Calibration of the Force Balance for the AF-100 Low-Speed Wind Tunnel

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This experiment focuses on the calibration of a 3-component force balance (AFA3) within an AF100 wind tunnel. It measures fore, aft, and drag forces through three distinct load cells, with the fore and aft load cells connected by flexible cables to a common pulley. Calibration involves generating calibration curves for masses ranging from 0 kg to 5 kg, using the voltage output from strain gauge-equipped load cells. After correcting for offsets, the calibration curves are found to be linear with high precision (R^2 values of approximately 0.99). The calculated percent errors for the load cells and weight readings are generally below 1%, except for the 0 kg mass at 5%, possibly due to ring weight at 0 N. Sensor variations are observed, with the fore, aft, and drag load cells showing the highest variations at 2 kg, 1-3 kg, and 4-5 kg masses, respectively. Sample measurements of lift, drag, and pitching moments are obtained using the corrected calibration curves. The loading range for the load cells is determined to be 99.89 N and -99.98 N for the fore cell, 99.59 N and -99.56 N for the aft load cell, and 100.21 N and -100.31 N for the drag load cell, for the specified ± 10 V sensor range. Going beyond 9 kg of masses may introduce significant errors and non-linearity in the system. Potential sources of error are attributed to mass movement, electrical components, load cell positioning, and uneven sensor data.

I. Nomenclature

$Fore$	=	force of fore load cell
Aft	=	force of aft load cell
$Drag$	=	drag force from drag load cell
F	=	force
K	=	slope
V	=	measured voltage
V_{offset}	=	voltage at no force applied
B	=	y-intercept
m	=	added mass
g	=	acceleration due to gravity, 9.81 m/s^2
C_m	=	pitching moment

II. Introduction

A more direct form of force measurements for a wind tunnel model is by the use of force balances. Forces can be measured indirectly by using pressure scanners attached to the surface, e.g., an airfoil. However, for more complex geometries, a more direct and accurate way of measurement is needed to reduce potential errors from many devices. There are three kinds of force balance: 1-component, 3-component, and 6-component. The one-component force balance is capable of measuring a single force. The three-component force balance can measure lift, drag and pitching moment. Lastly, the six-component force balance can measure lift, drag, sideforce and the moments (roll, pitch, and yaw).

In this experiment, a three-component force balance is calibrated, and calibration curves are generated to check the accuracy and precision of the instrument before use. This allows us to learn the fore, aft and drag force characteristics of the force balance. With the calibration curves for each type of load cell, the resolution of the system, error and sensitivity can be quantified. The force balance uses an electrical strain gage internal set up that measures the voltage due to movement. The stretch in the strain gage corresponds to the voltage difference due to an elongation. The force balance used for this experiment is called AFA3, capable of measuring the lift (fore and aft) and drag forces. The final values of lift, drag and pitching moment can then be calculated using the equations below [1]:

$$Lift\ (N) = Fore\ (N) + Aft\ (N) \tag{1}$$

$$Drag\ (N) = Drag\ (N) \tag{2}$$

$$Pitching\ Moment\ (Nm) = \big(Fore\ (N) - Aft\ (N)\big) * 0.0635 \tag{3}$$

From the Eq. (1=3) above, the forces and moments are measured in metric units. Notice, the lift force is comprised of the fore and aft forces. This is because the load acting downward on force balance is assumed to be evenly distributed between the fore and aft load cells. The voltage measured is proportional to the force applied, thereby having a linear relationship – assuming the Poisson's ratio is very small. This means the area is assumed to remain constant. The strain gage uses a Wheatstone bridge electrical setup where four resistors are connected in between a sensing element. When there is an imbalance in one of the resistors, it creates a voltage difference at the bridge that can be recorded [1].

The load cells on the force balance measure the voltage when a new force is applied. Knowing this, a calibration curve is generated that relates the measured voltage to applied force [1].

III. Experimental Procedure

A. Apparatus

As mentioned in the introduction, this experiment uses an AFA3, three-component force balance. The many parts of the instrument are labelled in Fig. 1. It contains a mounting plate and a force place (triangular) connected together by three supporting legs. The mounting point is used to change the angle of incidence for the force plate. The three legs of the force plate make it possible to move parallelly along the plane of the mounting plate utilizing spherical U-joints [1].

