Calibration of the Wright Brothers' Lift Balance

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The procedure that the Wright Brothers used to calibrate the Lift Balance for their 1901-1902 wind tunnel experiments has recently been discovered in the archives of Wright State University. This procedure, written by Orville Wright, describes the iterative process that not only allowed the Wrights to calibrate the lift balance so that accurate lift measurements could be made, but also reduced errors introduced into the lift measurements due to the design of the lift balance itself.

Nomenclature

L	= Lift, pounds	k	= Smeaton's Coefficient
V	= Wind velocity, MPH	S	= Planform area of wing, ft^2
C_l	= Lift coefficient of wing	L_a	= Lift force acting on airfoil
S_a	= Planform area of airfoil	C_l^a	= Lift coefficient of airfoil
D_a	= Drag force acting on airfoil	C_d^a	= Drag coefficient of airfoil
D_f	= Drag force acting on resistance fingers	S_f	= Surface area of resistance fingers
C_d^f	= Drag coefficient of resistance fingers	d	= Length of (I) and (H) arms

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D_e = Drag force acting on (I) arms

D_{rp} = Drag force acting on resistance plate

β = Ratio of drag on resistance plate to drag on resistance fingers

I. Introduction

The information presented in this paper came about as the result of a junior high school science fair project. This project quickly became a journey through the early history of the Wright Brothers' work to design and build the world's first powered, heavier-than-air flying machine. With the simple request, "Dad, I want to build a replica of the Wright Brothers wind tunnel for my science fair project," the process of discovery began.

Based on that request, engineering plans for the Wright Brothers Wind Tunnel and Balances[1] were purchased in February of 2004. By April of 2004, a full size replica of the Wright Brothers wind tunnel and lift balance had been constructed. The tunnel and balance operated admirably, and lift measurements on several airfoils were made. However, after using the wind tunnel and lift balance, we had one fundamental question about the lift balance that we could not answer. How did the Wright Brothers know that the measurements that they were making were accurate? We began a literature search to obtain answers to this question.

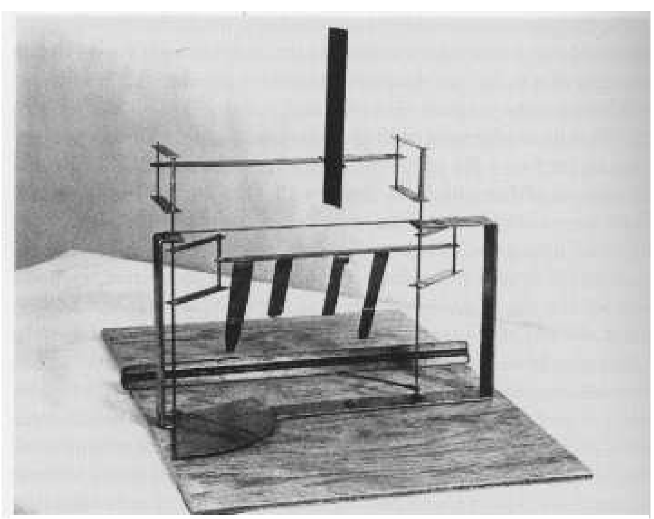

Figure 1: Wright Brothers Lift Balance

In late 1901, the Wright Brothers designed and built a simple wind tunnel and two devices to measure the lift and drag of airfoil shapes. Obviously, the invention of the first powered, controllable airplane is a much more interesting subject for many authors, so the Wright's wind tunnel work is often glossed over in the numerous books and articles written about their work. Nevertheless, it is well documented that their 1901 wind tunnel work was a significant turning point in their journey of invention. Of particular interest for this article is the instrument that they designed to measure the lift of various airfoils. They referred to this instrument as the lift balance (Figure 1). The lift balance was built using materials that the Wrights had readily available in their bicycle shop: scrap steel, old bicycle spokes and broken hacksaw blades. It was an instrument that could be used to accurately and quickly measure the lift generated by small, model airfoils. Even the airfoils, made from sheet steel, could be made very quickly using simple hand tools that were readily available.

The lift balance is a simple device in principle, but its design is an elegant statement of the Wrights understanding of the forces working on an airfoil. Details of the lift balance construction and operation will be presented in the next section.

To fully appreciate the significance of the Wright's wind tunnel experiments, we must first understand the frustrations that the Wrights felt after their 1900 and 1901 glider experiments at Kitty Hawk, North Carolina. Always striving to learn as much as they could from their experiments, as the Wrights flew their gliders as kites during these two seasons, they made measurements of the lift and drag characteristics of their gliders using a spring scale and inclinometer. During the 1900 glider tests at Kitty Hawk, the Wrights found that the lift produced by their glider was only one-half of what they had predicted.[2] The glider built for the 1901 trip to Kitty Hawk produced lift that was only one-third of their predictions.[3] The Wrights returned to Dayton in August of 1901 disheartened.

The Wrights were confident of their calculations of lift and drag, but after experiencing the poor performance of the gliders during the previous two years, they became uncertain of the data they were using to calculate the lift of their machines. The well-known equation of lift that the Wright Brothers used to calculate the lift of their gliders was

$$L = kV^2 SC_l \tag{1}$$

At Kitty Hawk, they used a spring scale and an inclinometer to determine the total lift of the machine. The planform surface area of the wing was easily calculated. The wind velocity term was measured using an anemometer loaned to them by Octave Chanute. The values of Smeaton's coefficient and the lift coefficient (at the measured inclination) were obtained from work previously published by other experimenters.

Smeaton's coefficient was a constant value that related air velocity to air pressure. It basically is a measure of the force necessary to move a one square foot plate through the air at one mile per hour, with the flat plate oriented perpendicular to the airflow. The British engineer, John Smeaton, published his work in 1759, and this coefficient became a standard value that was used without question for close to 150 years. The Wrights used the same value of Smeaton's coefficient that Otto Lilienthal, the German experimenter who had died in a gliding accident in 1896, had used in his experiments.

