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A Low-Cost, Adaptable System for Lift and Drag Measurement in an Educational Wind Tunnel

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Abstract

Wind tunnel testing augments the undergraduate fluid dynamics curriculum by providing hands-on application of the course material, and a low-cost version of a force balance is desirable. To maximize the utility of wind tunnel-based lessons and laboratory demonstrations, there is also a need for a setup that is easily adaptable to different tests and loading applications. This paper provides such a force balance design, along with detailed evaluation and benchmarking to characterize the accuracy of the force balance. Our force balance uses readily available materials having a total cost under \$125. Static load tests show that the force balance is accurate with a mean absolute percentage error of only 2.5%. We demonstrate the system's usefulness and adaptability with classic examples of measuring drag on a sphere and characterizing a NACA 0012 wing, as well as with measuring lift on a foldable wing. Finally, we pilot the force balance in an undergraduate mechanical engineering lab setting and find that students are able to explore the setup, understand the load cell functionality, and use the system to measure drag on a sphere. The force balance enables students to gain hands-on learning experience related to both fluid mechanics and statics, and our user study shows that the force balance is durable through classroom use. The low cost, robustness, and high adaptability of the system makes it suitable for incorporating in multiple labs or for allowing student project teams to utilize the system in their own experiments.

1 Introduction

Access to a wind tunnel enables students to gain real world experience with fluid dynamics concepts. This is beneficial in the fields of aerospace, civil, and mechanical engineering. To measure the aerodynamic loads in a wind tunnel, a force balance is additionally required. However, force balances are often expensive, costing tens of thousands of dollars, which has led to the development of low-cost alternatives that are about \$1000 [1] or less [2]. These low-cost force balances each claim to have an accuracy of $\pm 10\%$ on the coefficients of lift and drag [1, 2]. Our resulting force balance costs less than \$125, and our static loading tests show that the setup is able to achieve an accuracy of $\pm 8\%$ error, with a mean absolute percentage error of 2.5% compared to the ground truth value. Our force balance is also precise, with an average standard deviation of only 0.05 g for measurements at a given loading condition. We also provide a benchmark of measuring the drag on a sphere and find that the force balance can determine the coefficient of drag to within 4% of the theoretical value on average. Our design also allows for easy modification for different project test requirements. The fabrication files and instructions for using the force balance can be found at `https://sung.seas.upenn.edu/publications/wind-tunnel-force-balance/`.

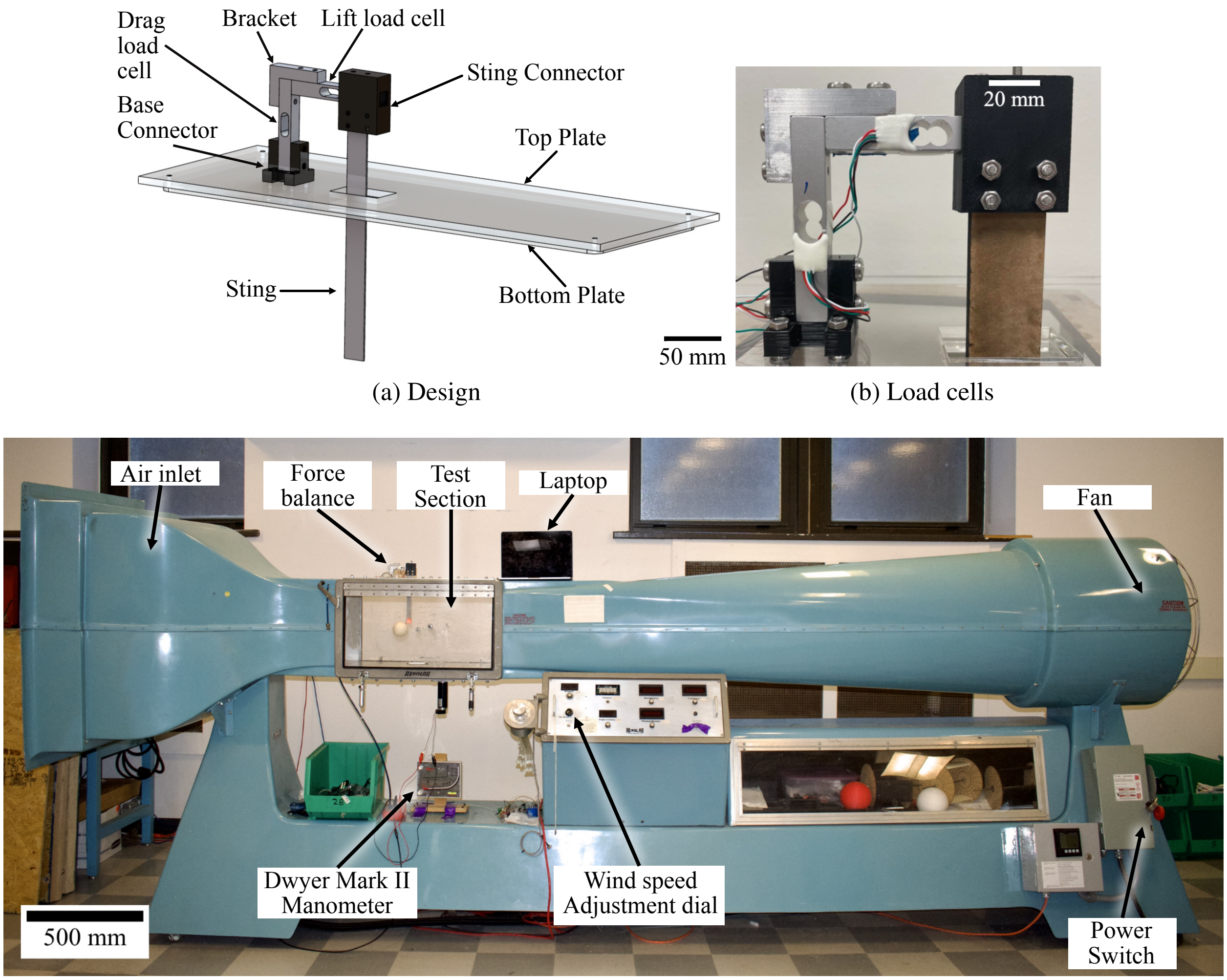
A common application of wind tunnel force balances is wing characterization. There are several existing methods for measuring the lift and drag of a wing. Wind tunnel setups may use the "two-dimensional" wing method, fixing the airfoil though both sides of the wind tunnel and using pressure taps around the surface to measure lift [3, 4]. Alternative approaches mount the wing to one side of the wind tunnel [5] or mount the wing from its center and use a force balance to obtain measurements [1, 2]. These methods can all work well for rigid wings. However, in the case of deployable [6, 7] or morphing [8, 9] wings, pressure taps cannot be included and the wing must be mounted in a cantilever style to avoid constraining its degrees of freedom. Increased interest in novel morphing and deployable wing design [10] motivates the development of a wind tunnel force balance that is versatile enough to measure a deployable wing, and accurate enough to allow for comparative studies.

We have developed a two component wind tunnel force balance suitable for measuring the lift and drag. The objectives of the design were that it be adaptable to cantilever mounting, have error of $\pm 10\%$ or better [1, 2], use low-cost components, and be feasible to create using a small machine shop. The system was primarily designed, fabricated, and benchmarked by undergraduate researchers (two of whom are authors of this paper), indicating that its construction may be replicated by undergraduate students in the future as part of a course. The components we choose are similar to those used in a previously developed educational force balance [2], but we use a different mounting configuration that allows the load cells to be visually prominent, aiding student exploration. In addition, the previously developed force balance used rods to isolate the component forces, but found that the friction introduced error into the drag measurements [2]. Our design overcomes this challenge by using a rigid coupling between load cells, and we confirm that our approach is viable by conducting tests on a single load cell.

We demonstrate the use of the wind tunnel force balance as part of an undergraduate lab. We provide an outline for an inquiry-based [11] lab during which students discover the functionality of the load cells, learn how to use the force balance, and measure drag on a sphere. Our analysis includes feedback from the lab instructor and results from student surveys. We also include suggestions of other labs for which the force balance could be used.

Our contributions include:

- A wind tunnel force balance design that may be constructed by undergraduate students;
- Evaluation of the force balance's performance showing a mean absolute percentage error of 2.5% in static tests and an average error of 4% deviation from the expected value for measuring coefficient of drag on a sphere;
- A sample modification of the force balance to allow it to characterize the lift and drag of a wing by motorizing the pitch angle; and
- A description of a sample lab using the wind tunnel force balance, along with the results from a student survey.