The computer unit used is a Dell PC with an external Data Acquisition System (DAQ) with a PCI-6034E DAQ card and an SCB-68 DAQ connection box. The computer hosts the LabView software that can display recorded readings in real-time. An AF100 wind tunnel by TecQuipment Ltd along with a AFA3 three-component force balance is used [1].

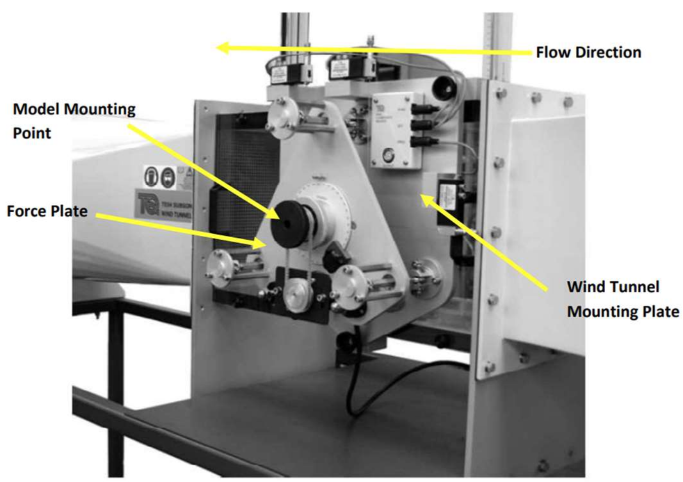

Fig. 1 AFA3 force balance connected to AF100 wind tunnel [1].

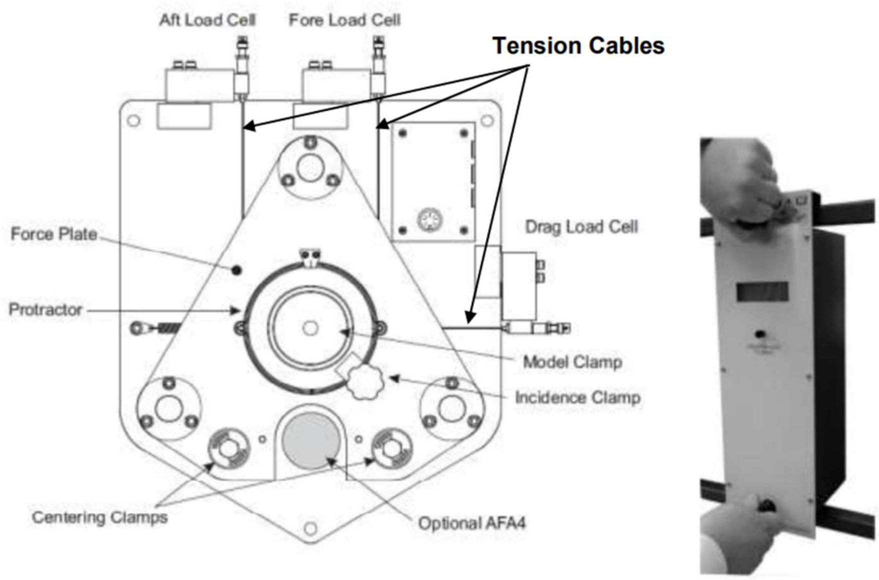

Fig. 2 Schematic of major components of AFA3 and control module [1].

The Fig. 2 shows the schematic of the force balance along with the control module connected to the load cells. The load cells that measure the fore, aft and drag forces are connected to cables that are in tension. For the fore and aft cells, the cables are spread in a vertical direction, joining at the center pully. The end of cable is used to attach weights of different mass. This type of placement also allows for the calculation of pitching moment. The weight is assumed to be equally distributed along both the fore and aft load cells. However, the drag load cell has a horizontal cable orientation since the mass applied will be equal to the measured drag voltage. The cable is placed such that it acts through the center of model support. A drag balance spring is present to add pre-load to the drag load cell. Lastly, the cables used are flexible, hence, compressive loads cannot be applied in this setup [1].

Fig. 3 Storage frame along with the AFA3 force balance [1].

The force balance comes with a support frame for calibration purposes as seen in Fig. 3. Note, the pully must be attached to the other end of drag load cell as shown in Fig. 7. The calibration bar is used along with the roller to change that position of pulley. The calibration bar and pulley must be aligned and leveled as seen in Fig. 4, the incidence clamp is used to tighten the calibration bar into its position [1].