The values that the Wrights used for their airfoil's lift and drag coefficients were also taken from the work of Lilienthal. Lilienthal had published tables of lift and drag coefficients which related the lift generated by an airfoil to its angle of attack. The Wrights had read all of Lilienthal's work, and were using the coefficients that Lilienthal had measured for the wing shape used in his gliders.[4]

As the Wrights considered the potential errors in the data they were using, several possibilities surfaced. The first possible source of error in their calculations was the value of Smeaton's Coefficient that they were using. The second possibility was that the values of lift they were using from Lilienthal's work were in error. Finally, both values might be incorrect.

By 1901, more than a dozen values of Smeaton's coefficient had been published[5]. Lilienthal had used the standard figure of 0.13. The system of units the Wrights used in their calculations differed from the units used by Lilienthal, so the equivalent value used by the Wrights was 0.005. After the 1901 gliding season, the Wrights attempted to validate their value of Smeaton's Coefficient. To do this, they used the lift and drag data that they had measured at Kitty Hawk. They rearranged the lift equation and solved for Smeaton's coefficient. Using the measured results from many different kiting experiments, the average value of Smeaton's Coefficient that they arrived at was 0.0033. This value also compared favorably to values published by Charles Marvin of the U.S. Weather Bureau[6]. Based on this information, the Wrights felt that a value of 0.0033 was more appropriate for their use.

Since Lilienthal had used an erroneous value for Smeaton's Coefficient of 0.005, they thought that his values for the lift coefficient might also be in error. To test the possibility of incorrect values of the lift coefficient, they devised a simple experiment. They placed a small model airfoil in an air stream. The lift forces acting on this model were balanced against the drag forces acting on a flat plate oriented perpendicular to the same airflow. With this device, the Wright's could determine the airfoil angle of attack at which the lifting force on the wing was equal to the drag force on the flat plate. Attaching this device to a bicycle and riding at a constant speed helped them produce a steady airflow for this experiment. Since the results of this experiment differed from the calculations based on Lilienthal's data, they were certain that Lilienthal's lift coefficient data was also in error.

This apparatus allowed the Wrights to determine that Lilienthal's data were incorrect, but it was not sufficiently accurate to provide them with data that they felt comfortable using in their designs. The Wrights set out to design a more accurate device to measure the lift coefficient. Ultimately, they built a wind tunnel that was 6 feet long, with a square cross section 16 inches on each side. Two balances were designed that provided them with a measure of the lift coefficient and the drag coefficient of a model airfoil. The 'lift balance" allowed them to directly measure the lift coefficient of a model airfoil. The "drift balance" allowed them to measure the ratio of drift to lift. With this ratio and the previously measured value of lift, the drift of the airfoil as a function of the angle of attack could be calculated. Note that in early aeronautics, the term "drift" was synonymous with today's use of the term "drag."

In our project, we focused our attention on the lift balance and its operation. The next section will describe how the lift balance was operated, and the concepts behind its design.

II. Lift Balance Construction and Operation

On January 19, 1902, Wilbur Wright wrote a letter to Octave Chanute describing the lift balance that they had developed.[7] In this letter, Wright explains to Chanute how the design of the lift balance eliminates errors associated with variation in wind velocity and atmospheric conditions. Wright also tells Chanute that the design also eliminates errors due to the travel of the center of pressure and variations in the angle of attack.

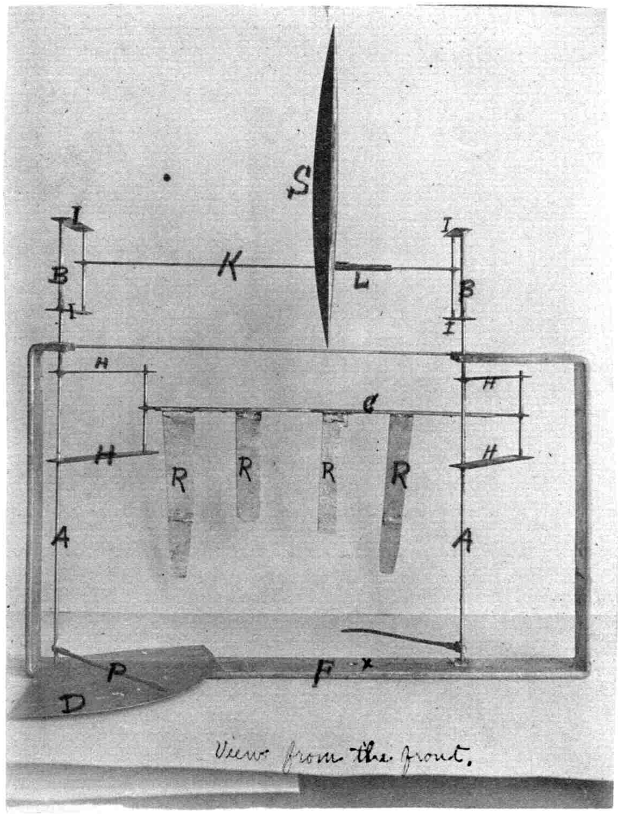

Figure 2: Picture of lift balance included in January 19, 1902 letter from Wilbur Wright to Octave Chanute.

Also included in this letter were Wilbur Wright's description of the lift balance operation, a picture of the lift balance (Figure 2) and a sketch of the device with important components labeled. Together, they give the reader a reasonable understanding of the method of operation. However, it does not describe the ingenious design of the device, and how it provided the Wright's with a method for accurately measuring the lift coefficient of a small airfoil and simultaneously eliminating their concerns over Smeaton's Coefficient.

Referring to Figure 2, the lift balance consists of a frame (F) that is securely attached to the bottom of the wind tunnel. This frame supports the other components of the balance. Two vertical axles (A) pass through holes in the upper arms of the frame and support 4 horizontal arms labeled (H). The (H) arms are firmly soldered to the axles (A). A crossbar (C) is supported by the 4 arms (H). A short axle is soldered near each end of the crossbar (C). These short axles pass through small holes in the upper (H) arms, and rests on the lower (H) arms. Attached to the crossbars (C) are the four resistance fingers (R). Four additional horizontal arms (I) are attached to the vertical axles (A). These arms are not soldered directly to the vertical axles, but are attached to the axles through "Friction Sleeves". Similar to the lower (H) arms, the (I) arms support a crossbar (K) supported by short axles. The friction sleeves allow the (I) arms and the crossbar (K) to be rotated manually relative to the axle (A). However, the friction is sufficient to prevent the (I) arms from rotating relative to the axles (A) as the wind tunnel is operating and the lift and drag forces of the airfoil being tested are acting on the lift balance. The airfoil being tested (S) is attached to the upper crossbar (K) using a small bracket (L). The airfoil is attached to the crossbar such that the angle of attack of the airfoil relative to the airflow in the tunnel can be adjusted. Due to the 4 bar linkage design of the lift balance, as the axles (A) rotate due to the forces acting on the airfoil and resistance fingers, the airfoil is always presented to the direction of the airflow at the same angle. This prevents the angle of attack from changing as the lift balance swings as it reaches equilibrium in the airflow.