(a) Design (b) Load cells

(c) Wind Tunnel

Figure 1: **a)** The wind tunnel force balance CAD assembly with structural components labeled. **b)** The two Sparkfun load cells are rigidly coupled to eliminate friction in the setup. **c)** The educational wind tunnel with the force balance prepared for measuring the drag on a sphere.

The remainder of the paper is structured as follows. Section 2 gives an overview of the wind tunnel force balance system. Section 3 details construction and data collection procedures. Section 4 shows the evaluation of the accuracy of the force balance through static benchtop tests. Section 5 demonstrates the use of the force balance in the wind tunnel on a benchmark case, as well as for characterizing wings. Section 6 details the use of the wind tunnel force balance in an educational lab setting, including the results from an interview with the instructor and feedback from surveyed students. Finally, we close the paper with concluding remarks in Section 7.

2 System Overview

The wind tunnel force balance is designed to be able to measure both lift and drag on an object placed on the sting (beam that holds the sample). The core functional components include two load cells and an Arduino microprocessor. The load cells are used to collect the lift and drag force readings. The signal from each load cell is passed through an amplifier and then read by the Arduino. The Arduino prints the readings over a serial connection, allowing the user to view and store the data.

The force balance, shown in Fig. 1a, consists of a load cell assembly, a base, a circuit, and a sting that extends into the wind tunnel for attaching the samples. Two load cells (10 kg, Straight Bar (TAL220)) are rigidly coupled to prevent friction via a machined aluminum bracket (Fig. 1b). The vertical load cell is for drag measurements, while the horizontal one is for lift measurements, as seen in Fig. 1a.

The base consists of two 6.35-mm-thick acrylic plates sized to fit the opening at the top of the wind tunnel. The bottom plate is sized to drop inside the wind tunnel so that it is flush with the surrounding interior, while the top plate is sized to sit on a metal lip at the top of the wind tunnel. A 3D printed base connector mounts the drag load cell to the base. A 3D printed sting connector attaches the beam to the load cell. The sting is a beam having a length of 220 mm and a thickness of 1.6 mm, manufactured by waterjet cutting a steel sheet, but a similar beam could be fabricated on a milling machine, or even by laser cutting (though beams made of thicker material would introduce additional error into the system). Two holes on the low end of the sting allow the sample to be mounted.

Load measurements are taken using an Arduino Uno and two Sparkfun HX711 load cell amplifiers (SEN-13879). The amplified load signal is uploaded from the Arduino Uno to a connected laptop using serial communications over USB with a baud rate of 57600. When the experiment is complete, the data from the serial monitor is exported to a .csv file.

3 Design and Fabrication

Our design concept involves a rigid perpendicular coupling of two load cells. One way to isolate the loading directions in a force balance is to use a low friction connection between the load cells [2], but friction will become a source of error. Our preliminary tests used rods to isolate the loading directions, but we found that even slight misalignment of the rods during loading leads to friction causing drift, such that the force balance will not return to zero when loads are removed. The rigid coupling of the load cells eliminates friction, overcoming this challenge. Each load cell consists of four strain gauges in a wheatstone bridge formation [12], making them only sensitive to loads in the designed loading axis. We experimentally verify this by evaluating the ability of the load cell to reject off-axis loads in Sec. 4.1.

The list of components and materials required to build the force balance, along with their costs, is shown in Tab. 1. The electronics are all readily available off-the-shelf components, and the custom components can be fabricated by a small machine shop. The fabrication files are available on our webpage.

3.1 Circuit and Load Cell Calibration

The circuit design is shown in Fig. 2, and comprises two load cells, two HX711 amplifiers, and one Arduino Uno. While a breadboard may be used to connect the amplifier to the Arduino, it is

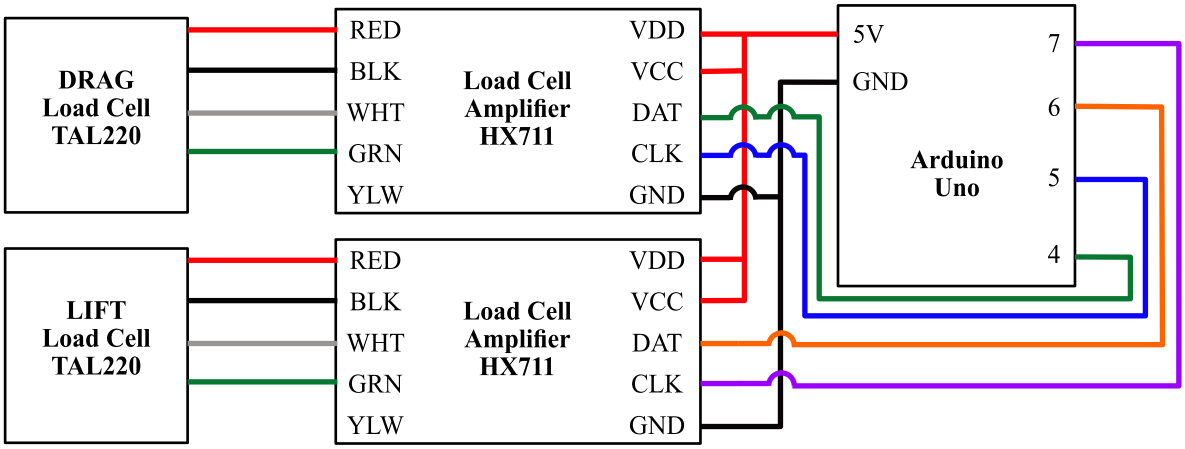


Figure 2: The circuit diagram for the wind tunnel force balance. Note that the connection between the load cells and the amplifier must be soldered directly to avoid introducing noise into the system.

critical that the wires from the load cells be soldered directly to the amplifiers to avoid introducing noise into the signal before amplification.

Each load cell needs to be calibrated prior to assembly in the wind tunnel force balance because the appropriate scaling factor differs for individual load cells. The calibration code and procedures are from Sparkfun [12]. Calibration involves clamping one end of the load cell to a table, taking care not to let any of the strain region overlap with the table, and then running the `Calibration.ino` script. The script will prompt the user to apply a known load and input its value, and then the script will generate a calibration value, which should be recorded and used for all code that reads the load cell, including the `Read_2X_load_cell.ino` that we distribute. The HX711 library will automatically multiply the load cell readings by the reciprocal of the calibration value.

Calibration values change slightly over time and with environmental changes. The calibration procedure should be repeated periodically, either by removing the load cells from the assembly or by clamping the entire assembly to a horizontal surface for lift and a vertical surface for drag. We verified that the calibration may be done while assembled by performing multiple calibrations of each load cell while in the assembly and individually. In each condition for each load cell, the calibration procedure was repeated six times using three different weights. Then, a t-test was conducted on the calibration values for each load cell. The null hypothesis was that the two samples (assembled vs individual) come from distributions with equal means and equal variances, and we were unable to reject the null hypothesis at the 5% confidence level. Thus, the data demonstrate no significant difference between calibration of load cells before or after assembly (though it is easier to clamp individual load cells).

3.2 Assembly

All of the components are joined using M4 or M5 bolts, and the sting connector is additionally designed to be press fit onto the load cell.

First, the top plate and bottom plate are attached to each other using the four corner holes. Since

Table 1: Cost Breakdown of the Wind Tunnel Force Balance

Component	**Quantity**	**Unit Price ($)**	**Total Price ($)**
Off-the-shelf Components			
HX711 Load Cell Amplifier	2	10.95	21.90
Load Cell - 10kg, Straight Bar (TAL220)	2	9.50	19.00
Arduino Uno	1	32.00	32.00
Material Stock			
Acrylic Sheet 1/4"	1	5.00	5.00
3D printed base connector	2	7.09	14.18
3D printed sting connector	1	8.86	8.86
Aluminum	1	20.53	20.53
Total			121.40

acrylic stock thickness tends to be undersized, we add two washers between the plates at each corner so that the bottom of the base is flush with the top of the wind tunnel. Then, the base connector is attached to the base plates using the mounting holes.