Fig. 4 Calibration bar aligned with pully (left) and aligned calibration bar (right) [1].

For the control unit connections, a 7 pin DIN type lead connects the display module to the force balance as seen in Fig. 5. The display module is a display for calibration purposes that connects to computer unit through VDAS. A pre-programmed graphical interface from LabView is used to display the force inputs, measured voltages, and record data. Allow up to 15 minutes for the system to start prior to the experiment [1].

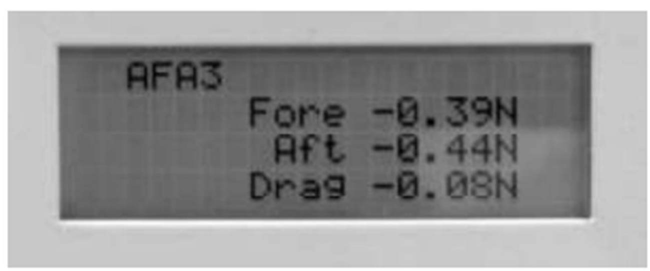

Fig. 5 Force balance connector (left) and display module (right) [1].

B. Procedure

The measured voltage range for the load cells is $\pm$ 10 VDC. To start, hold the "zero" button and turn on the display module. The readings for fore, aft and drag must appear on the display, showing near zero values. If not, adjust the tension cables by either loosening or tightening about the respective load cell. Then, switch on the LabView DAQ software where the voltages for the load cells must read near zero for fore, aft and drag readings. Start with recordings for fore and aft voltages by hanging the cable along the ring from the calibration bar pulley as seen in Fig. 7. Then, start the data collection by hitting the "start" button with no weights added initially. Record the data for five seconds approximately. Stop data collection by pressing the "start" button again, do not press "stop" as it will save data into different files. Then, with care, attach additional weights (1 kg, 2 kg, 3 kg, and 5 kg) to the ring and holder. Repeat the data collection for each mass added. Once the recordings for fore and aft voltages are completed, the cable position is changed for drag measurements and hung along the side pulley as seen in Fig. 7. Please note, while adding weights, the lighter masses may rotate. Hence, wait for a few seconds till the spinning stops before data collection [1].

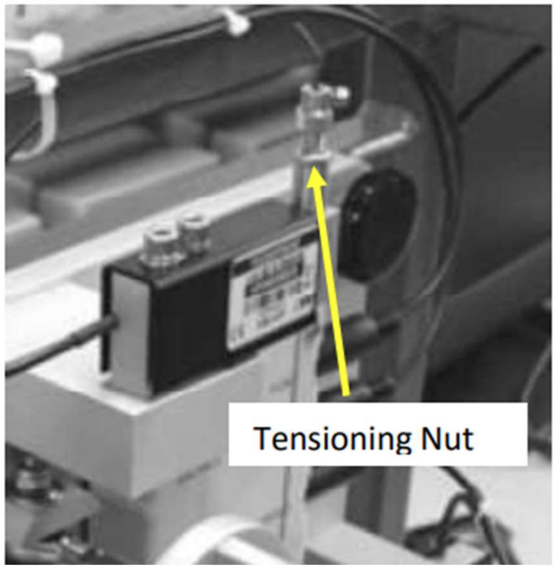

Fig. 6 The tensioning nut on the AFA3 load cell [1].

Fig. 7 Thread positions for fore/aft (left) and drag (right) calibration [1].

IV. Results and Discussion

For the data processing part, the data from the drag load cell file is averaged for each mass applied (0kg, 1kg, etc.) since many readings are taken with the 5 seconds. The data is processed using Microsoft Excel. The average voltage measured is collected, and the masses are converted to force ($F = mg$) by mutliplying with an assumed acceleration due to gravity of 9.81 m/s^2. The forces calculated and voltages measured are plotted for a calibration curve as seen in Fig. 8. The same procedure is followed for the fore and aft load cell data file, seen in Fig. 8-10. Except, as mentioned, the weight is evenly distributed between the fore and aft load cells. Hence, half the mass is used for force datapoints.

The trendline equation and R^2 values are presented on the plots. The R^2 value represents the proportion of data that is predictable by the given trendline. For better precision, the R^2 value must be closer to 1. At R^2 value of 0, it gives the worst precision.