A pointer (P) is attached to each axle (A) near the bottom of the axle. One pointer is placed over dial (D), and allows the operator to determine the number of degrees that the axles have rotated. As will be shown, the amount of rotation is directly proportional to the measured lift coefficient.

Referring again to Figure 2, the airflow from the wind tunnel travels from the observer's position towards the lift balance. The longitudinal axis of the airfoil is oriented vertically and lift produced by the airfoil acts towards the right. The vertical orientation of the airfoil prevents the force of gravity from entering into the lift measurement. The drag produced by the airfoil acts in the direction of airflow over the airfoil, and thus acts towards the rear of the lift balance.

During normal operation of the lift balance, there are three basic forces acting on the device. These forces include the lift force acting on the airfoil, L_a, the drag force acting on the airfoil, D_a, and the drag force acting on the resistance fingers, D_f.

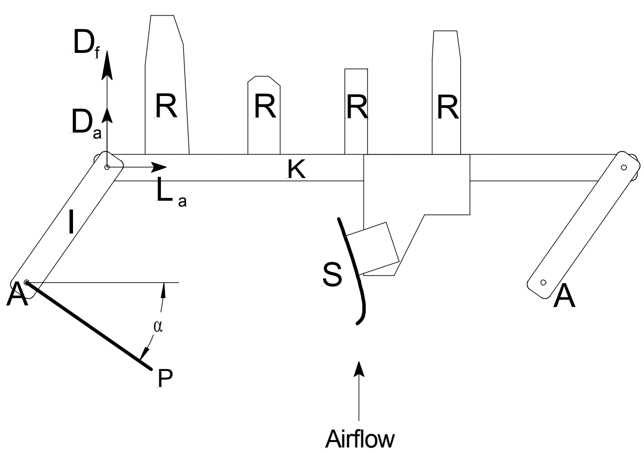

Figure 3: Plan view of lift balance with forces acting on airfoil (S) and resistance fingers (R) shown. The (I) arms are oriented directly over the (H) arms in this figure.

Referring to Figure 3, these forces are drawn in a plan view of the lift balance. While the forces are acting directly on the airfoil and the resistance fingers, they can be translated to the short axles on each end of the upper and lower crossbars. The airfoil lift and drag forces act on the upper crossbar, while the resistance finger drag force acts on the lower crossbar. Since one half of each force acts equally on each end of the crossbar, the entire force acting on the crossbar is translated to one short axle on each crossbar for the purpose of this analysis.

The lift balance configuration shown in Figure 3 is the typical starting configuration during normal operation. The upper crossbar is placed directly over the lower crossbar. The airfoil (S) is placed on the upper crossbar (K) and the airfoil's angle of attack is adjusted to the desired angle. With the airflow in the wind tunnel started, the lift balance quickly comes to an equilibrium position due to the forces acting on the airfoil and resistance fingers. At this point, it is important to understand the three aerodynamic forces acting on the lift balance.

First, the lift produced by the airfoil, L_a, is described as

$$L_a = kV^2 S_a C_l^a \tag{2a}$$

where C_l^a is the coefficient of lift of the airfoil. The second force acting on the lift balance is the drag force acting on the airfoil:

$$D_a = kV^2 S_a C_d^a \tag{2b}$$

The third force acting on the lift balance is the drag force produced by the resistance fingers:

$$D_f = kV^2 S_f C_d^f \tag{2c}$$

In the early days of aeronautical research, the coefficient of lift was measured relative to a known resistance force. In the case of the Wright Brother's lift balance, the lift coefficient was measured against the drag produced by a flat plate oriented perpendicular to the airflow. At that time, the coefficient of drag of a flat plate was defined to be exactly equal to 1.0. Therefore, in equation 2c, the C_d^f term is equal to 1.0.

As the lift balance is operated, the moments produced by these three forces L_a, D_a, and D_f achieve equilibrium at some angle, α, as shown in Figure 3. Since the Wright's only wanted to measure the force due to the lift of the airfoil and not the drag force on the airfoil, they devised an ingenious step in their experiment. They eliminated the moment due to the drag on the airfoil by rotating the upper crossbar (K) relative to the lower crossbar (C). This rotation was achieved through the friction sleeves. Figure 4 shows the configuration of the lift balance when the drag force due to the airfoil, D_a is eliminated.

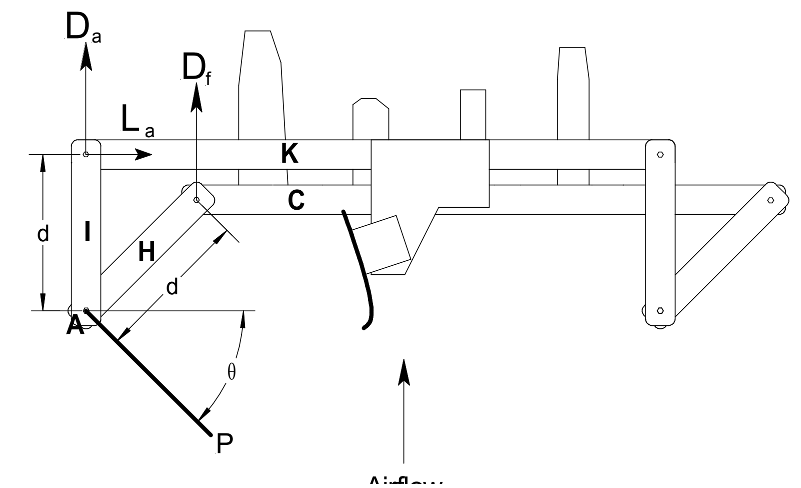

Figure 4: Plan view of lift balance configured to eliminate the torque due to the drag on the airfoil.

