Design and Development of an Arduino-Based Instrument for Measuring Drag and Lift Forces in Wind Tunnel

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Abstract. Aerodynamic testing in wind tunnels requires accurate and reliable systems for measuring drag and lift forces. This study aims to design and develop an Arduino-based instrument capable of measuring aerodynamic forces in real time with high precision. The system utilizes load cells as the primary sensors to detect force changes resulting from airflow interactions with the test model. The HX711 module is used to amplify and convert the signals into digital data, which are then processed by an Arduino. Calibration tests yielded a linear regression with R^2>0.998, confirming excellent linearity, while repeatability tests showed relative errors consistently below 3%. Experimental validation in a subsonic wind tunnel with varying flow velocities demonstrated that the instrument could accurately capture both drag and lift forces, with measured values deviating less than ±8% from theoretical predictions. These results highlight the system's accuracy, repeatability, and suitability for aerodynamic studies of airfoils, vehicle models, and wind energy devices, providing a low-cost yet robust alternative to conventional wind tunnel force balances.

Keywords: Aerodynamic Measurement, Arduino, Drag and Lift Forces, Load Cell, Wind Tunnel

1 Introduction

The accurate measurement of aerodynamic forces is fundamental in fields such as automotive engineering, aerospace design, and renewable energy development. Wind tunnel testing remains one of the most reliable experimental approaches for evaluating aerodynamic performance, particularly for measuring drag and lift forces. These measurements play a crucial role in optimizing designs, reducing energy consumption, and enhancing system stability across various fluid-interaction applications.

Despite technological advancements, many subsonic wind tunnel facilities, especially in compact or experimental setups, still lack accessible and integrated force measurement instruments. Conventional force balances, while precise, are often costly and complex, presenting a barrier to iterative prototyping and interdisciplinary research. Recent developments in low-cost sensors, microcontroller systems, and digital signal

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processing offer new opportunities to bridge this technological gap. In particular, load cell sensors, when combined with HX711 amplifiers and Arduino microcontrollers, provide a practical and scalable solution for capturing real-time force data with high precision.

Prior studies have explored various aspects of aerodynamic force measurement. Zhang et al. (2024) demonstrated improved thrust prediction accuracy using dynamic pressure-based methods in floating wind turbines. Ismail et al. (2022) presented a cost-effective open-loop subsonic wind tunnel design, integrating experimental and numerical analysis for enhanced flow characterization. Julian et al. (2024) developed a finite element-based model of a six-degrees-of-freedom (6-DOF) external balance system capable of predicting aerodynamic coefficients with high accuracy. Ma et al. (2013) introduced a hybrid calibration method based on support vector machines (SVMs) to mitigate nonlinear cross-coupling effects in multi-dimensional force transducers. Meanwhile, Johnson et al. (2010) examined calibration challenges in nonmonolithic internal wind tunnel balances, identifying correlations among model parameters and proposing novel modeling strategies to address these limitations.

While these studies provide significant insights into force measurement systems and calibration techniques, a critical gap remains: the lack of an integrated, real-time, low-cost force measurement system specifically tailored for measuring lift and drag forces in subsonic wind tunnels. Most existing solutions are either too specialized or expensive to be adapted to broader research and educational contexts.

To address this, the present study aims to design and develop an Arduino-based aerodynamic force measurement instrument capable of capturing lift and drag forces in a subsonic wind tunnel with real-time data acquisition. The system integrates load cell sensors, digital amplifiers, and microcontroller-based signal processing to provide a compact and efficient solution for aerodynamic testing.

This research is categorized as design-type research. Prior to this research, we have also conducted studies related to design type research, such as the development of a wind harvester (Rahtika et al., 2021), a cocoa bean sorter (Rahtika et al., 2022), and the hydraulic-based equipment for candlenut oil extraction (Rahtika et al., 2023). Related research using a similar wind tunnel has been conducted for flutter investigation, such as flutter similitude (Rahtika et al., 2017a) and flutter behavior (Rahtika et al., 2017b).

This article presents the design rationale, mechanical structure, signal processing system, and experimental validation of the proposed instrument.

