Advancements in Microcontroller Technology for Wind Speed Measurement in Wind Tunnels

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2023 International Conference on Electrical and Information Technology (IEIT) | 979-8-3503-2729-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/IEIT59852.2023.10335512

***Abstract*—The wind speed gauge is essential in wind tunnel airflow simulations to accurately replicate real-world conditions. Traditional methods for measuring wind speed involve using a manometer with red fluid, which generates analog data. However, due to the expense and unavailability of the red manometer fluid in Indonesia, wind tunnels that still rely on manometers face a challenge. To overcome this, a new wind speed measuring instrument has been developed using easily obtainable materials and microcontroller technology. The instrument's design involved hardware, software, and system design stages, utilizing an Arduino Uno R3 microcontroller, a differential pressure sensor MPXV7002DP, and an LCD. This wind speed gauge is based on Bernoulli's principle, which uses a pitot tube to measure wind speed up to 25m/s, and displays the results on the LCD screen. To ensure its accuracy, the instrument was compared to a calibrated anemometer, confirming its suitability for measuring wind speed in low subsonic wind tunnels.**

Keywords—wind speed gauge, microcontroller technology, Bernoulli's principle, pitot tube.

I. INTRODUCTION

Wind tunnel is a tool used in aerodynamics research to study the effects of air movement passing through a solid object. Wind tunnels are critical equipment for studying aerodynamics, such as the flow of air or gas passing through a test object such as vehicles, buildings, wind turbines, and so on. Wind tunnels are typically used to simulate the conditions of airflow passing through a test model [1]. They are the most widely used experimental testing facilities. Aircraft scale models or components, such as wings, are used in wind tunnel tests in the field of aviation. An aerodynamic force balance is a common instrument found in wind tunnels because forces and moments are general parameters measured in wind tunnel testing [2]. Additionally, other supporting instruments such as wind speed, temperature, and pressure gauges are necessary equipment in wind tunnel testing. Wind speed measurement in a wind tunnel plays an important role in simulating airflow so that it is similar to the desired real conditions. The wind speed meter in wind tunnels still largely uses a special liquid manometer, and the resulting data is analog. The special manometer fluid (red manometer fluid) is difficult to obtain and expensive in Indonesia, making it a challenge for wind tunnels still using manometers. Therefore, a new wind speed measuring tool needs to be created that is easy to use and utilizes easily available materials while still applying the same measurement principles as the manometer in measuring wind speed in wind tunnels.

There are several types of wind tunnels divided into two main categories: open circuit and closed circuit wind tunnels. In an open circuit wind tunnel, there is no circulation of airflow, but the airflow entering the wind tunnel comes from an open area and exits back to an open area. In contrast, in a closed circuit wind tunnel, there is airflow circulation with little or no exchange of air with the surrounding environment [3]. In this study, the wind tunnel category is an open circuit wind tunnel with low subsonic speed.

In measuring wind speed, a static pitot tube is commonly used as a speedometer along the longitudinal axis of an airplane [4]. The pitot tube measures wind speed based on Bernoulli's equation [5]. The pitot measures the difference between the total pressure and static pressure, or the dynamic pressure that describes the kinetic energy of a fluid per unit volume.

An anemometer is a tool used to measure wind speed. A good wind speed measurement tool should provide accurate results. There are various types of anemometers, the most common being the cup anemometer. A cup anemometer consists of several cups fixed to a central axis. Other types of anemometers include the hot wire, which measures changes in temperature of an electrically heated wire passed through the wind, the pitot probe that uses the Bernoulli principle, and the propeller anemometer that uses a propeller to measure wind speed [6]. A microcontroller technology can be utilized to create a device for measuring wind speed. Comparable to a computer system, the microcontroller can be customized and configured to meet the specific requirements of the wind speed measuring tool.

The wind speed measuring tool based on Arduino microcontroller has been widely created and developed in several previous research studies [6,7,8,9,10,11,12]. However, most of them are the cup anemometer type, which adopts the measurement principle by utilizing the relationship between angular velocity and linear velocity using an optocoupler sensor, making its use limited to certain purposes. For the wind tunnel needs used in aviation, especially aerodynamics, the anemometer must adopt the Bernoulli principle that utilizes the pitot tube. The main goal of this research is to design a wind speed measuring instrument or

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anemometer as a replacement for the existing measuring tool in the wind tunnel. The anemometer created is based on Arduino, utilizing a pressure sensor connected to a Pitot tube that adopts the Bernoulli principle.

