drag forces by the load cell. Device detects load, the sensor will automatically read and send a signal then weight of a load will be display(Sam et al., 2020). There are several rollers attached at the bottom part of the main box which aim to support the weight of the system. The main beam is connected to the main box by block bearing, so that the main beam can freely rotate in its axis. The rotation of main beam determines the airfoil angle of attack. Motor stepper is connected to the main beam by rubber belt to control the rotation of beam. Belts are used to connect the wheels gear to the reduction gear of the drive motor(Sindak Hutauruk et al., 2021). The load cells are bolted to the main box and slider box. Slider box ensures the load cells to react only one direction of force. Two parameters mainly describe a compliant structure: stiffness and admissible stroke. Stiffness describes the force to displacement ratio. In the case of force sensing, it is related to the ultimate sensitivity of the load cell (Smreczak et al., 2021). The load cell basically is a strain gauge that implements Wheatstone Bridge concept. Four resistors in the Wheatstone Bridge circuits with an excitation voltage applied accros it (Al-Dahiree et al., 2022). One of the resistive components is the strain gauge that has unknown resistance depends on the strain occurred in the gauge. If the resistive component is balance, the output voltage is zero. When there is load, the strain gauge is deformed that leads to the change in the gauge resistance. Any change in gauge resistance gives the bridge unstable and the output voltage is not zero. Once strain is found, it can be converted into value of force applied to the sensor.

2.3 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. As shown in the diagram, the load cell sensors are the main sensor to read the lift and drag forces. This system uses 4 sensors, in which 2 sensors to measure lift force and 2 sensors for drag force measurement. The rotary motor stepper is employed in the system to set the angle of attack. User can set the angle of attack step by rotating the potentiometer, then press the left and right button to rotate the motor stepper. This stepper motor only produces rotational motion, where as to make a machining system not only requires rotational motion, but also uses translational motion (Suryati, 2019). There is reset button to reset the airfoil position to zero without pressing the right or left button to rotate back the airfoil. Motor stepper is able to rotate the airfoil in angle of attack range between -20° until +20°. The forces measurement and airfoil angle of attack is shown in the 12x6 cm LCD display. The accuracy of the output voltage of the prototype power supply according to the setting voltage showed good results, so all functions work (Nurlana et al., 2019) .

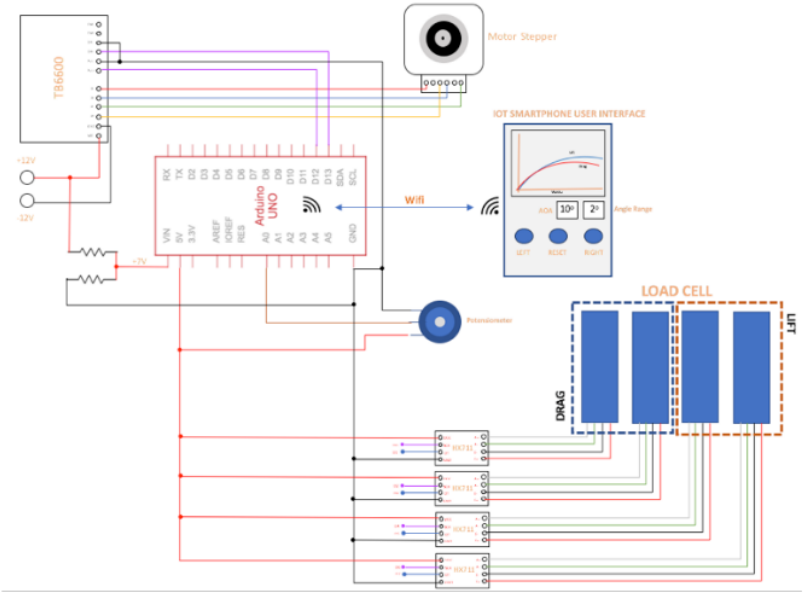

Figure 4. Wiring Diagram

2.4 Arduino Program Design

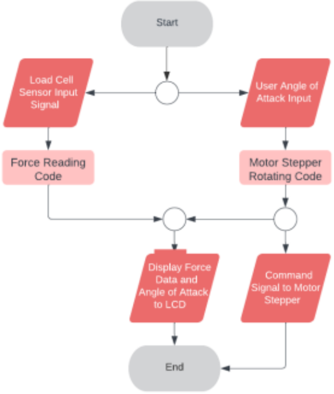

Figure 5. Arduino Program Design

The Arduino is programmed using language similar to C++ language programming (Junaidin et al., 2022). The general flowchart of the Arduino program for this force balance system is as shown in Figure 5. The flowchart can be divided into 2 main parts, first part is to read the airfoil lift and drag forces and the second part is to set the airfoil angle of attack. Arduino receives signal from 4 load cell sensors. The signal is used as an input for force reading code. This code mainly processes the signal into lift and drag forces in N unit. The reading is displayed in the smartphone with graph realtime . User can give input of desired angle of attack by pressing the available smartphone. The input signal is processed by Arduino and then command signal is sent 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

Figure 6. shows the force balance mechanism that have been produced and assembled. The main bar is made from steel, while boxes are made using glass fiber composite. Motor stepper is positioned on the side of the main boxes. It is powered by 12V DC input (Dadi et al., 2021). Motor stepper mechanism to adjust angle of attack airfoil test because Stepper motors are known for their precise control and accuracy. Motor stepper have 32 steps of micro-step control 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 (Khairudin et al., 2020) .