In Figure 4, if we sum the torques created by the L_a, D_a, and D_f forces about the pivot axle (A) the following static balance equation can be written:

$$L_a d = D_f d \cdot \sin(\Theta) \tag{3}$$

where d is the length of the (I) and (H) arms. Notice how the drag force acting on the airfoil, D_a, is not present in this equation since that force acts through the pivot (A), therefore producing no moment. The procedure to eliminate the drag force acting on the airfoil is a very important concept in the design of the lift balance.

Next, substituting Equations 2a and 2c into equation 3, we obtain

$$kV^2 S_a C_l^a d = kV^2 S_f C_d^f d \cdot \sin(\Theta) \tag{4}$$

Another very important concept behind the design of the lift balance becomes very obvious at the next step in the analysis. Setting C_d^f equal to 1.0 and simplifying Equation 4 shows us that Smeaton's Coefficient and the velocity squared terms both cancel, leaving

$$C_l^a = \frac{S_f}{S_a} \sin(\Theta) \tag{5}$$

From equation 5, the measured lift coefficient of an airfoil at a specific angle of attack is calculated by taking the sine of the angle measured on the lift balance dial. That value is multiplied by the ratio of the resistance finger area to the airfoil area. In the Wright's notes, the area of the resistance fingers is usually given as 8 square inches. Most of their airfoils had a surface area of 6 square inches[8].

Once a measurement was taken, the airfoil's angle of attack was changed and the process was repeated. The Wrights completed the measurement of an airfoil's lift characteristics by measuring the lift coefficient at 14 different angles of attack ranging from 0° to 45°.

The design of the lift balance allowed the Wrights to easily determine the lift coefficient of an airfoil at a specific angle of attack, independent of Smeaton's Coefficient and the velocity of the air flowing over the airfoil. Specifically, they could investigate a large number of airfoil configurations quickly without having to consider if the value of Smeaton's Coefficient that they were using affected their test results. The lift balance design is an elegant step towards finding answers to some troubling problems that the Wrights were facing regarding the performance of their gliders in 1900 and 1901.

III. Intriguing Questions

Despite the ease and simplicity of the lift balance operation, several questions arose as the young author used the lift balance in his science fair experiments. How did the Wright's know that the resistance fingers produced the same drag as an eight square inch plate? Looking at the shapes of the resistance fingers, one also wonders how the Wright's arrived at those shapes. The Wright's letter to Octave Chanute on January 19, 1902 describing the lift balance provides an interesting hint to those questions.

In an attachment to this letter, Wilbur Wright states, "*The resistance planes RRRR, are used instead of a single square plane to avoid deflecting the direction of the wind which strikes the surface S. They have no definite area themselves, but along with the crosspiece C have a pressure equal to that of a square plane of 8 sq. inches mounted at the place where S appears in illustrations.*" This statement implies that the resistance fingers are equivalent to an 8 square inch plate, but the area is not necessarily 8 square inches. In fact, the area of the resistance fingers is approximately 7.35 square inches. The statement also hints to the fact that an 8 square inch plate may have been mounted in the airfoil position (S) to verify the drag of the resistance fingers. We wondered if this was done during a calibration procedure.

After reviewing many publications regarding the Wright's work, no evidence of a procedure to calibrate the lift balance was found. We contacted the National Air and Space Museum (NASM) and inquired about a possible calibration procedure. Wright historians at NASM were not aware of any documented method used to calibrate the lift balance.

To obtain accurate values for the lift coefficients, the Wrights had to know that the drag produced by the resistance fingers was equivalent to the drag produced by a flat plate of 8 square inches placed perpendicular to the airflow. How did they know this? This question led us on a journey of discovery, which ultimately provided us with another look into the genius of the Wright Brothers.

IV. "To Calibrate Lift Balance"

Since the authors reside in the greater Cincinnati, Ohio area, a wealth of Wright Brothers resources are available a short distance away in Dayton, Ohio. During our search for information regarding the lift balance, we found the Internet web site for The Wright State University's Special Collections & Archives Department. In this department is a collection of Wright Brothers documents and information. Since we were so close to Dayton, we decided to contact the University to see if we could gain access to their Wright Brothers Collection. We discussed our interests with Jane Wildermuth in the Special Collections and Archives Department, who suggested that we come to the University to look through the Wright Collection. She also suggested reviewing their Max Baker Collection.

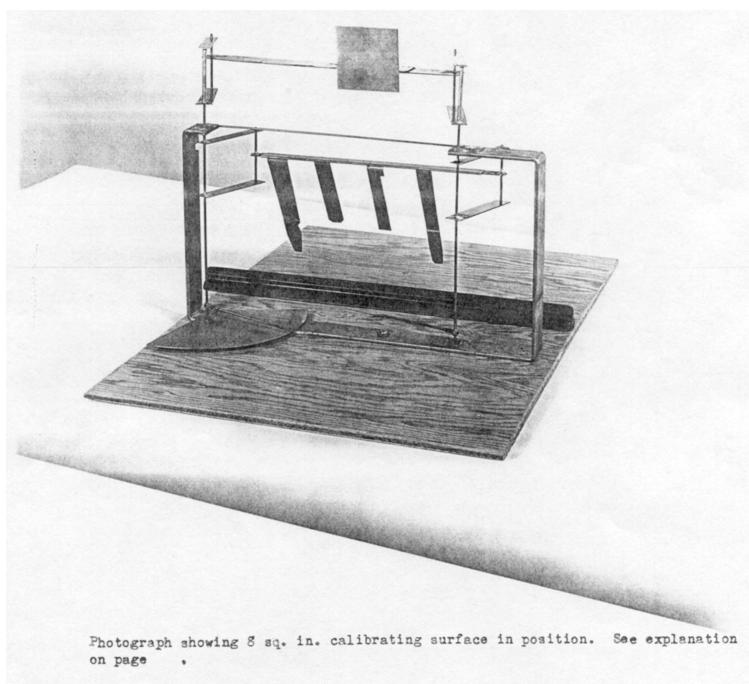

Figure 5: Picture showing lift balance with calibration surface

While at Wright State, we searched through the Wright Brothers Collection, but found nothing relating to the calibration of the lift balance. Somewhat disappointed, we decided to take a quick look through the Max Baker Collection. Max Baker was an engineer in the Dayton area that became interested in aeronautics and the Wright Brothers as a young boy after witnessing some Wright Brothers flights from 1910 to 1915. Throughout his career, Baker worked for several automotive companies as well as aerospace companies. While working at Waco Aircraft, Baker became Assistant Chief Engineer. After Orville Wright's death in 1948, Max Baker assisted the technical advisor to the Wright Estate, Harvey Geyer. This enabled Baker to collect information for his research about the Wright Brothers.