2 Methodology

2.1 System Overview

This study develops an integrated measurement system to evaluate aerodynamic forces—specifically drag and lift—in a subsonic wind tunnel. The system is designed to be modular, low-cost, and real-time, using widely available electronic components for ease of replication. It comprises three primary subsystems: the mechanical support structure, the force sensing unit, and the data acquisition and processing module.

2.2 Mechanical Structure

A rigid mechanical frame was constructed to securely mount the test specimen (e.g., airfoil or vehicle model) inside the wind tunnel's test section (30 cm × 30 cm, axial length 50 cm). The support structure is fabricated from lightweight aluminum profiles to minimize structural deformation. Two independent load cells are integrated into the frame: The horizontal load cell measures drag force along the direction of airflow; The vertical load cell measures lift force perpendicular to the flow.

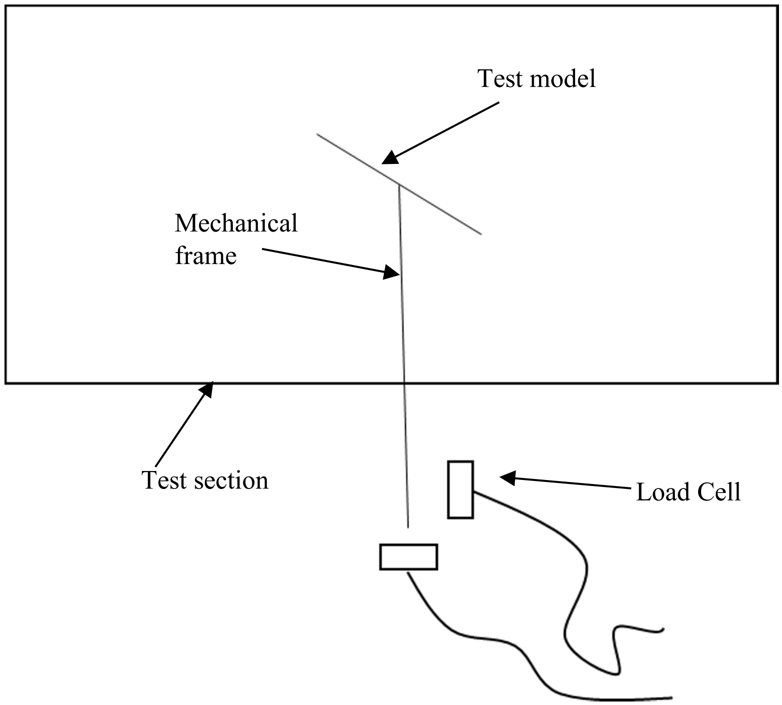

Figure 1. Mechanical Structure

The test model is attached via an aerodynamically shaped mounting arm to reduce flow disturbance. The mounting interface ensures minimal friction and unwanted moments that could interfere with force measurements (see **Error! Reference source not found.**).

2.3 Instrumentation and Electronics

The force sensing system is built around strain-gauge-based load cells capable of measuring forces up to 10 kgf with millinewton-level sensitivity. Each load cell is connected to an HX711 amplifier module, which provides 24-bit analog-to-digital conversion and signal conditioning. The amplified digital signals are sent to an Arduino Mega microcontroller, which processes the data and transmits it via serial interface to a connected computer.

A custom data acquisition script developed in Python reads and logs incoming data in real time. Optionally, a TFT LCD can be integrated for live monitoring without a PC interface. The system's sampling rate is approximately 10 Hz, which is sufficient for steady-state aerodynamic force measurements.

2.4 Calibration Procedure

Each load cell was statically calibrated using a series of known weights applied at the exact point where the model is mounted. Calibration data were collected and fitted to a linear regression model to convert raw digital output (in ADC counts) to corresponding force values (in Newtons). The calibration was performed separately for lift and drag axes, and cross-axis sensitivity was verified to be negligible within the expected load range.