Next, the two calibrated load cells are attached to the load cell bracket. The end that does not have any wires on it will be the lift load cell and is inserted into the sting connector. It is critical that the sting connector is slid onto the bare aluminum side, because it otherwise risks damage to the wires. The wires are very thin, so care must be taken not to pull, pinch, or delaminate them from the load cell to avoid breakage. The sting connector is also bolted into place on the lift load cell. Due to the press fit, it is not advisable to remove this part unless necessary to replace the load cell. Next, the drag load cell is attached to the base connector so that the sting connector is over top of the square hole in the base, as shown in Fig. 1b. Finally, the sting is attached to the sting connector using the mounting holes.

For storage, it may be useful to laser cut a stand for the device or to find a stack of books to prop each side. Impacts with the sting may damage the load cells, so care should be taken to ensure proper storage. Alternatively, the sting may be removed when not in use.

3.3 Data Collection

The code we distribute is based on code from Sparkfun[a], and it is adapted to read two load cells simultaneously and add keyboard input for flagging sections of the data.

The `Read_2X_load_cell.ino` should be uploaded to the Arduino. Open the Arduino Serial Monitor to verify that the data is displaying. Data can be collected directly from the Arduino Serial Monitor by selecting all data, copying, and pasting into a text document. However, it may be preferable to download PuTTY (or a similar application) for logging the serial data.

The code outputs four readings, Drag (g), Lift (g), Trial Number, and Time (ms). The Trial

[a] `https://github.com/sparkfun/HX711-Load-Cell-Amplifier/tree/master`

Number allows segments of data to be flagged by the user so that multiple loading conditions may be included in one file and separated into groups in post-processing. The Trial Number starts at 0. The code included with this paper allow the user to send '1' through the serial connection, which will cause the data to increment the Trial Number to the next unused integer. Sending '0' over serial will set the Trial Number to 0. The recommended use of the Trial Number is to set it to 0 while the loading conditions are changing (so that the data is discarded easily in post-processing), and send '1' when while the loading condition is constant to mark that section of data for analysis.

3.4 Learning of Student Designers

The undergraduates who participated in the design learned design principles related to troubleshooting a system, working with micro-controllers, and data processing.

During development of the load cell setup, we noticed a noisy and drifting signal. We investigated possible root causes of the noise and learned about methods of signal conditioning that could be implemented in our system. In the end, we found that soldering the connections is important to avoid introducing noise in the first place. We also learned that taking benchmark data of a fully-functioning load cell can enable us to diagnose whether a potentially defective load cell is working by repeating the diagnostic test.

We gained experience working with an Arduino library to adapt sample code for our application. We modified the script for collecting load cell readings in order to take user input of the test condition for unit testing of load cells. We also wrote code that can read two load cells simultaneously. This required us to understand how to correctly configure the pins on Arduino and use the functions provided in the library.

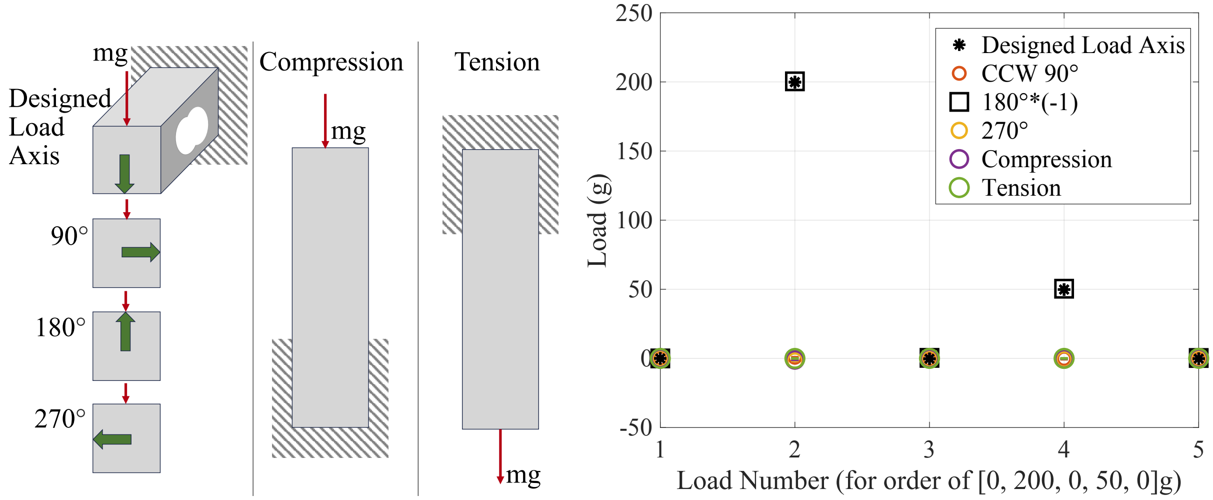
We wrote scripts in MATLAB to organize and plot multiple load cell datasets simultaneously in order to compare and evaluate the results of various loading conditions. We also used data processing techniques to fit a model to the data and to evaluate the error in the load cells.

4 Experimental Validation of the Force Balance

To validate the force balance's load cell configuration and determine its accuracy, we conducted tests on a single load cell and static loading tests on the assembled force balance.

4.1 Single Load Cell Off-Axis Load Tests

Each load cell (TAL220) was designed to measure the load along one axis and to reject other loads, due to the placement of four strain gauges in a wheatstone bridge [12]. However, the data sheet does not specify how off-axis loading may affect the measurements. Since the wind tunnel force balance design relies on the load cells' ability to reject off-axis loads, we verified that the excitation to other loading directions remains low. One end of a calibrated load cell was clamped to a table and a sequence of known loads was applied. This was repeated for six orientations of the load cell, such that loading was performed in the designed loading axis and in each orthogonal loading direction, including pure compression and pure tension. Data from the off-axis test is shown in Fig. 3. The average of the first loading condition in each orientation was taken to be 0 g



(a) Loading Directions

(b) Off-Axis Data

Figure 3: **(a)** For the off-axis loading tests, the load cell is rotated in 90° increments and subjected to a loading sequence –0 g, 200 g, 0 g, 50 g and 0 g– in each orientation. **(b)** The data from the off-axis tests show that the error from the load cells when an off-axis load is applied is only 0.30 g. The black color indicates that a sensitive reading is expected because the load is aligned with the designed loading axis. The data in each loading condition is averaged and the mean of the initial 0 g load is subtracted from each measurement to tare the load cell in the new position. Data from the reversed direction (180°) is multiplied by -1 to check the load cell symmetry. The load cell reads accurately in the designed loading axis, in both the designed and reversed directions, with minimal excitation in the other axes. The error bars on all the data are very small.

in force, since the load cell measures its own weight when it is rotated during data collection. We see that all the off-axis loading conditions stayed near 0 g in the force measurement when a load was applied. The mean squared error of the off-axis load conditions was computed and found to be 0.30 g. So, the error from off-axis loading was determined to be negligible, and the approach of rigidly attaching the two load cells together is valid.

4.2 Static Loading of the Force Balance

The accuracy of the wind tunnel force balance was verified across a range of loading conditions by using a set of fixtures that allowed the top plate to be statically supported at five different angles (from horizontal: 15°, 30°, 45°, 60°, 75°). For the 0° and 90° loading configurations, we did not require a fixture and instead mounted the force balance to a horizontal or vertical surface using clamps. At each angle, the force balance was zeroed to account for the effect of gravity on the force balance itself, and then a sequence of weights was hung from the sting. At each angle, 30 seconds of data were collected for each loading condition of a sequence – unloaded, 20 g, 200 g, 50 g, 100 g, unloaded. The data from the load cells was then compared to the ground truth force components determined using trigonometry as

$$D_{g.t.} = m\sin(\theta) \tag{1}$$

$$L_{g.t.} = m\cos(\theta) \tag{2}$$

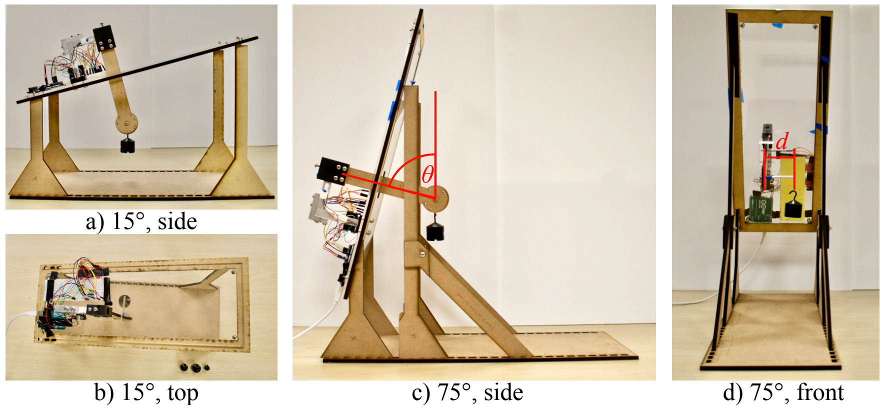


Figure 4: Photos from the static loading tests. In our static loading datasets, θ varies from 0° to 90°, and we also collect data with and without an offset d to assess the ability of the load cells to reject a torque from cantilever loading.