While looking through a file of unpublished technical papers that were written by Max Baker, we found one paper that contained a section entitled, "To Calibrate Lift Balance". We also found a picture, shown in Figure 5, which shows a "calibrating surface" installed on the lift balance. We also found an annotated sketch of the lift balance similar to the one sent to Octave Chanute by Wilbur Wright in his January 19, 1902 letter.

After reading this section of the paper, we were very excited to find a description of the procedure that the Wright Brothers used to calibrate the lift balance. Moreover, Baker wrote "*Despite the beautiful simplicity of the instrument, the arms R, R, which held the resistance beam were always at some cross angle to wind, and this added a resistance couple which could not be directly measured. To get around this difficulty the Wright's developed a calibration procedure which is best described in Orville's own words*"

The next page contained a quoted section that described a procedure of adjusting and manipulating the lift balance under very specific conditions. Upon initial review of this document, the written calibration procedure made little sense to us. It was clear that we were not going to be able to understand the procedure while we were at Wright State, so we made copies of the relevant documents, picture, sketch, and departed.

The calibration procedure written by Orville Wright is as follows[9]:

"In measuring lift, the arms H, H must be kept parallel with the air stream so that there is no drag included in the measurement of the lift. Otherwise, a different correction for every different angle of H, H, H^1, H^1, so that direct readings of pointer P may be used, calibrate instrument as follows:

a. *Measure the drag H, H, H^1, H^1, including J, when H, H stands at 60° to the left. The pointer P will probably indicate two or three degrees on the dial D.*
b. *Add the sine of the small angle a, so determined, to the sine of 60°.*
c. *Find the angle of which this sum is the sine (angle c).*
d. *Mount a square plate measuring 2.8284 inches to the side (8 in^2 area) on K parallel to J (90° to the air stream).*
e. *Adjust B, B, till H, H is held at 60° by the air pressure on R, R, R, R. If R, R, R, R are of proper area, H, H should be held at 60° when the pointer stands at the angle c determined above (60° plus).*
f. *If the angle is found to be greater than the angle c add to the area of R, R, R, R until the plane H, H, H^1, H^1 at 60 balance R, R, R, R at the angle c.*
g. *If the angle is found to be less than the angle c, reduce the area of R, R, R, R.*

The above operations may have to be repeated several times if exact results are desired.

When the machine is properly calibrated a plane 2" by 2" (4 sq. in.) mounted in the place of the 8 sq. in. plane should indicate an angle the sine of which equals sine angle c."

Some of the instructions in the written calibration procedure were ambiguous, while some of the terminology was undocumented. Specifically, we believe that the sketch we found with the unpublished Max Baker paper does not match the nomenclature used in the written calibration procedure. Arms were called H, H in the procedure, but were not labeled as such in the sketch. The component J was not shown in the sketch, but was referred to in the written procedure. Initially, these discrepancies made the written procedure hard to understand.

Using the wind tunnel and lift balance that we had at our disposal, we tried to follow the procedure of calibrating the lift balance, but were unsuccessful in our initial attempts. After several tries, we finally developed an understanding of the procedure as it was written, and will describe each step below.

In the first step,

a. Measure the drag H, H, H^1, H^1, including J, when H, H stands at 60° to the left. The pointer P will probably indicate two or three degrees on the dial D.

the lift balance is adjusted as shown in Figure 6. Using the terminology adopted in this paper, the H, H arms are labeled as (I) instead. The (I) arms must be adjusted in an iterative process to make them stand at 60° to the left. Once this is accomplished, the pointer does indicate a small angle, labeled '**a**', in Figure 6. Angle 'a' is due to drag on the (I) arms as they stand at a 60° angle to the airflow. If there was no drag on the (I) arms, the angle '**a**' would be 0°. Also, the measured angle **'a'** is different for different positions of the (I) arms.

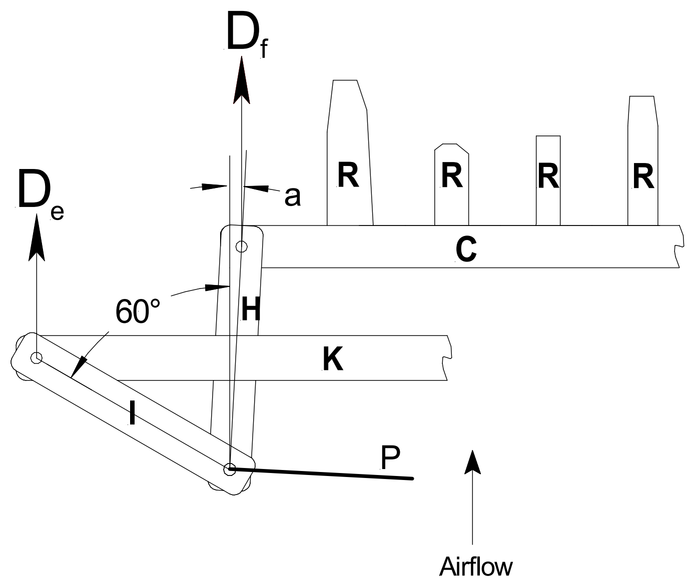

Figure 6: Plan view of lift balance configured with the (I) arms standing 60° to the left.

The D_f term shown in the figure is the total drag due to the resistance arms (R), the cross bar (C), and the (H) arms. The drag error term, D_e, shown in Figure 5 is the drag due to the (I) arms and the cross bar (K). Since no airfoil is installed on the lift balance, D_f and D_e are the only forces acting on the lift balance.