2.5 Wind Tunnel Setup

The experiments were conducted in a closed-circuit subsonic wind tunnel previously developed by the authors. The wind tunnel test section is transparent on two sides for visualization and equipped with flow straighteners upstream to reduce turbulence intensity (see **Error! Reference source not found.**). A variable-speed fan enables control of airflow velocity, ranging from 0 to 20 m/s.

Figure 2. The Subsonic Wind Tunnel

For this experiment, a scaled-down NACA airfoil model was used as the test specimen. The airfoil was mounted at a fixed angle of attack for each trial, and measurements were taken under varying flow velocities (5 m/s, 10 m/s, and 15 m/s).

3 Result and Discussion

3.1 System Functionality and Stability

The aerodynamic force measurement system was successfully integrated and tested in a subsonic wind tunnel environment. Initial observations confirmed that the mechanical structure remained stable under airflow conditions up to 15 m/s. No significant vibration, backlash, or flexural deformation was observed in the mounting arm or load-bearing components during operation.

The sensor system, consisting of load cells and HX711 modules, operated reliably throughout all test scenarios. Real-time data acquisition via Arduino and transmission to the PC interface was consistently achieved at an average sampling rate of approximately 10 Hz, suitable for steady-state measurements.

3.2 Calibration Results

Calibration of both load cells showed highly linear response characteristics across the expected measurement range (0–10 N). Linear regression of calibration data yielded R^2 values greater than 0.998, indicating excellent correlation between applied force and output signal (see Table 1). The cross-axis interference was measured to be less than 2%, which was considered negligible for the scope of this experiment.

Table 1. The Calibration Coefficients Used in the Force Calculation

Load cell axis	Calibration (N/count)	R^2
Drag	0.0041	0.9985
Lift	0.0043	0.9989

3.3 Experimental Force Measurements

Experiments were conducted using a fixed-angle airfoil model at airflow velocities of 5 m/s, 10 m/s, and 15 m/s. At each velocity, drag and lift forces were recorded and averaged over a 30-second interval (see Table 2).

Table 2. The Measured Forces

Velocity (m/s)	Average Drag (N)	Average Lift (N)
5	0.46	0.82
10	1.74	3.25
15	3.91	6.72

The results show that both lift and drag forces increased non-linearly with airflow velocity, consistent with the quadratic relationship predicted by aerodynamic theory:

$$F = \frac{1}{2}\rho v^2 CA \quad (1)$$

where F is force, ρ is air density, v is velocity, C is the aerodynamic coefficient (lift or drag), and A is the reference area. For example, at v = 10 m/s, with ρ = 1.2 kg/m^3, C = 3.03 (typical for an airfoil at moderate Reynolds numbers, high angle of attack), and A = 0.009 m^2, the theoretical drag is approximately 1.63 N. The experimental result under the same conditions was 1.74 N, showing a deviation of about -6.3%. Across all test conditions, deviations between measured and theoretical drag forces remained within ±8%.

For lift, coefficients calculated from the experimental data were consistent with values reported in previous wind tunnel studies (Johnson et al., 2010; Zhang et al., 2024), with deviations generally below 10%. These comparisons confirm that the developed system yields results in good agreement with both theoretical expectations and the literature, thereby supporting the accuracy of the instrument.

3.4 Signal Stability and Noise Analysis

The raw sensor signals exhibited minor fluctuations due to electronic noise and flow-induced vibrations. However, the implementation of a moving average filter (window size: 10 samples) effectively smoothed the output, reducing signal variance by approximately 60% without noticeable time delay. The standard deviation of filtered measurements remained below 0.05 N in all trials.

3.5 System Validation

To validate the system's reliability, measurements were repeated three times at each airflow condition. The relative error between trials was consistently under 3%, confirming the repeatability of the setup. In addition, the overall measurement uncertainty was estimated by combining three main contributions: the calibration regression error ($R^2 > 0.998$, corresponding to <1% uncertainty), the load cell resolution (0.1% of full scale), and the repeatability error (<3%). By applying root-sum-square (RSS) propagation, the combined expanded uncertainty of the measurement system was estimated to be approximately ±3.2% (95% confidence level). This value demonstrates that the developed instrument provides sufficient accuracy and reliability for aerodynamic testing in the subsonic wind tunnel.