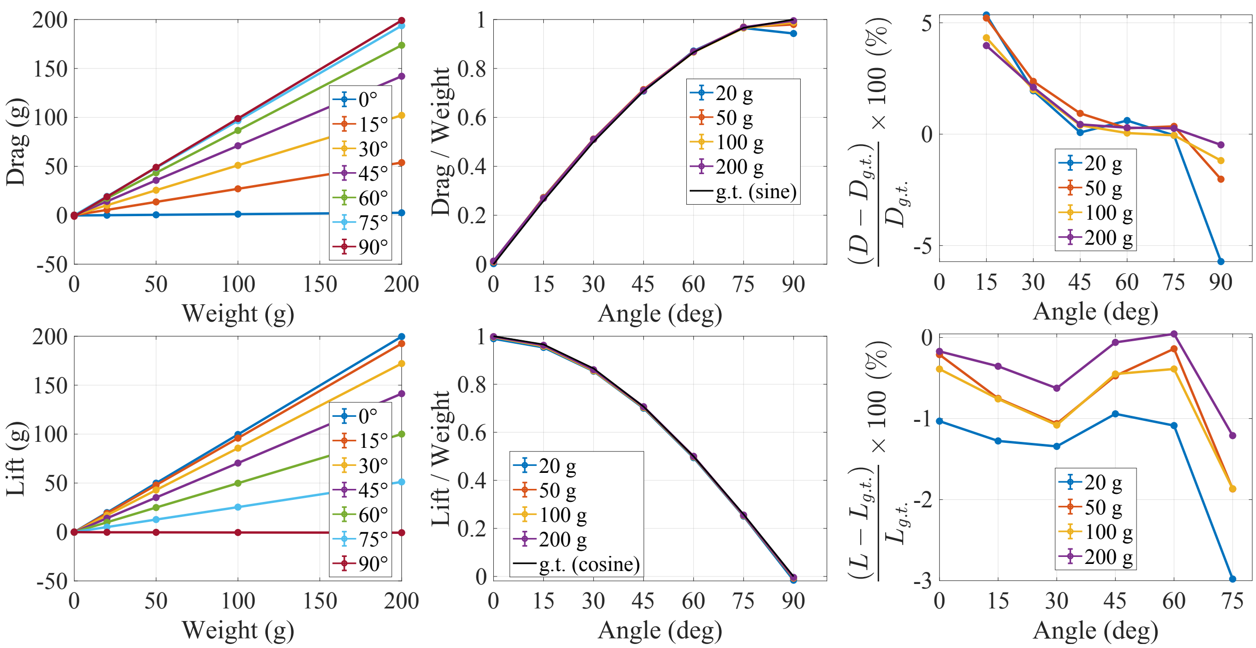


Figure 5: [Top Row] shows the drag data, and the [Bottom Row] corresponds to the lift data from static loading tests. [Left] The raw data is plotted. Each data point is the average measurement during that loading condition. The standard deviation only averages 0.05 g, so the error bars are not visible. [Middle] The data is normalized by mass and plotted against the ground truth value (sine for drag and cosine for lift). [Right] The percent error with respect to the ground truth, as determined using trigonometry, is low.

where $D_{g.t.}$ is the ground truth value for the drag load cell, $L_{g.t.}$ is the ground truth value for the lift load cell, m is the applied load in grams-force, and θ is the angle of the base from horizontal (which is the same as that of the sting from vertical).

Three datasets are collected to determine the accuracy of the force balance: drag in the standard loading direction (direction of air flow when in the wind tunnel), drag in the reverse loading

Table 2: Mean Absolute Percentage Error, and Maximum percent error for the Static Load Tests

Dataset	L MAPE (%)	D MAPE (%)	L Max %error	D Max %error
Standard (Wind direction)	0.86	1.69	3.0	5.7
Reverse Drag	0.74	1.55	3.2	3.8
Standard+Reverse Combined	0.80	1.62	3.2	5.7
Cantilever Torque	1.28	2.53	4.8	7.6

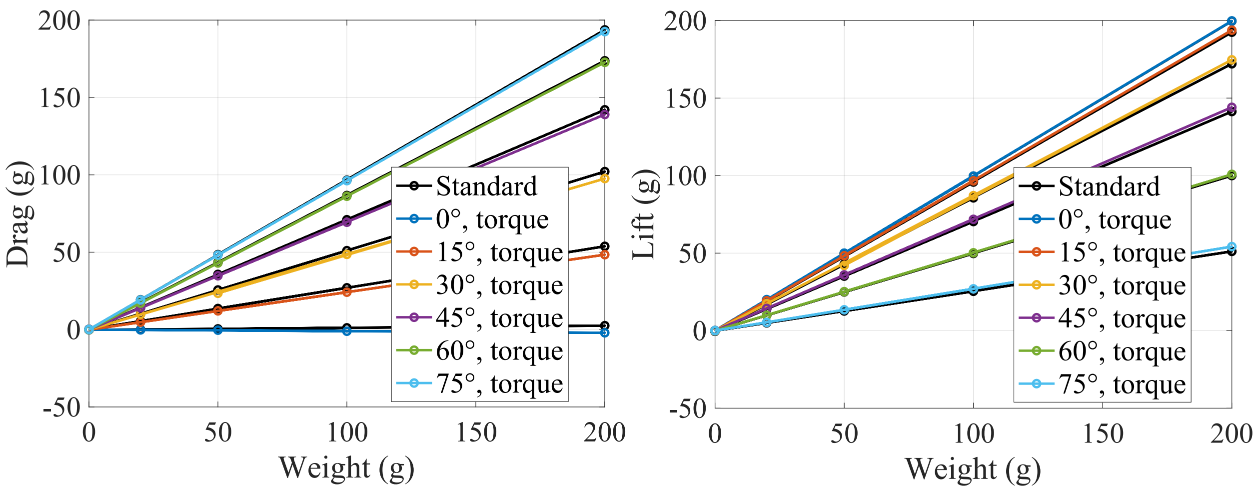


Figure 6: The agreement of the data having an additional applied torque compared to the "standard" symmetric baselines at each angle shows good agreement, indicating that we can still obtain accurate results in the cantilever loading condition.

direction, and standard direction with torque. The torque condition simulates the effect of the cantilever loading condition by hanging the weight from the end of a 55 mm standoff, as seen in Fig. 4d.

4.2.1 Accuracy of the Force Balance

The data are analyzed and the standard deviations and percentage errors are computed. The plots in Fig. 5 display the data from the standard loading condition. The tests show that the data are precise, having a standard deviation averaging only 0.05 g. The plots show that the percentage error from the ground truth value for both the lift and drag load cells is qualitatively small. The mean absolute percentage error (MAPE) and maximum percentage error of each dataset are displayed in Tab. 2. MAPE is computed as

$$MAPE = \text{mean}\left[\frac{|x - x_{g.t.}|}{x_{g.t.}}\right] \times 100 \tag{3}$$

where x corresponds to the reading from the load cell (either D or L) and $x_{g.t.}$ is the ground truth value determined using Eq. (1) and Eq. (2). Note that the MAPE computation excludes data points for which the ground truth value is zero.

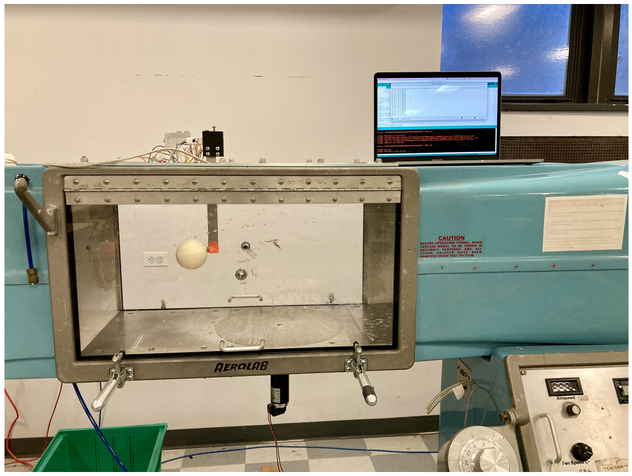


Figure 7: The wind tunnel force balance while measuring the drag on a sphere. This is the same setup used for the educational lab session.