Writing a moment balance about the pivot point for these two forces acting on the lift balance produced the following equation:

$$D_e = \frac{D_f \sin(a)}{\sin(60°)} \tag{6}$$

This drag error, D_e, is the error due to the drag acting on the arms (I), when (I) is at some angle to the flow, and the cross bar (K). This drag quantity is not included in the calculation of the lift coefficient in equation (5), so at this point the Wrights are quantifying this error by measuring the effect this drag component has compared to the drag created by the resistance fingers D_f.

The second, third, and fourth steps,

b. Add the sine of the small angle a, so determined, to the sine of 60°.

c. Find the angle of which this sum is the sine (angle c).

d. Mount a square plate measuring 2.8284 inches to the side (8 in 2 area) on K parallel to J (90° to the air stream).

describe the calculation procedure for determining an angle referred to as the angle '**c**'. According to the written calibration procedure, angle **'c'** can be calculated as follows:

$$c = \sin^{-1}[\sin(a) + \sin(60°)] \tag{7}$$

The purpose of this calculation was not documented in Orville Wright's calibration procedure. Through further analysis, this angle '**c**' was determined to be a "calibration" angle that would indicate when the lift balance was calibrated. The significance of this angle will be shown in the following analysis.

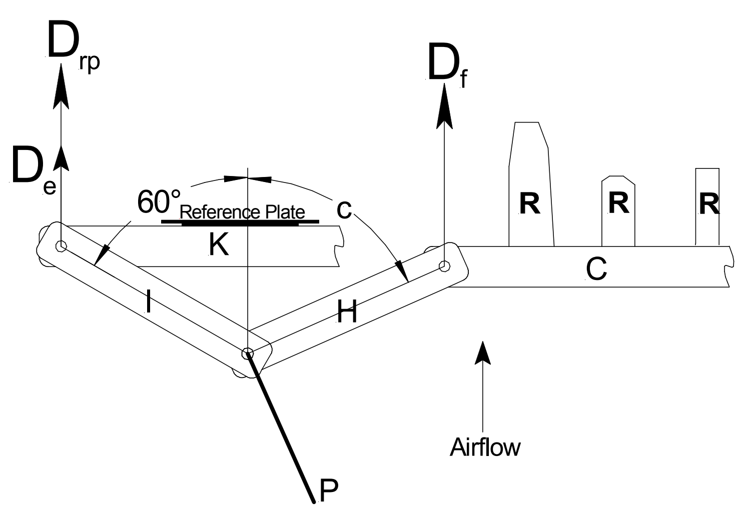

Figure 7: Plan view of lift balance configured with the (I) arms standing 60° to the left, and an 8 square inch reference plate installed on cross bar (K).

Following the fourth step in the calibration procedure, an 8 square inch reference plate was mounted to the upper cross bar (K) as shown in Figure 7.

In this diagram, the D_{rp} force represents the force on the lift balance due to the drag generated by the reference plate. The D_e term represents the drag generated by the (I) arms and the (K) cross bar as defined in equation 6.

At this point, let's assume that the (H) arms stand at an angle '**c**' to the airflow as shown. The D_f force shown in Figure 6 represents the force acting on the lift balance resulting from the drag produced by the resistance fingers.

Writing the moment balance for the forces shown in Figure 7 produces

$$(D_e + D_{rp})\sin(60°) = D_f \sin(c) \tag{8}$$

Substituting equation 6 into equation 8 and simplifying yields,

$$D_f \sin(a) + D_{rp} \sin(60°) = D_f \sin(c) \tag{9}$$

The primary purpose of the calibration procedure is to ensure that the drag produced by the reference fingers is equal to the drag produced by the reference plate. In equation 9, the D_f and D_{rp} terms represent those quantities. To simplify equation 9, a ratio of the reference plate drag to the resistance finger drag will be introduced

$$\beta = \frac{D_{rp}}{D_f} \tag{10}$$

This quantity will be used later in the calibration procedure to check the calibration results against a 4.0 square inch reference plate.

Substituting equation 10 into equation 9 gives

$$\sin(a) + \beta \sin(60°) = \sin(c) \tag{11}$$

For now, the β term is equal to 1.0. Solving for angle '**c**' gives

$$c = \sin^{-1}[\sin(a) + \beta \sin(60°)] \tag{12}$$

This equation is equal to equation 7, which is the result of the calculation done in steps *b*. and *c*. of the calibration procedure.

Using this analysis, a better explanation of the "calibration" angle 'c' can be developed. The physical significance of the angle '**c**' is two-fold. First, adjusting the resistance fingers until they provide a drag equivalent to the reference plate ensured the Wright Brothers that the lift measurements that they were making were accurate. Secondly, this calibration procedure reduces the errors that are related to the drag created by the lift balance mechanism that is not included in the normal measurement procedure.

As calculated, the angle '**c**' will be larger than 60°, which implies that the drag produced by the resistance fingers will be *less* than the drag produced by the reference plate. This reduction in drag is made to balance the additional unaccounted drag produced by the arms (H) and cross bar (K). If no drag was produced by the (H) arms and the (K) cross bar, then the small angle '**a**' measured in the first step of the procedure would be zero. Calculating the **'c'** angle in the second and third steps would yield an angle **'c'** of 60°. In this case, the drag from the resistance fingers would exactly balance the drag from the reference plate.

The Wrights developed this procedure in an attempt to reduce the errors due to the unaccounted for drag in the lift balance.

Continuing on with the calibration procedure, the fifth step is the measurement of the angle **'c'**.

e. *Adjust B, B* (friction sleeves)*, till H, H is held at 60° by the air pressure on R, R, R, R. If R, R, R, R are of proper area, H, H should be held at 60° when the pointer stands at the angle c determined above (60° plus).*

In an iterative process, with the reference plate installed on the lift balance, the (I) arms are adjusted until the (H) arms are standing at a 60° angle to the airflow. The '**c**' angle is then read from the pointer (P). If this angle **'c'** is equal to that calculated in the third step, then the lift balance is calibrated. If the measured angle is not equal to the calculated angle '**c**', then one of the next two steps in the calibration procedure is required.