II. Design

Designing a wind speed measuring instrument is a complex process that requires careful planning and execution. The process typically involves three stages, each of which is critical to the success of the project. The first stage is the hardware design stage, where the physical components of the instrument are designed and assembled. The second stage is the software design stage, where the programming and coding of the instrument are developed. The third stage is the system design stage, where the hardware and software components are integrated and tested as a complete system.

A. Hardware Design

When designing a hardware component, it is essential to have a clear understanding of the system concept that it will be a part of. This helps in determining the necessary hardware requirements for the system to function properly. In the case of a wind speed measuring instrument, the system concept can be understood by referring to the block diagram shown in Fig. 1. The block diagram shows the various components of the system and how they are interconnected. It helps in visualizing the flow of data and signals between different parts of the system. By studying the block diagram, it becomes apparent that the hardware components required for the system include a microcontroller, a differential pressure sensor, and an LCD. However, it is worth noting that the pitot tube is not included as a hardware component in this system. This is because the pitot tube is not directly related to the system process. Instead, it is used to measure the pressure difference between two points in the system, which is then used to calculate the wind speed. Hence, the pitot tube is considered as an external component that is not directly integrated into the system.

To further clarify the hardware connection and layout, a hardware connection illustration is provided in Fig. 2. This illustration shows how the various hardware components are connected to each other and to the microcontroller. It provides a visual representation of the system's hardware components and their respective functions.

Overall, having a clear understanding of the system concept is crucial when designing hardware components. It helps in determining the necessary hardware requirements and ensures that the system functions optimally.

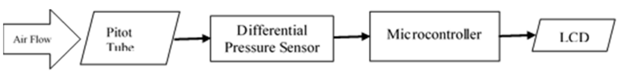

Fig. 1. Block diagram of a wind speed measuring system.

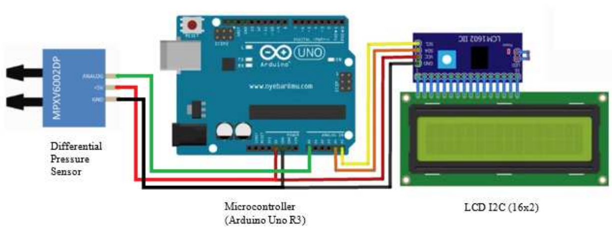

Fig. 2. Hardware connection illustration.

B. Software Design

The Arduino programming language is a simplified version of C++ that is specifically designed for use with Arduino microcontrollers. It is known for being easy to learn and use, making it accessible to beginners and experts alike. The software for the system is written using the Arduino programming language, and is designed to control the function of measuring wind speed. The programming process involves writing commands in the Arduino programming language that tell the microcontroller what to do. In this case, the commands are used to read data from a pressure difference sensor, which is used to calculate wind speed. The wind speed data is then displayed on an LCD screen, making it easy to read and understand.

The software workflow for the system is designed according to Fig. 3, which outlines the steps involved in measuring wind speed. The first step is to initialize the system and set up the necessary variables and pins. The next step is to read data from the pressure difference sensor and convert it into wind speed. This is done using a series of mathematical calculations that take into account the properties of the sensor and the environment. Once the wind speed data has been calculated, it is displayed on the LCD screen using a series of commands that control the display. The system then waits for a short period of time before repeating the process and measuring wind speed again. This loop continues until the system is turned off or the program is stopped.

Overall, the Arduino programming language and software workflow make it easy to control the function of measuring wind speed using an Arduino microcontroller. By following the steps outlined in Fig. 3, it is possible to create a reliable and accurate system for measuring wind speed in a variety of environments.

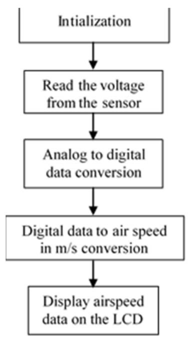

Fig. 3. Software workflow.