Tab. 2 shows similar MAPE for the drag in the standard and reverse loading conditions, so we combine them and find that in the absence of torque, lift has a MAPE of 0.8% and drag has a MAPE of 1.6%. All of the percent errors are within $\pm 6\%$.

A comparison of the symmetric loading data with loading that includes torque from a cantilever loading condition is shown in Fig. 6. Tab. 2 shows that there is an increase in MAPE from 1.6% to 2.5% error in drag and from 0.8% to 1.3% error in lift. So, the cantilever loading condition will introduce error in the load cell readings, but the percent error is still within $\pm 8\%$, demonstrating that the system is at least as accurate as existing low-cost options [1, 2], while enabling the cantilever loading condition.

5 Wind Tunnel Testing

In order to test the force balance in a hands-on wind tunnel laboratory setting, experiments are conducted in the AEROLAB Educational Wind Tunnel shown in Fig. 1c. The intake is on the left of the wind tunnel, and a fan is on the right end. The test section in the middle has a cross section of 12” by 12”, where samples can be placed and tested. The console panel is used to toggle the fan power and adjust the wind speed. The other gauges on the console panel are unused (they are for a force balance from the manufacturer). A Dwyer Mark II Manometer is used to measure the wind speed by reading the pressure change due to the flow. Assuming a temperature of 25 °C and a pressure of 1 atm, using the datasheet [13] gives the conversion to wind speed in m/s as

$$v = 20.4952\sqrt{P_v} \tag{4}$$

where v is the wind speed in m/s and P_v is the pressure reading in inches of water.

5.1 Benchmarking Drag on a Sphere

The drag on a sphere is a well-studied quantity in fluid mechanics, so we use it as a benchmark for evaluating the accuracy of our system. For Reynolds numbers between 10^4 and 10^6, the drag

Table 3: Results from Measuring Drag on a Sphere

Inches of Water	Airspeed v (m/s)	Coefficient of Drag	Error
0.1	6.4812	0.4946	0.0523
0.25	10.2476	0.4424	-0.0587
0.5	14.4923	0.4865	0.0351
1	20.4952	0.4764	0.0136

coefficient of a sphere is known to be approximately 0.47 [14]. The sphere in this experiment had a diameter of 2.5" (0.0635 m) and was 3D printed on a Fortus 450mc. The Reynolds number is computed using

$$Re = \frac{\rho v L}{\mu} \tag{5}$$

Where L is the characteristic length, which is the diameter of the sphere, ρ is the air density, and μ is the kinematic viscosity. Assuming $\rho = 1.225$ kg/m^3 and $\mu = 1.48 \times 10^{-5}$ m^2/s, our Reynolds numbers range from 3.4×10^4 to 1.1×10^5 for the airspeeds given in Tab. 3. This matches the range for using a coefficient of drag C_D of 0.47 as ground truth [14]. The drag coefficient C_D is computed as

$$C_D = \frac{F_D}{\frac{1}{2}\rho v^2 A} \tag{6}$$

where F_D is the drag force in N and A is the cross sectional area of the sphere in m^2. Note that we need to convert the averaged load cell reading from gram-force to Newtons to get F_D.

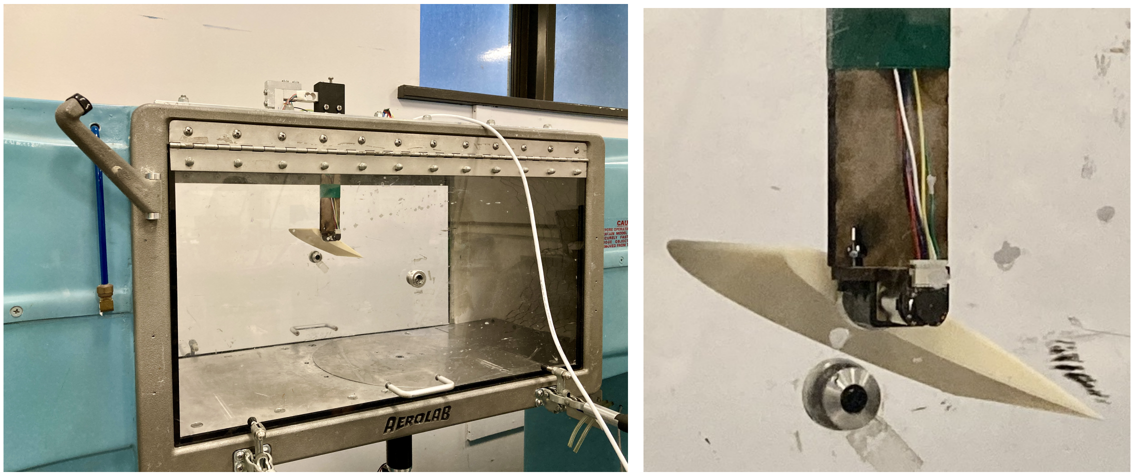
The coefficient of drag from our experimental data, shown in Tab. 3, is close to the expected value of 0.47 [14]. All errors are within $\pm 6\%$ and the mean absolute percentage error is 4%. In addition to the error in the force balance, there is error in the manometer readings used to obtain wind speeds, from oscillations of the beam due to vortex shedding effects, and from manufacturing inconsistencies for the sphere. Students could gain experience identifying sources of error with this experiment.

5.2 Characterizing a Low Aspect Ratio Wing

A 3D printed NACA 0012 wing is characterized by measuring the lift and drag at different angles of attack α. The wing studied has a chord of 0.1 m and a span of 0.1 m, giving it an aspect ratio of 1.

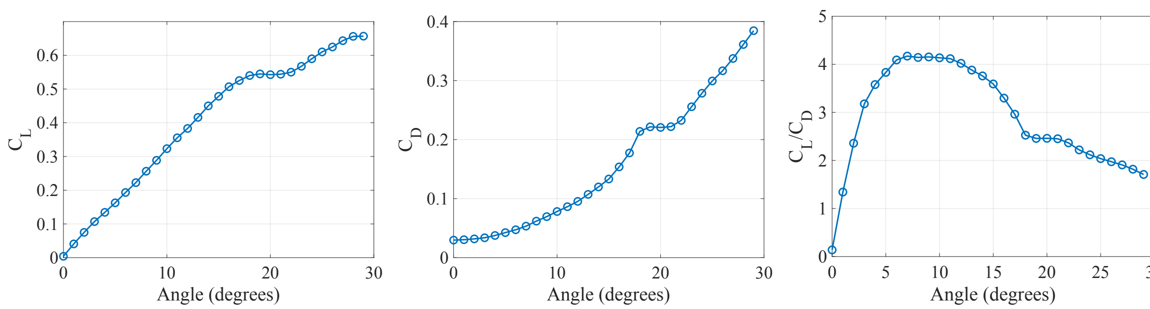
The wind tunnel force balance can be readily modified with a motor and encoder for adjusting the angle of attack. A 1000:1 micro metal gear motor (Pololu #2373) with an encoder was wired to the Arduino, and 6V of power was supplied to the motor. The Arduino was programmed to collect lift and drag data for 15 seconds and then adjust the angle of attack by 1°. Data was collected at thirty different angles of attack. The setup of the wing during data collection can be seen in Fig. 8, and the files and instructions for implementing the modification are on our webpage.

In this experiment, the thickness of the sting was 6.35 mm to allow for easy attachment to the motor. While measuring the drag on the sphere, the sting had been assumed to have a minimal



(a) (b)

Figure 8: **(a)** The addition of a motor to the force balance sting enables the characterization of a low aspect ratio NACA 0012 wing. **(b)** A close up view of the motor and encoder used to adjust the pitch.