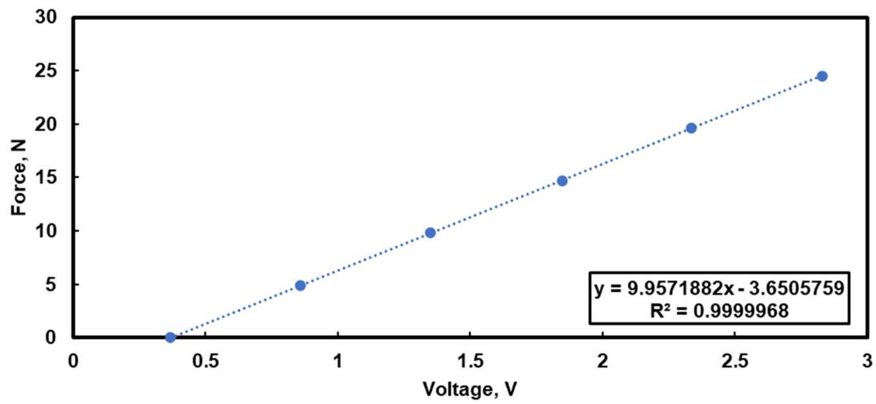

Fig. 8 Original fore force vs. voltage measured calibration curve.

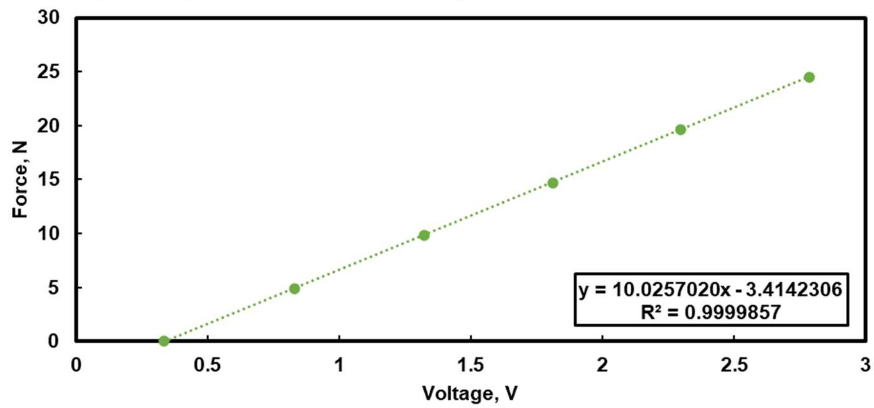

Fig. 9 Original aft force vs. voltage measured calibration curve.

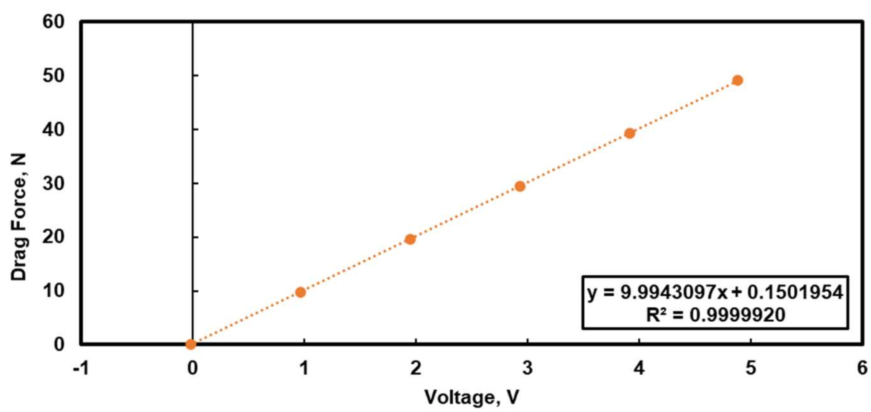

Fig. 10 Original drag force vs. voltage measured calibration curve.

Notice, for 0 N of force, the voltage still gives a positive or negative reading. It is more prominent in the fore and aft calibration curves (Fig. 8-9). The drag calibration curve is closer to the origin; however, the measured voltage is near zero (Fig. 10). This offset is corrected using the following relation below:

$$F = K * (V - V_{offset}) + B \tag{4}$$

Here, F is the desired force, K is the slope of the calibration curve, V is the measured voltage from the load cells, V_{offset} is the first voltage reading at 0 N and B is the y-intercept [1].