If the measured angle '**c**' is greater than the calculated angle '**c**', then the sixth step is used to correct that condition.

f. If the angle is found to be greater than the angle c add to the area of R, R, R, R until the plane H, H, H^1, H^1 at 60 balance R, R, R, R at the angle c.

If the measured angle '**c**' is greater than the calculated angle, that indicates the drag created by the resistance fingers is too small, and must be increased. One way to increase the drag is to add to the area of the fingers. If the difference in the two angles is small, another possible way to add to the drag created by the resistance fingers would be to bend the resistance fingers towards the air stream, increasing the projected area of the resistance fingers.

If the measured angle '**c**' is less than the calculated angle, then the seventh step in the calibration procedure is used to correct that condition.

g. If the angle is found to be less than the angle c, reduce the area of R, R, R, R.

If the measured angle '**c**' is less than the calculated angle that means the drag created by the resistance fingers is too great, and must be decreased. Area can be removed from the resistance fingers to accomplish this, or the fingers could be bent away from the air stream to reduce the projected area of the resistance fingers.

Finally, the last statement in the procedure

The above operations may have to be repeated several times if exact results are desired.

means that all of the steps in the procedure must be repeated if any changes are made to the resistance fingers. Any change to the resistance fingers will change the measured angle '**a**', which changes the calculated angle '**c**'.

Repeating the entire process several times will lead the experimenter to the point where the resistance fingers are adjusted such that they produce the necessary drag for accurate measurements.

V. Experimental Results

After working through the calibration procedure and understanding the mathematics and logic that were employed by the Wright Brothers, we used the procedure to calibrate our reproduction lift balance. When we constructed our lift balance, the four resistance fingers were built as closely as possible to the plans, and were bent backwards at a forty-degree angle to the airflow, as indicated in the plans.

Before discovering this calibration procedure, we had found that adjusting the angle of the resistance fingers would change the amplitude of the lift coefficient curve. As we experimented with this in a trial-and-error fashion, we found that if the fingers were bent at a twenty-five degree angle rather than a forty-degree angle our results agreed better with the Wrights original data. Since the objective of the original science fair project was to determine if a curved airfoil produced more lift than a flat plate with the same aspect ratio, absolute measurements were not required, so we abandoned our efforts to reproduce the Wright's data exactly. After finding the written calibration procedure and working through the procedure to understand what the Wrights had done, we had a renewed interest in arriving at an absolute calibration.

Using the calibration procedure, we initially measured the "small angle a" as 3.5 degrees. This was close to the expected value that Orville stated in the first step of the calibration procedure, *"The pointer P will probably indicate two or three degrees on the dial D.*" We used a measurement tolerance of 0.5 degrees in all of our experiments.

After three iterations of the process, our measured angle '**c**' matched our calculated angle '**c**' within 0.2°. We increased or reduced the drag of the resistance fingers by adjusting their angles relative to the air flow with a measurement tolerance of half a degree. The results of our calibration experiment are shown in Table 1.

Iteration Number	Measured Angle 'a'	Calculated Angle 'c'	Measured Angle 'c'	Comments
1	3.5°	68.0°	55.0°	Bent all resistance fingers from 25° to 32°
2	2.0°	64.3°	67.0°	Bent two center fingers back to 25°
3	2.0°	64.3°	64.5°	Calibrated

Table 1: Experimental results for lift balance calibration using 8 square inch reference plate.

One last step in the written calibration procedure refers to a check of the calibration by testing the lift balance against a 4 square inch calibration plane. As it stated,

When the machine is properly calibrated a plane 2" by 2" (4 sq. in.) mounted in the place of the 8 sq. in. plane should indicate an angle the sine of which equals sine angle c."

Referring back to equations 10 and 12, when the 8 square inch reference plate is replaced by a 4 square inch reference plate, the β term is:

$$\beta = \frac{D_{rp}}{D_f} = \frac{\frac{1}{2}}{1} \tag{13}$$

In other words, the fingers were calibrated to produce drag equivalent to an 8 square inch plate. When this 8 square inch reference plate was used during the calibration procedure, the β term is 1.0 after the lift balance is calibrated. When a 4 square inch reference plate replaces the 8 square inch reference plate, the drag produced by the 4 square inch reference plate is one-half of the drag produced by the 8 square inch reference plate. In this case, the β term becomes ½, and the equation for calculating the '**c**' angle becomes

$$c = \sin^{-1}[\sin(a) + \frac{1}{2}\sin(60°)] \tag{14}$$

Since the reference fingers were not changed in any way after calibrating the lift balance with the 8 square inch plate, the angle '**a**' used for the calibration check does not have to be measured. The value from the last step of the calibration process is used in the calibration check. Therefore, the 2.0° measured angle '**a**' is used. Table 2 shows the results from the calibration check. The agreement between the calculated angle '**c**' and the measured angle **'c'** is within our measurement tolerance.

Measured Angle ‘a’	Calculated Angle ‘c’	Measured Angle ‘c’	Comments
2.0° [a]	27.9°	28.0°	Calibration check is successful

[a] Angle measured during last iteration in 8 square inch reference plate calibration experiment

Table 2: Experimental results for lift balance calibration check using 4 square inch reference plate.

A question arises as to why sixty degrees is used in step “*a*” of the calibration procedure. Orville Wright does not indicate why sixty degrees was chosen. In truth, any angle would suffice and would lead to a successful calibration. Sixty degrees was probably chosen for several reasons. If some angle less than sixty degrees were chosen, the measured angle ‘**a**’ would be correspondingly smaller, making it more difficult to read on the dial. Ideally, larger angles make ‘**a**’ easier to read, but if an angle much greater than sixty degrees is chosen, then the sides of the wind tunnel start to physically interfere with the lift balance operation.

Also, as the lift coefficient curve is measured, the higher values of lift are measured when the (I) arm is at higher angles to the airflow. Using a higher angle for the (H) arm during the calibration process helps to reduce the error in the lift measurements at the conditions at which the Wright’s were most interested. Sixty degrees appears to be a good compromise.

One additional comment is included in the written calibration procedure. Since this comment does not have a direct bearing on the lift balance calibration, it is presented and discussed briefly in the Appendix.