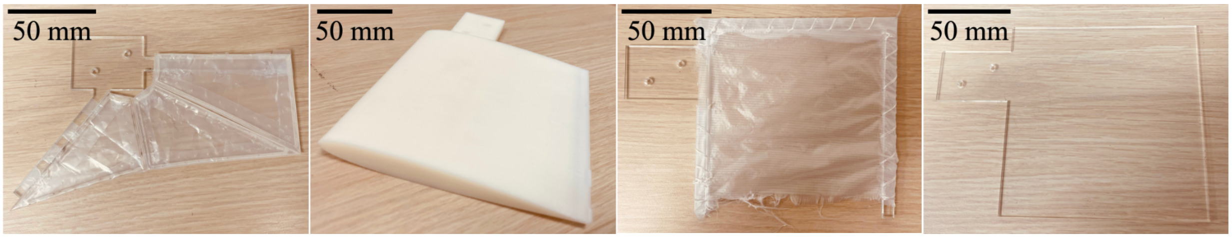
(a) C_L vs α (b) C_D vs α (c) C_L/C_D vs α

Figure 9: Coefficient of Lift and Coefficient of Drag vs Angle of Attack α for the NACA 0012 wing with aspect ratio of 1 at low Reynolds numbers.

influence on the drag measurement. The thicker sting will have a greater influence on the drag measurements, so we first took data of the sting at each airspeed with no wing attached. The average drag at each airspeed was computed and subtracted out of the drag measurements for the wing in post-processing.

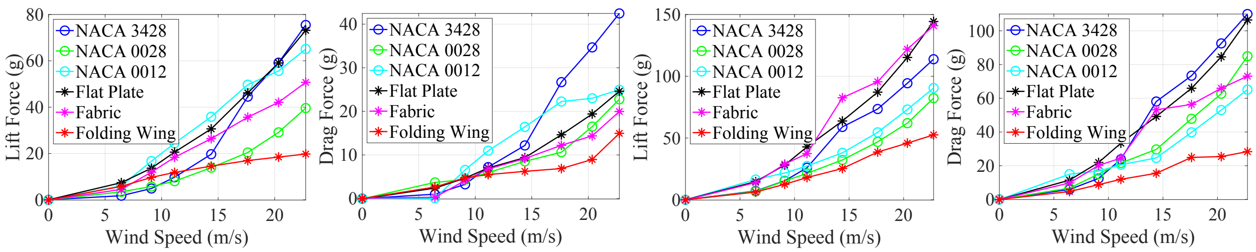
The wing was manually oriented at 0° angle of attack in the wind tunnel. Due to uncertainty in the visual alignment, the wing was intentionally pitched slightly downward so that the lift data will pass through 0 N. To align the data, we used the fact that for the symmetric wing, the lift is 0 N at 0°, and we shifted the data by 1° in post-processing.

On a plot of coefficient of lift, the stall angle is identified as the peak value before it begins to decrease. From Fig. 9c, we find that there is strange behavior around 18°, but then the lift coefficient continues to climb and looks to be beginning to peak towards the end of data collection. This indicates that the stall angle is higher than the results in a previous study [5],



a) Folding Wing Panels b) Airfoil shape c) Fabric Flat Plate d) Rigid Flat Plate

Figure 10: The wind tunnel force balance is able to accommodate various experimental wings for testing.



a) Lift, 15° b) Drag, 15° c) Lift, 35° d) Drag, 35°

Figure 11: The comparison of **(a)** lift and **(b)** drag of different prototypes at 15° angle of attack indicate that at high angles of attack, it is better to use a flat plate as wing, rather than an airfoil cross-section. **(c)** At 35°, the fabric wing begins to perform similarly to the flat plate in lift, **(d)** while having slightly lower drag .

which found a stall angle of 12° for a NACA 0012 that has an aspect ratio of 2. It is expected that our value should be higher since the stall angle generally increases with decreasing aspect ratio [15]. Our data has similar features to that of a previous study on NACA 0012 wing with aspect ratio of 1, where the onset of stall was found to be very delayed for the low aspect ratio wing [16]. Due to wingtip vortex formation, the coefficient of lift on a low aspect ratio wing is expected to be lower than that of the corresponding infinite-span case.

5.3 Comparative Study on Nontraditional Wings

One of the initial objectives in building the wind tunnel force balance was to allow testing of wings that require a cantilever mounting configuration. The force balance allowed undergraduate researchers to compare standard airfoils, thick airfoils, flat plates, wings with a fabric surface, and origami-inspired wings (Fig. 10).

The data in Fig. 11 were collected at 15° and 35° angle of attack, and show that the rigid flat plate performs similarly to the airfoils in lift, while having a lower drag than thick airfoils. This is due to the high angle of attack, causing the airfoils to operate in a post-stall regime. The fabric flat plate has lower lift than the rigid flat plate, likely due to slack in the fabric material causing it to operate at an effectively lower angle of attack. This preliminary study aided the selection of the fabric wing concept for a morphing aerial vehicle [17], since the vehicle is likely to operate at high angles of attack and the fabric design is very lightweight.

Table 4: Approximate Lab Schedule

Time	Activity	Duration (mins)
00-10	Introduction before entering lab	10
10-15	Introduction to lab space and tasks. Students find groups	5
15-30	Determine serial output meaning OR Assemble load cell circuit	15
30-45	Measure drag on a sphere OR Calibrate load cell	15
45-60	Instructor prompting deeper understanding, Instructor-led experiments	15
60-70	Discussion between teams	10
70-80	Student Survey Time	10

6 Student Lab Use

The wind tunnel force balance was used in a sophomore level mechanical engineering laboratory course, MEAM 2470. We designed a sample lab using the wind tunnel force balance, as well as a survey for the students to complete following the lab. The students in the lab were all currently or previously enrolled in a sophomore level fluid mechanics course as well as a statics course. So, the lab was designed to encourage students to apply knowledge from both courses to the experiment.

The lab course had fifty-three students across four sections. All student attendees were invited to participate in a research study by filling out a short survey after completing the lab. Thirty-three students volunteered to participate in the study[b].

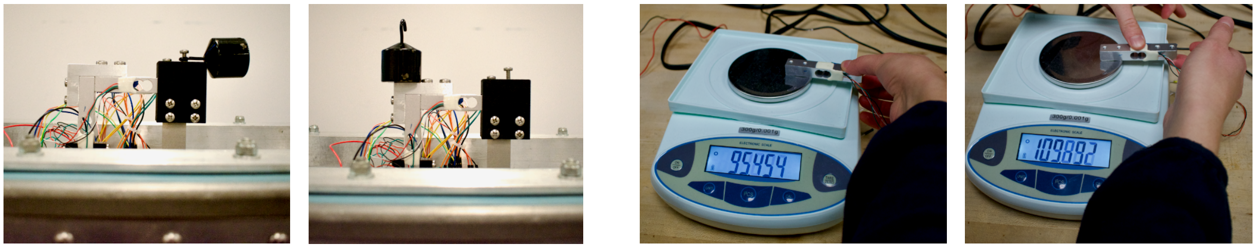
6.1 Lab Activity Description

Students were asked to figure out how the force balance works and then use it to measure the drag on a sphere (repeating our experiment from Sec. 5.1). The force balance was placed in the wind tunnel with a sphere attached to the sting. In addition to the force balance, the lab was also equipped with a two extra load cells that had already been soldered to the HX711 amplifiers, as well as two extra Arduino Unos, breadboards, and wires. Students also had access to string, scissors, a 200 g weight, and a scale.

The lab was conducted in an inquiry-based style [11]. Rather than being provided with documentation for the force balance, students were asked to figure out which of the four readings from the Arduino corresponded to drag, as well as what the units were. Students were also prompted to figure out which physical load cell corresponded to which measurement on the force balance, encouraging them to think critically about which axis the load cells measure.

Students were permitted to self-organize into groups. Since the wind tunnel can get crowded, about half of the students were encouraged to try and figure out how to calibrate the load cells, and were told to reference the HX711 guide on Sparkfun [12] for instructions. This means that some students worked mainly with the force balance that was in the wind tunnel, while others focused on learning how to calibrate the load cells and understanding how an individual load cell

[b]University of Pennsylvania IRB Protocol #854898



a) b) c) d)

Figure 12: The instructor assists student inquiry by conducting a two experiments midway through the lab session. In the first experiment, the loading condition shown in **(a)** is compared with the loading condition shown in **(b)**. In the second experiment shear loading **(c)** is compared with bending **(d)**.

works. Discussion between groups of students during the lab was also encouraged, effectively using divide and conquer to allow students to teach each other.

An approximate time breakdown of the lab is shown in Tab. 4. The instructor gave students time to work amongst themselves and complete the main tasks, but then aided students in their discovery of the underlying load cell functionality by conducting two experiments. The instructor asked questions and provided students with data that helped them reach their own conclusions about the load cell functionality, rather than offering direct explanations.