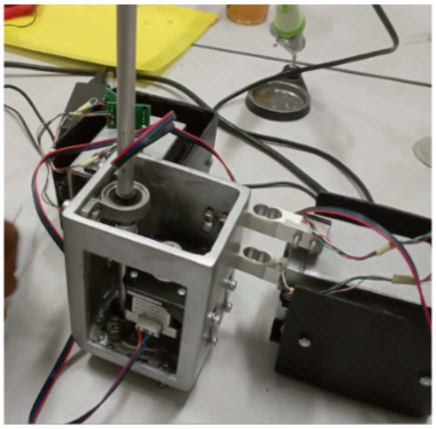

Figure 6. The Force Balance and Angle of Attack Control System Mechanism

To validate and check the reading of the overall system, the main bar is pulled with spring balance in 5 different angles. Figure 7. 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. It means that if the reading is correct, when the spring is pulled the system in 0° direction, the lift reading is 1 kgf and drag reading is 0 kgf. Otherwise, when pulling force is in 90° direction, the lift should show 0 kgf and drag shows 1 kgf. The lift and drag reading on the other directions are the function of 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.

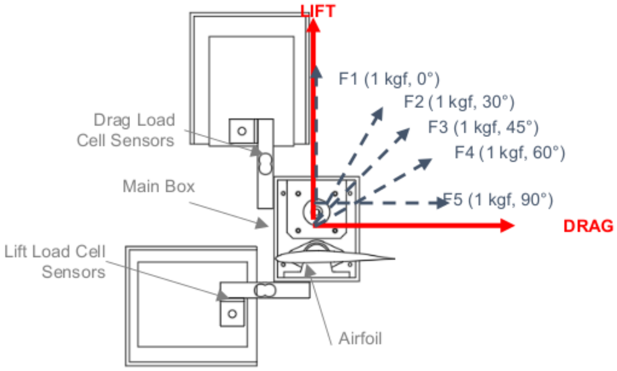

Figure 7. Spring Balance Pulling Force Angle (Top View*)*

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 in accordance with 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

Force	Magnitude (kgf)	Angle (deg)	Theoretical		Force Measurement		Error	
			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
Force	Magnitude (kgf)	Angle (deg)	Theoretical		Force Measurement		Error	
			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
Force	Magnitude (kgf)	Angle (deg)	Theoretical		Force Measurement		Error	
			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
Force	Magnitude (kgf)	Angle (deg)	Theoretical		Force Measurement		Error	
			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
Force	Magnitude (kgf)	Angle (deg)	Theoretical		Force Measurement		Error	
			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 results of reading test by spring balance and ensure that the stepper shows correct angle of attack. The reading of the system is validated using spring balance that pulls the system with magnitude of 1, 1.5, 2, 2.5, and 3 kgf in some angle of pulling forces. Testing is carried out to detect accuracy between theory and experimental results. Table 1. shows percentage error lift and drag have been testing. Force accuracies are not up to 5% for 15 testing test system. Shown Figure 9. Error detection accuracies only 3% between drag and lift (T and F) at 30 degrees with magnitude 1kgf.

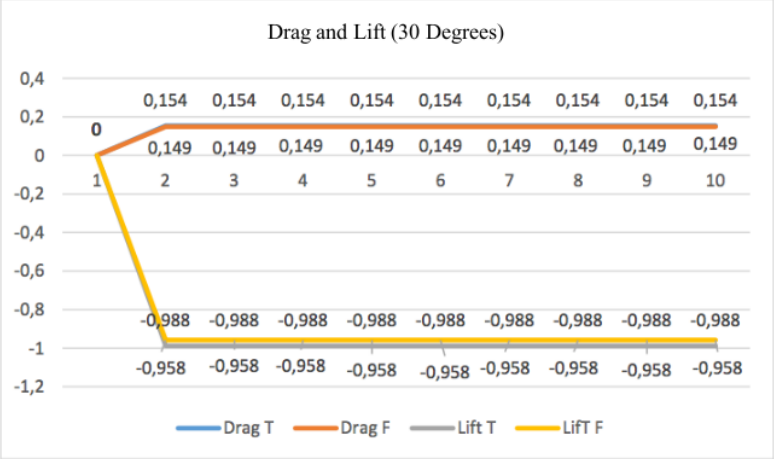

Figure 3 Drag and Lift (30 degrees)

4. 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 %.

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