Using the calibration curves obtained, the new corrected voltages are obtained and presented in Table. 1-3 for the fore, aft and drag load cells. The corrected datapoints (solid lines) are plotted with originally measured averages (single data points) in Fig. 11-13 with new calibration curves for all three load cells. The new trendline equations and R^2 values are also shown.

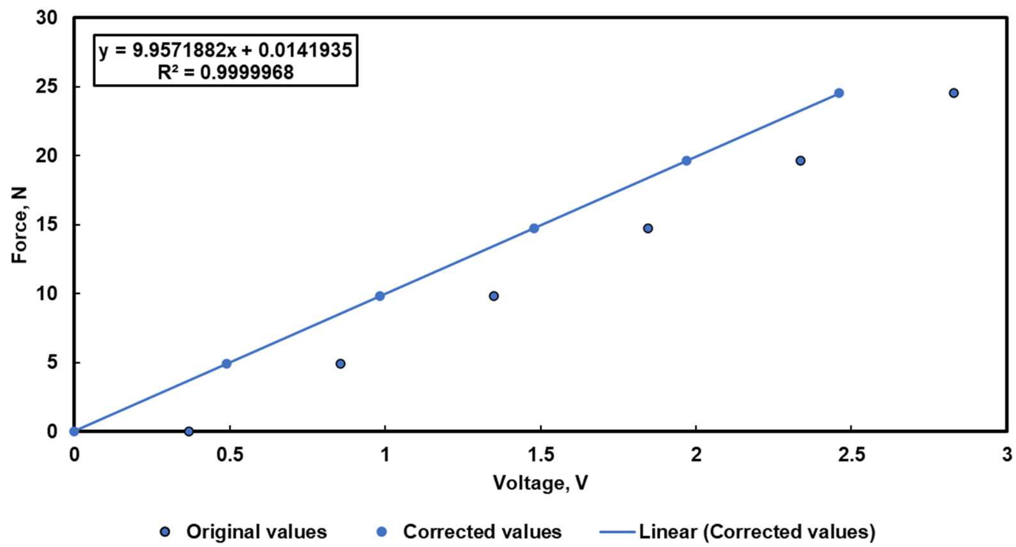

Fig. 11 Corrected fore force vs. voltage calibration curve.

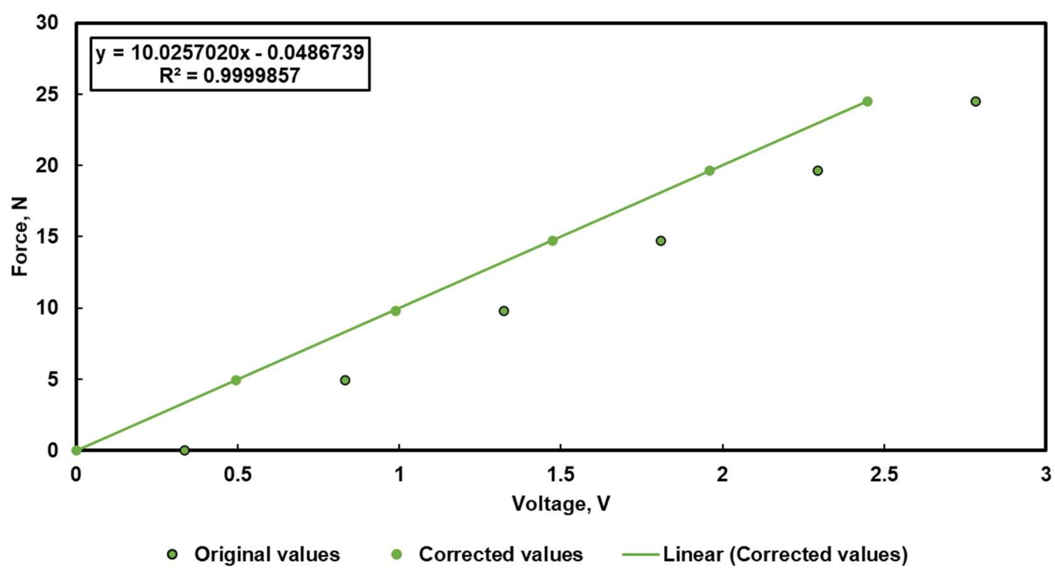

Fig. 12 Corrected aft force vs. voltage calibration curve.