The instructor asked students working with the force balance to figure out which axis of force the load cells are reading. First, the instructor reminded students of the tools available and gave them time to work together and design their own experiment to discover the load cell functionality. After a while, the instructor asked the students to explain how the load cell worked. If the students became stuck or settled onto an assumption of functionality without justification, the instructor aided the discovery by leading an experiment for the students to explain. The instructor set the 200 g weight on the end of the lift load cell, as shown in Fig. 12a, and asked the students for the reading. Then, the instructor set the 200 g weight on the top of the drag load cell (Fig. 12b) and asked the students for the reading, and what they think it implies. This was intended to help students discover which axis of force the load cells read in an experimental fashion.

Once the students involved in the bench tests had calibrated the load cell, the instructor asked the students to explain the underlying functionality of the load cell. The instructor gave the students time to think about it and reminded them of the materials available in lab, such as the weight and the scale. When the students either settled on an interpretation or became stuck, the instructor asked them to explain their reasoning and prompted further discovery by leading an experiment. The instructor asked students what would happen if a pure bending moment were applied to the load cell. After student predictions, the instructor guided exploration and asked the students to take load cell readings as one end of the load cell was pressed onto a scale (Fig. 12c). Then, the instructor grasped the load cell in both hands and bent it “really hard” and asked for the reading. Since it is difficult to apply pure bending by hand, the instructor also applied a three point bending configuration to the load cell by placing one end on the scale, supporting the other end, and pressing down on the midpoint (Fig. 12d). This helped students realize that the load cell measures shear, rather than bending.

6.2 Instructor Interview

Following are some reflections from the instructor on his experience using the force balance in the lab.

1. *To what extent did the wind tunnel force balance support your educational goals for the lab session?* The force balance was essential to the lab. Strain gauge technology is the industrial standard for measuring forces and students had not yet worked with any such devices. Furthermore, the clever mechanical design of the balance presented a challenge to the students, both in terms of conceptual understanding, and also with respect to precisely deploying their new technical vocabulary (stress, shear, bending, torsion, etc.).

2. *Could you comment on the adaptability of the force balance?* The balance was easy to adapt from the the wing measurements it was originally designed for to sphere drag measurement. I also have aspirations to adapt it to measure thrust on a small propeller.

3. *What features (if any) of the force balance make it well-suited to an educational setting?* I always look for instrumentation in which the functional elements are transparent: in this case, the locations of the strain gauges on the device are easy to discern, so students can puzzle out how it must be working. Another key aspect of the design is robustness: we want students to be able to be very hands-on without risking damage to the instrument.

4. *Compared to the preparation for other labs, how much effort was required to prepare for a lab using the wind tunnel force balance?* I did almost no preparation at all! The balance had already been fitted to our wind tunnel, but once that part is taken care of, it is very plug-and-play.

5. *What changes (if any) would you make to the force balance?* I would have preferred a mounting that was centered in the tunnel. I also would like a bit stiffer sting (the part of the balance that holds the model in place). At some airspeeds, we got close to having the natural frequency of the sting-plus-model match the aerodynamic vortex shedding frequency.

6. *What changes (if any) would you make to the way that you incorporate the force balance in lab sessions?* I would probably add a second week of activity where students play with the strain gauge outside of the balance design, working on calibration and other aspects of coding and basic understanding. Then the homework assignment could be to explain the balance design, perhaps before arriving in the wind tunnel itself.

7. *Do you have any other comments or reflections you would like to share?* I think the drag balance was an especially nice counterpart to the “pendulum angle” balance that we used at the beginning of the semester. We had nice bookends of “static equilibrium” and “linear elasticity” that define a lot of what the sophomore mechanics experience is about.

Table 5: Survey Questions and Results

Question	Mean	Std.
Before coming to lab today, I had a lot of experience working with electronics	2.73	0.86
Before coming to lab today, I had a lot of experience using load cells	1.27	0.51
Before coming to lab today, I had a lot of experience using Arduino	2.82	0.90
I feel confident that I understand how the wind tunnel force balance works	3.41	0.86
I am confident that I know how to measure drag using the wind tunnel force balance	3.34	0.81
The wind tunnel force balance is easy to use	3.28	0.67

6.3 Student Survey

6.3.1 Structure

Students were asked to complete a survey that included six Likert scale questions [18]. Students were asked to rate the following questions from 1 to 5, with 1 being strongly disagree and 5 being strongly agree. The first three questions were designed to assess student prior knowledge with the concepts relevant to working with the force balance, while the latter questions were designed to assess student understanding of the force balance and their experience using it in lab. The questions along with the mean and standard deviation of student responses are shown in Tab. 5

Students were also given a pair of free response questions: What was the most difficult part of using the wind tunnel force balance today? What was the easiest part of using the wind tunnel force balance today?

6.3.2 Results

Since students were permitted to self-organize, about half of the students did not use the wind tunnel force balance directly and were more focused on the load cells. However, at the time of survey creation we had assumed that each student would take a turn using the force balance. So, the survey questions do not fit this group as well. Unfortunately, we do not have a question in the survey regarding which group the student was in, but we attempt to infer this based on the free response questions. Responses focused on Arduino code or load cell calibration are labeled as being in the group doing bench tests. Responses that mention the wind tunnel or figuring out which load cell is which are labeled as having used the force balance. Three responses have both labels, and those students are thought to have rotated between groups during the session. Ambiguous or blank responses to the free response question did not get placed in either group. The histograms of the results for selected questions, broken down by group, are shown in Fig. 13. The histograms in Fig. 13 show that while none of the students agreed that they had experience with load cells, the majority of the students who used the wind tunnel force balance agreed that they understood how it worked by the end of the lab.

Among students who mention the wind tunnel in the free response questions, six respondents said that determining which output corresponds to the drag reading was the most challenging part, while three respondents said that this was the easiest part. Three respondents said that estimating

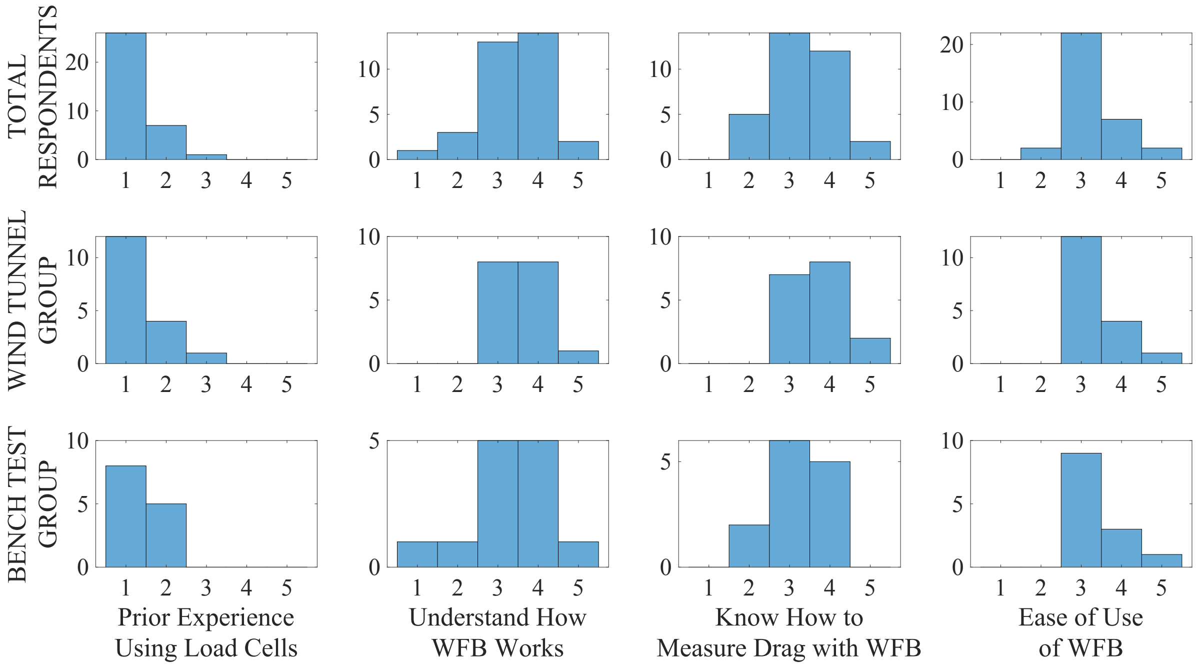


Figure 13: The survey results at a glance show that while nearly all of the students strongly disagreed that they had a lot of prior experience using load cells, most students agreed that they understood how the wind tunnel force balance (WFB) worked and how to use it to measure drag by the end of the lab. A rating of 5 corresponds to strongly agree while a rating of 1 corresponds to strongly disagree.

the values was the most challenging part since they were changing dramatically. Three respondents said that determining the units was the most challenging part. Four respondents said that changing the wind speed was the easiest part of the lab.