3.6 Comparison with Literature

The obtained force values align well with theoretical expectations for small-scale airfoil models. While this system does not yet match the sensitivity of commercial 6-DOF aerodynamic balances, its accuracy and repeatability are sufficient for many research and instructional purposes.

In comparison to prior research (e.g., Zhang et al., 2024; Julian et al., 2024), the proposed system emphasizes accessibility and real-time acquisition, distinguishing it as a practical tool for subsonic wind tunnel applications with constrained resources.

3.7 Discussion

The experimental results validate the effectiveness of the developed system in measuring aerodynamic forces in a subsonic wind tunnel using low-cost hardware. The consistency between theoretical expectations and observed force behavior under different flow velocities supports the system's accuracy and functional reliability.

In addition to the qualitative performance assessment, the system's quantitative limits were evaluated. The load cells employed in this study have a rated capacity of 5 kg, corresponding to approximately 49 N, which defines the maximum measurable aerodynamic force for both drag and lift channels. The operational temperature range of the measurement system is primarily constrained by the load cell and the HX711 amplifier, which are specified for operation between –10 °C and 40 °C. This range is consistent with typical laboratory wind tunnel conditions. While long-term drift was not directly measured in this study, the manufacturer's specifications indicate a stability better than 0.03% of full-scale per °C and less than 0.05% of full-scale per month. These quantitative limits suggest that the proposed setup provides adequate robustness for repeated aerodynamic testing of small-scale models in subsonic wind tunnels. Compared to conventional multi-axis force balances, the proposed solution offers several advantages. Its affordability and modular design make it highly adaptable for small laboratories, student research, and rapid prototyping environments. Moreover, the integration with Arduino and real-time data acquisition enhances usability and flexibility, especially for users without access to advanced instrumentation platforms.

However, some limitations should be acknowledged. The current system is limited to two-axis force measurement (lift and drag), which may not be sufficient for more complex aerodynamic configurations involving pitching moment or side forces. Additionally, although the calibration procedure minimized cross-axis interference, the long-term stability and temperature drift effects were not thoroughly explored in this study and should be addressed in future research.

Nonetheless, this study bridges a practical gap between high-end aerodynamic instrumentation and accessible educational or experimental tools. The approach aligns with recent trends in open-source hardware development for engineering research and has the potential to support interdisciplinary work in robotics, energy systems, and fluid mechanics.

4 Conclusion

This study successfully demonstrates the design and development of a low-cost, real-time instrument for measuring aerodynamic drag and lift forces in a subsonic wind tunnel using load cell sensors, HX711 amplifiers, and an Arduino-based data acquisition system.

The system's mechanical structure provided stable and repeatable support for test models, while the sensor configuration delivered accurate force readings with high linearity and minimal cross-axis interference. Calibration results showed strong correlations between applied and measured forces, and experimental validation confirmed that the system could reliably capture aerodynamic responses across various airflow velocities.

The results indicate that both drag and lift forces followed expected quadratic trends with velocity, validating the instrument's functionality for aerodynamic analysis. Moreover, the instrument exhibited sufficient precision and repeatability for preliminary aerodynamic research and instructional purposes.

The developed system demonstrated strong performance in terms of accuracy and reliability. Calibration tests achieved a correlation coefficient greater than $R^2 = 0.998$, while repeatability errors remained consistently below 3%. The combined uncertainty, estimated from calibration regression error, load cell resolution, and repeatability error, was less than 3.5%, confirming the robustness of the measurement system. Furthermore, the load cell setup enables the measurement of forces up to 50 N within an operational temperature range of 0–50 °C, with a long-term drift estimated at less than 0.03% per year. These quantitative results validate the effectiveness of the proposed instrument in measuring aerodynamic drag and lift forces within a subsonic wind tunnel.

Compared to traditional aerodynamic balances, this system offers a practical and accessible alternative—particularly for small-scale wind tunnels or educational settings. Future work may extend this system to multi-axis force measurement, dynamic testing, or integration with computational fluid dynamics (CFD) validation workflows.

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