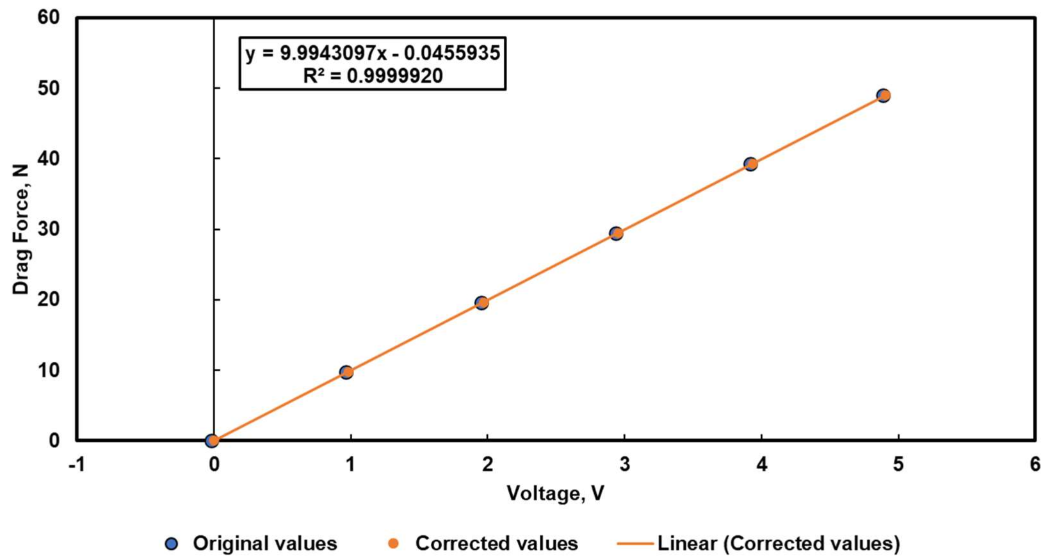

Fig. 13 Corrected drag force vs. voltage calibration curve.

Using the corrected voltage values in Table 1-3 and the trendline equations from Fig. 11-13, the corresponding forces are estimated for each of the load cells. The results are presented alongside in Table 1-3. The error between the actual forces and respective point on the calibration curves are calculated using:

$$\frac{F(actual) - F(Estimated)}{F(Estimated)} * 100 \tag{5}$$

Table 1. Results for fore force and errors from calibration curve.

Mass [kg]	Actual Force [N]	Original Voltage [V]	Corrected Voltage [V]	Force Estimate [N]	Error [%]
0	0.00	0.368053	0.000000	0.014194	1.4194
1	4.91	0.856980	0.488927	4.882532	0.4602
2	9.81	1.350941	0.982889	9.800999	0.0918
3	14.72	1.846746	1.478693	14.737823	0.1549
4	19.62	2.337117	1.969064	19.620534	0.0027
5	24.53	2.829061	2.461009	24.518918	0.0248

Table 2. Results for aft force and errors from calibration curve.

Mass [kg]	Actual Force [N]	Original Voltage [V]	Corrected Voltage [V]	Force Estimate [N]	Error [%]
0	0.00	0.335693	0.000000	-0.048674	4.8674
1	4.91	0.831853	0.496160	4.925677	0.4198
2	9.81	1.323507	0.987814	9.854860	0.4552
3	14.72	1.810415	1.474722	14.736447	0.1455
4	19.62	2.295964	1.960271	19.604416	0.0795
5	24.53	2.784494	2.448801	24.502273	0.0928

Table 3. Results for drag force and errors from calibration curve.

Mass [kg]	Actual Force [N]	Original Voltage [V]	Corrected Voltage [V]	Force Estimate [N]	Error [%]
0	0.00	-0.019590	0.000000	-0.045594	4.5594
1	9.81	0.965205	0.984795	9.796755	0.1352
2	19.62	1.953274	1.972864	19.671825	0.2634
3	29.43	2.934396	2.953986	29.477456	0.1610
4	39.24	3.914401	3.933991	39.271934	0.0813
5	49.05	4.885523	4.905113	48.977625	0.1478

Notice, from the tables above, the highest error is seen for the no force applied (0 N) data points. This can be attributed to the fact that when the cable is left to hang with the ring, it may move slightly contributing to error in the data. This means, that some amount of force is being applied – thing could be the small weight of the ring. For all the other data points, the error is less than 1%, hence, the calibration is accurate and reliable.