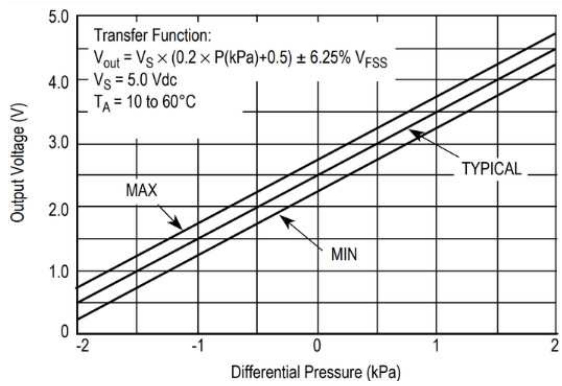

Fig. 4. Output versus pressure differential.

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C. System Design

The purpose of a wind speed measuring instrument is to accurately measure the speed of wind passing through a wind tunnel. To achieve this, a pitot tube is installed in the wind tunnel to measure the pressure of the air flowing through it. The pitot tube consists of two ports, the static port and the total port, which measure the pressure of the air at two different points. The differential pressure between these two points is measured using a differential pressure sensor, specifically the MPXV7002DP sensor. The MPXV7002DP sensor provides an analog voltage output that represents the pressure difference between the static and total ports. To calibrate the sensor, the relationship between the output voltage and the pressure difference is obtained from the product datasheet, which can be seen in Fig. 4.

The wind speed measuring instrument can measure wind speeds up to 50m/s, exceeding the wind tunnel's maximum speed of 25m/s, making it suitable for various applications beyond the wind tunnel.

The relationship between pressure difference and sensor output voltage in Fig. 4 can be expressed as (1).

$$V_r = \frac{V_s}{5}\Delta P + \frac{V_s}{2} \tag{1}$$

Where V_r is the output voltage of the sensor, V_s is the source voltage, and ΔP is the pressure difference. The output voltage of the sensor will be read by the microcontroller as an analog input which will then be converted to digital by an analog-to-digital converter (ADC) and converted again to a speed value using (2).

$$\upsilon = \sqrt{\frac{10000\cdot\left(\frac{R}{2^{10}-1}-0{,}5\right)}{\rho}} \tag{2}$$

Where υ is the velocity in m/s, ρ is the air density at the elevation of the measurement location in units of kg/m^3, and R is the digital data resulting from the ADC conversion. The velocity value calculated according to (2) is displayed on the LCD. The system diagram designed as shown in Fig. 5.

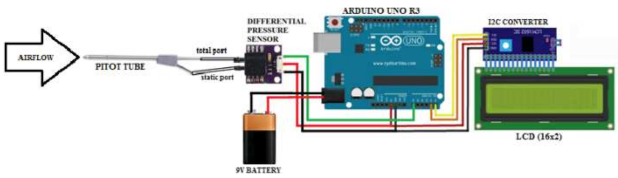

Fig. 5. The Schematic diagram of the system.

III. Results and Discussion

After the system design process is completed, the testing process is carried out to determine the performance of the built wind speed measuring instrument.

A. Instrument Testing

The testing process for the wind speed measuring instrument is a crucial step in the development and evaluation of the instrument's performance. The test is carried out in a low subsonic wind tunnel, as shown in Fig. 6, to ensure that the measurements obtained are accurate and reliable. During testing, varying the frequency inverter value enables the wind speed measuring instrument to obtain a range of wind speed values, ensuring accurate measurements across a wide range of speeds, which are then displayed on the LCD screen of the instrument. The displayed values are then compared with the results obtained from a calibrated factory measuring instrument to evaluate the accuracy and precision of the wind speed measuring instrument.

The LCD display on the wind speed measuring instrument provides a clear and concise representation of the measured wind speed values, making it easy to compare the results with those obtained from the calibrated factory measuring instrument. The LCD display, as shown in Fig.7, is designed to be user-friendly and intuitive, ensuring that the measured values can be easily understood and interpreted by the user.

Determination of wind speed values based on the operational requirements of low subsonic wind tunnels with minimum and maximum speed limits of 5 m/s up to 25 m/s, despite the wind speed measuring instrument that has been designed is capable of measuring wind speeds up to 50 m/s. The results of the wind speed measuring instrument testing that has been conducted are shown in Fig. 8. The test results show that the inverter frequency is directly proportional to the wind speed generated by the wind tunnel. The frequency of the inverter has a direct impact on the power supplied to the wind tunnel fan motor, which plays a critical role in producing the necessary airflow within the tunnel. As the inverter frequency increases, the input power to the fan motor also rises, thereby enhancing the motor's rotational speed and intensifying the airflow generated inside the wind tunnel.