Among students who mention calibration, nine respondents said that the most challenging part was calibrating the load cell, while five said that setting up the Arduino or the code was the most challenging. Four respondents said that reading forces once calibrated was the easiest part, two said the easiest part was wiring, and two said the easiest part was getting the code from Sparkfun.

6.4 Discussion

The instructor particularly appreciated the robustness of the setup. The force balance endured six hours of use by students without issue, and none of the sticking points reported by students involved the force balance not working appropriately. Students were given no specific handling instructions for the force balance and were permitted to apply loads as they desired, yet incurred no damage to the force balance. Further, the use of low-cost components means that spare components could be kept on hand in case it does need repair. In fact, it would be feasible to have a whole spare force balance ready to go.

The usefulness and adaptability of the force balance in the classroom setting is evident by the instructor's interest in expanding its use during lab, potentially having a sequence of labs using the force balance rather than having students working on parallel tasks during the lab. The force balance is easy to set up, and allows for easy adaptation by replacing the sting.

The visual prominence of the load cell layout aids student learning. The qualitative survey data indicates that students thought finding which output measures drag and which corresponds to lift is the main challenge, which aligned with our intent for this lab. While the students felt challenged, they were eventually able understand the force balance and how to measure drag, with over half agreeing they are confident in their understanding. This suggests that the wind tunnel force balance construction is such that students can probe it in various ways in order to gain a thorough understanding of both the force balance and the individual load cells. However, a set of pre-lab questions that ask students to plan tests and make predictions may encourage students to be more systematic in discovery, such as asking them to design an experiment that would determine whether a sensor is more sensitive to bending moments or shear forces.

The aspects the instructor wants to improve can be readily changed by modifying the mechanical hardware of the sting and the base plates. While the sting in this design was constrained by requirements for cantilever mounting, it could be centered in the wind tunnel by adjusting the base plate design. A stiffer sting could also be created, either by choosing a different material, or by modifying the 3D printed sting attachment to accommodate a two-beamed sting for greater rigidity [2]. Neither of these modifications would affect the operating principles of the force balance.

The discovery-based lab session has learning outcomes that emphasize the load cell functionality and test design, where students gained practice with systematic reasoning and debugging. Additional labs could be designed to transfer other aspects of the student designers' learning from Sec. 3.4. Students could create their own version of `Read_2X_load_cell.ino` or add a button to flag sections of data during testing. Students could also use MATLAB or Python to plot and analyze their data following experiments.

7 Conclusion

The wind tunnel force balance presented shows demonstrable usefulness in a classroom setting as a low-cost and adaptable means of gathering lift and drag data. The benchmarks show that the setup is accurate within $\pm 8\%$, making it suitable for educational use. The deployment of the force balance in an educational laboratory setting shows that it is robust to student usage, it requires minimal setup for the instructor, and its construction allows students to clearly see and understand how the device is measuring forces. The force balance allows students to gain hands-on experience with strain gauges in a real-world application. Following initial educational lab usage, the wind tunnel force balance shows promise as a platform for conducting both foundational fluid mechanics experiments, as well as less common tests such as measuring the thrust of a propeller in non-hover conditions. The force balance has also already been adopted by researchers [19]. The affordable system has the potential to be implemented by senior design teams or undergraduate researchers, empowering them to design and run their own experiments.

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References

[1] S. Post and M. Morris, "Force balance design for educational wind tunnels," in *ASEE Annual Conference & Exposition*, pp. 15.594.1 – 15.594.10, American Society for Engineering Education, 2010.

[2] M. Tomin, M. Scipioni, and B. Gatti, "Design, construction and testing of a 3-component force balance for educational wind tunnels in undergraduate aerodynamics," *Journal of Aviation/Aerospace Education & Research*, vol. 29, no. 1, pp. 89–105, 2020.

[3] W. Mokhtar and S. Fleischmann, "Introducing CFD and wind tunnel testing in an undergraduate fluid mechanics course," in *ASME International Mechanical Engineering Congress and Exposition*, vol. 46507, p. V005T05A030, American Society of Mechanical Engineers, 2014.

[4] Z. Husain, M. Abdullah, and T. Yap, "Two-dimensional analysis of tandem/staggered airfoils using computational fluid dynamics," *International Journal of Mechanical Engineering Education*, vol. 33, no. 3, pp. 195–207, 2005.

[5] S. Martínez-Aranda, A. García-González, L. Parras, J. Velázquez-Navarro, and C. Del Pino, "Comparison of the aerodynamic characteristics of the NACA0012 airfoil at low-to-moderate reynolds numbers for any aspect ratio," *International Journal of Aerospace Sciences*, vol. 4, no. 1, pp. 1–8, 2016.

[6] X. Li, J. McWilliams, M. Li, C. Sung, and C. Jiang, "Soft hybrid aerial vehicle via bistable mechanism," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 7107–7113, Institute of Electrical and Electronics Engineers, 2021.

[7] P. Cao, J. Phillips, T. Bewley, and F. Kuester, "Quadglider: Towards the design and control of a bio-inspired multi-modal uav with compliant wings," in *2023 IEEE Aerospace Conference*, pp. 1–17, Institute of Electrical and Electronics Engineers, 2023.

[8] N. K. Pham and E. A. Peraza Hernandez, "Modeling and design exploration of a tensegrity-based twisting wing," *ASME Journal of Mechanisms and Robotics*, vol. 13, no. 3, p. 031019, 2021.

[9] D. M. Boston and A. F. Arrieta, "Multistable honeycomb architecture for spanwise wing morphing," in *AIAA Scitech 2021 Forum*, American Institute of Aeronautics and Astronautics, 2021.

[10] R. M. Ajaj, M. S. Parancheerivilakkathil, M. Amoozgar, M. I. Friswell, and W. J. Cantwell, "Recent developments in the aeroelasticity of morphing aircraft," *Progress in Aerospace Sciences*, vol. 120, p. 100682, 2021.

[11] M. Pedaste, M. Mäeots, L. A. Siiman, T. De Jong, S. A. Van Riesen, E. T. Kamp, C. C. Manoli, Z. C. Zacharia,

and E. Tsourlidaki, “Phases of inquiry-based learning: Definitions and the inquiry cycle,” *Educational research review*, vol. 14, pp. 47–61, 2015.

[12] S. Al-Mutlaq and A. T. Giant, “Load Cell Amplifier HX711 Breakout Hookup Guide - SparkFun Learn — learn.sparkfun.com.” https://learn.sparkfun.com/tutorials/load-cell-amplifier-hx711-breakout-hookup-guide, 2016. [Accessed 17-01-2024].

[13] Dwyer Instruments Inc., “Mark II Series molded plastic manometers specifications - installation and operating instructions,” in *Mark II Model No.25 inclined-vertical manometer datasheet*, May 2013.

[14] S. F. Hoerner, “Fluid-dynamic drag. theoretical, experimental and statistical information,” *SF Hoerner Fluid Dynamics*, 1965.

[15] L. Prandtl, “Applications of modern hydrodynamics to aeronautics,” tech. rep., United States National Advisory Committee for Aeronautics (NACA), 1923.

[16] R. Kant and A. Bhattacharyya, “Hydrofoil geometry and leading-edge modifications: Influence of section profile, aspect ratio, and sweep,” *Ocean Engineering*, vol. 262, p. 112306, 2022.

[17] J. Weakly, X. Li, T. Agarwal, M. Li, S. Folk, C. Jiang, and C. Sung, “Bistable Aerial Transformer: A Quadrotor Fixed-Wing Hybrid that Morphs Dynamically via Passive Soft Mechanism,” *Journal of Mechanisms and Robotics*, pp. 1–22, 03 2024.

[18] R. Likert, “A technique for the measurement of attitudes.,” *Archives of psychology*, vol. 22, no. 140, pp. 5–55, 1932.

[19] G. Chen, D. Chen, J. Weakly, and C. Sung, “Drag coefficient characterization of the origami magic ball,” in *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE)*, vol. 87363, p. V008T08A055, American Society of Mechanical Engineers, 2023.