Then, the sensor variation within each data set is determined to approximate the precision of the system using the calibration curve. To find the variation, the minimum and maximum values of each data set are recorded, and difference is calculated. This difference is the approximate upper and lower limit of variation for each measured data point as seen in Table 4-6.

Table 4. Variation of sensor data for fore load cell.

Mass [kg]	Minimum Voltage [V]	Maximum Voltage [V]	Difference [V]
0	0.364504	0.370997	0.006493
1	0.852729	0.860195	0.007466
2	1.347446	1.357834	0.010388
3	1.841191	1.849955	0.008764
4	2.332664	2.339806	0.007142
5	2.826736	2.833877	0.007141

Table 5. Variation of sensor data for aft load cell.

Mass [kg]	Minimum Voltage [V]	Maximum Voltage [V]	Difference [V]
0	0.331718	0.338211	0.006493
1	0.825136	0.836173	0.011037
2	1.319854	1.329917	0.010063
3	1.806781	1.820091	0.013310
4	2.291113	2.298579	0.007466
5	2.781613	2.787781	0.006168

Table 6. Variation of sensor data for drag load cell.

Mass [kg]	Minimum Voltage [V]	Maximum Voltage [V]	Difference [V]
0	-0.024062	-0.017245	0.006817
1	0.963423	0.968617	0.005194
2	1.949938	1.957729	0.007791
3	2.930939	2.937431	0.006492
4	3.906427	3.917139	0.010712
5	4.880948	4.893283	0.012335

Upon examining the variations above, the fore load cell gives the highest variation for the mass of 2 kg. Similarly, for the aft load cell, the variations are prominent for masses of 1 kg, 2 kg, and 3 kg. For the drag load cell, the highest sensor variation is observed for 4 kg and 5 kg masses. These variations can be correlated to the rotation of masses while recording the voltage readings. The lighter weights are observed to move much more than the heavier weights.

Additionally, the weights do not hang evenly, often inclining due to the rectangular cut in-between. This can result in a higher or lower measurement of force from each of the load cells.

The loading range of the sensor can be calculated using the known $\pm$ 10 V range of the sensor. For the drag load cell, using the corrected calibration equation below:

$$\left(F_{range}\right)_{Drag} = 9.9943097(\pm 10) - 0.0455935 = 99.89\ N, -99.98\ N \tag{6}$$

$$\left(F_{range}\right)_{Fore} = 9.9571882(\pm 10) + 0.0141935 = 99.59\ N, -99.56\ N \tag{7}$$

$$\left(F_{range}\right)_{Aft} = 10.0257020(\pm 10) - 0.0486739 = 100.21\ N, -100.31\ N \tag{8}$$

Suppose the recorded voltage readings during a wind tunnel test are 2.21 V, 2.56 V, 3.04 V for fore, aft and drag load cells, respectively. Then using the calibration equations from Eq. 6-8, the resulting forces can be calculated:

$$Drag = 9.9943097(3.04) - 0.0455935 = 30.34\ N \tag{9}$$

$$Fore = 9.9571882(2.27) + 0.0141935 = 22.62\ N \tag{10}$$

$$Aft = 10.0257020(2.56) - 0.0486739 = 25.62\ N \tag{11}$$

Then, using Eq. 1-3, the lift and pitching moment can be calculated:

$$Lift\ (N) = Fore\ (N) + Aft\ (N) = 22.62 + 25.62 = 48.24\ N \tag{12}$$

$$Drag\ (N) = 30.34\ N \tag{13}$$

$$Pitching\ Moment\ (Nm) = \left(Fore\ (N) - Aft\ (N)\right) * 0.0635 = -0.1905\ Nm \tag{14}$$

The drag force data from the display module is compared with the LabView data and tabulated in Table 7. As seen below, the error for the no weight (0 kg) is very high. This can be due to slight rotation of the ring or the weight of ring itself. The rotation of the ring creates a minute centrifugal force acting tangent to the velocity that may create an imbalance in the drag force measurement. In the case of fore and aft load cells, the assumption is equally distributed weights might be slightly inaccurate as the forces due to rotation can cause different force measurements as well.