VI. Supporting Data and Documents

At this point in our investigation we believed that we uncovered details on the calibration procedure used by the Wrights in 1901. We have also shown that the calibration procedure is viable and that it seemed to work well as described by Orville Wright. What we have not found is an original reference of the calibration procedure. We have only the unfinished Max Baker paper that quotes Orville Wright (without reference) describing the procedure step by step.

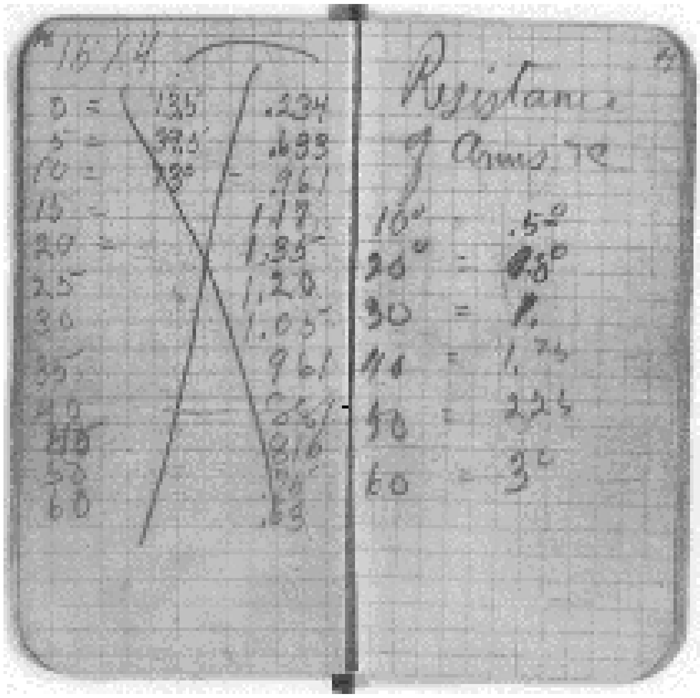

Figure 8: An excerpt from Wilbur Wright's diary circa August 1901

We have searched for the original description in all obvious biographies to no avail. However, while scanning the on-line Wright Archives at the Library of Congress, we found the entry from Wilbur Wright's diary shown in Figure 8. If one were not familiar with the calibration procedure, the meaning of this page may not be understood. With knowledge of the calibration procedure it is clearly recognizable as data taken from the wind tunnel corresponding to step "*a*" in the calibration procedure. The Wrights were measuring angle '**a**' at various arm angles. While this diary excerpt is not definitive proof that the Wrights calibrated the 1901 wind tunnel, it does tie Orville's calibration procedure of unknown date and origin to 1901 Wright activities.

Another reference to the lift balance calibration procedure was found in the Library of Congress on-line archives. In a letter dated October 10, 1945, Orville Wright wrote to Dr. Henry B. Allen, the Secretary and Director of the Franklin Institute in Philadelphia, Pennsylvania, to say that he would be sending him information regarding the wind tunnel and the lift and drift balances. In the list of enclosures that were sent with the letter, the last entry is "Method of Calibrating Lift balance". Since the Library of Congress obtained this document from the files of Orville Wright after his death in 1948, there were no copies of the enclosures sent with this letter. We contacted The Franklin Institute to see if they had retained this letter and the enclosures, but they had not.

To date, the holographic copy of this lift balance calibration procedure has not been found. The only reference to it that we found was in the unfinished, unpublished paper written by Max Baker that resides in the Special Archives Department at Wright State University.

VII. Conclusion

What started out as a seventh grade science fair project has lead to an unexpected look into the thought processes of the Wright Brothers. While the theory behind the lift balance and its operation is relatively straightforward, the question of its accuracy is not so simple. Little has been written concerning the accuracy of the lift balance measurements.[10] Considering the ultimate success of the Wright Brothers at Kitty Hawk on December 17, 1903, the Wrights wind tunnel data must have been reasonable. Just looking at the configuration of the drag fingers used on the lift balance, one must wonder how this accuracy was achieved by the Wrights. We questioned how the resistance fingers accurately represented the requisite drag reference. The cumulative area of the drag fingers did not add up to the expected eight square inches and their shapes were odd at best, and were bent downstream at various angles as seen in early photographs.

As we studied the wind tunnel and lift balance, we concluded that the lift balance had to have been calibrated in some manner when the drag fingers were employed. We further speculated that the drag fingers were trimmed and bent in the final stages of calibration.

Our study of the lift balance calibration procedure has given us a new appreciation of the genius of the Wright Brothers. Their attention to each and every detail is evident in this procedure. The lift balance calibration procedure was not only used to adjust the drag produced by the reference fingers to that of a reference plate, but it also reduced errors due to the design of the lift balance.

Appendix

The Wrights were clever in that they recognized that using a single pointer on the lift balance would generate a small but possibly measurable error in the lift balance measurements. If the airflow were allowed to impinge on a single pointer, an unmeasured moment would be created which would introduce a small error in the lift measurements. An easy solution to this problem was available. They installed a dummy pointer on the opposite side of the lift balance to negate the effects of the required pointer. While the two pointers rotate the same amount, they rotate in opposite directions. The moments created by the airflow hitting each pointer is equal and in opposite directions, so they cancel out of the lift measurements.

According to Orville Wright's final statement in the calibration procedure, as documented by Max Baker,

> *The pressure on the pointer P is not exactly balanced at large angles by the pointer P1 because the c.p. on P will be at a greater radius than on P1. However, this error will be small."*

We have not absolutely determined what the origin of the small error is that Orville is referring to.

Acknowledgments

We would like to thank Dr. John Anderson, Dr. Tom Crouch and Dr. Peter Jakab from the National Air and Space Museum for their support during this work. Early in the project we contacted Dr. Anderson with several questions regarding the resistance fingers on the lift balance. He conferred with Tom Crouch and Peter Jakab, and provided us with some answers, some resources, and further questions for us to consider. Their collective guidance and encouragement during this email exchange provided us with the desire to prove that the lift balance must have been calibrated in some manner. Further, after we had discovered Orville Wright's written calibration procedure, we were invited by Dr. Anderson to the National Air and Space Museum to present our findings.

Special thanks also go to Jane Wildermuth of the Special Collections & Archives Department at Wright State University. She provided invaluable assistance in guiding us during our search of the Wright Archives.

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