Fig. 6. Low subsonic wind tunnel.

Fig. 7. The LCD display of wind speed measuring instrument.

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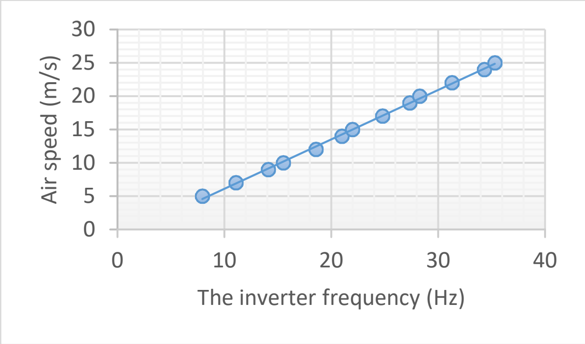

Fig. 8. The results of the wind speed measuring instrument testing.

B. Validation

To ensure the accuracy of the wind speed measuring instrument that was designed, it is crucial to validate its measurement results. This involves comparing the instrument's readings with those obtained from a calibrated measuring device to detect any deviation in instrument readings. For this purpose, commercial measuring device from manufacturers are ideal validation references as they have undergone calibration processes. In this study, a fan UT 363 anemometer from UNI-T was used as a reference for validation. The comparison of the test results was carried out by adjusting the inverter frequency value during the instrument testing to match the frequency value during the calibrated anemometer testing for the speed values being compared. The comparison results and deviation values are presented in TABLE I.

TABLE I. THE COMPARISON OF TEST RESULTS

Inverter Frequency	Test Results		
	Wind speed values read by the instrument	*Wind speed values read by calibrated anemometer*	*Deviation*
7.93	5	5	0
11.06	7	7	0
14.1	9	9	0
15.5	10	10	0
18.56	12	12	0
21	14	14	0
21.97	15	15	0
24.8	17	17	0
27.33	19	19	0
28.27	20	20	0
31.3	22	22	0
34.33	24	24	0
35.3	25	25	0

Based on the results presented in TABLE I, it can be concluded that the wind speed measuring instrument designed specifically for low subsonic wind tunnels is a reliable and accurate tool for measuring wind speed. The instrument provides precise readings, with no deviation observed in wind speed measurements when compared to the calibrated anemometer's results. The accuracy of the wind speed measuring instrument is based on the reference air density parameter used in the calculation, which is calibrated to the testing area's elevation and environmental conditions, such as temperature and pressure.

The wind speed measuring instrument's ability to consider the measurement environment is an advantage in obtaining more precise readings, providing a more comprehensive and accurate picture of the wind speed. However, this capability also poses a disadvantage since any change in the measurement location's elevation requires adjusting the air density parameter to the new location's environmental conditions. This adjustment is crucial to maintaining the instrument's accuracy, ensuring that the readings remain precise and reliable.

Furthermore, the accuracy of the wind speed measuring instrument is further enhanced by the sensor's ability to convert the pressure difference value from the pitot to the sensor output voltage accurately. The conversion is in accordance with the sensor manufacturer's reference, ensuring that the instrument's accuracy is not compromised. Overall, the wind speed measuring instrument's reliability, precision, and accuracy make it a valuable instrument for measuring wind speed in low subsonic wind tunnels..

IV. CONCLUSION

The research produced a wind speed measuring instrument that can be used to measure wind speed in low subsonic wind tunnels based on the Bernoulli principle, using a pitot tube. The microcontroller-based Arduino Uno R3 wind speed measuring device can display wind speed measurement results on an LCD screen in units of m/s. The wind speed instrument is considered valid for measuring wind speed because there is no deviation in wind speed measurements when compared to calibrated anemometer measurements. The precision in wind speed calculation owes to the precise determination of the reference air density parameter value utilized in the equation. Moreover, the conversion of the pitot pressure differential value to the sensor output voltage is carried out with precision in accordance with the manufacturer's reference. This meticulous approach ensures minimal deviation, guaranteeing reliable wind speed measurements.

ACKNOWLEDGMENT

I would like to extend my genuine appreciation to the Adisutjipto Institute of Aerospace Technology (ITDA) for providing me with laboratory facilities and for their invaluable support throughout the process of publishing my article.

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