As more weight is added, the cable becomes stiffer and less prone to movement. This is seen from the decreasing trend of percent error in the Table 7 below. Due to the high error, the measurements for no force applied are no useful. However, for the added weights, the error is less than 5% so they can be reliable, and calibration is complete. The force balance needs to be recalibrated if the system is moved, or when the tension cables are moved [1].

Table 7. LabView data and display module outputs error comparison.

Mass [kg]	LabView Drag [N]	Display Module Drag [N]	Error [%]
0	-0.045594	-0.41	88.8795
1	9.796755	9.34	4.8903
2	19.671825	19.07	3.1559
3	29.477456	28.83	2.2458
4	39.271934	38.61	1.7144
5	48.977625	48.28	1.4450

Apart from movement of masses during measurement being a source of error, another can emerge from the uneven number of recordings captured for each data set in a duration of 5 seconds. For this purpose, an average value is taken are calibration. Yet, the data is slightly offset with load cells measuring a voltage for no force applied. This can be related back to movement of the small ring attached to the tension cable that allows to hook masses on. The calibration bar alignment near the pulley can also be a source of error if not aligned properly. Lastly, there can be noise in data from various control and electric devices used.

The resolution of the system can be determined by checking the variation data. The maximum voltage range measured is $\pm$ 10 V and the load ranges are 99.89 N and -99.98 N for the fore cell, 99.59 N and -99.56 N for the aft load cell and, 100.21 N and -100.31 N for the drag load cell. The voltage range must not be exceeded to keep calibration within proper resolution. If exceeded, the errors may be large. This would mean the maximum loading mass is approximately 9 kg. It may be difficult to verify the data outside the resolution of the system. Above higher loads than the maximum load, the system may become non-linear and thus the calibration curves generated will not be useful.

V. Conclusion

In this experiment, the importance of calibration of an instrumentation system is understood by using a 3-component force balance (AFA3) for the AF100 wind tunnel. The fore, aft and drag forces are measured through three separate load cells. The fore and aft loads cells are assumed to be placed equidistant from each other connected to a mounting pulley using flexible cables. Due to the flexible nature of cables, they must remain in tension for force measurements. Two different orientations are used: vertical cable position for fore and aft load cells where horizontal position for the drag load cell. The weight is assumed to be distributed evenly between the fore and aft load cell. The force is expected to have a linear relationship to voltage measured by the load cell that uses strain gages.

The calibration curves are generated for the masses (0 kg to 5 kg) used with the averaged measured voltage data. These offset data are corrected by generating new calibration curves with offset corrected data. The corrected curves are linear and used to find respective forces using the trendline equations. The R^2 values for all the trendlines obtained are 0.99, close to 1 indicating precision. Then, using the force estimates and actual force values, the percentage error is calculated for all three load cells and six weight readings. The highest error is seen for no force applied (0 kg) values ranging from 1% to 5%. This can be attributed to the inherent weight of the ring attached at the end of the cable and its movement. For the other mass readings, the error is less than 1% giving reliability.

The sensor variation is calculated by finding the minimum and maximum recording values in each data set. Among these, the highest variation in sensors is quite varied for three load cells. For the fore load cell, the highest variation is seen at 2 kg, whereas 1-3 kg for the aft load cell. The drag load cell has higher variation for 4-5 kg. Since the masses are not evenly distributed, such that there is a rectangular cut in-between, this can cause variation in data through movement. Sample measurements of lift, drag and pitching moments are calculated using the corrected calibration curves resulting in values of 48.24 N, 30.34 N and -0.1905 N-m, respectively.

Using the known range of sensor at $\pm$ 10 V, the loading range was calculated for fore, aft and drag load cells. The maximum voltage range measured is $\pm$ 10 V and the load ranges are 99.89 N and -99.98 N for the fore cell, 99.59 N and -99.56 N for the aft load cell and, 100.21 N and -100.31 N for the drag load cell. This means going above 9 kg of masses may introduce large errors in the system and make it non-linear. Then, the calibration curves generated will not be effective. The possible sources of errors can stem from the movement of masses (sometimes rotation), the electrical devices, the location of fore and aft load cells, and uneven sensor data measurements for a given duration.

References

[1] MAE 3182: Calibration of the Force Balance for the AF-100 Low-Speed Wind Tunnel. The University of Texas at Arlington, Department of Aerospace and Mechanical Engineering, Fall, 2023.