DEVELOPMENT OF A SYSTEM FOR THE MEASUREMENT OF AERODYNAMIC FORCES ON ROTATING SPORTS BALLS

By

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The importance of sports engineering has increased in the past decade as the demand for athletes and their equipment has increased. Similarly, the aerodynamics of blunt bodies such as prolate spheroids is of particular interest to aerodynamicists seeking to reduce drag. A system was developed to measure aerodynamic forces on rugby balls. The rugby balls, which varied in size and surface textures, were tested at multiple angles of attack, rotational rates, and wind tunnel velocities. A force balance utilizing load cells in conjunction with a subsonic wind tunnel was used to obtain lift and drag forces. A detailed description of the complete test apparatus is given including methods of mounting, rotation, calibration and tare measurements. Several methods of data acquisition were investigated and the final method is outlined. The results for two balls are given along with the variation in data from repeated testing. Both the force data trends and a few interesting phenomena are discussed.
DEDICATION

My professor and mentors, Dr. Keith Koenig and my loving parents, who always wondered what I was up to and to my girlfriend, Chelly Parcus, who always knew.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>x</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. EXPERIMENTAL DETAILS</td>
<td>5</td>
</tr>
<tr>
<td>2.1 Ball Mount</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Test Apparatus</td>
<td>10</td>
</tr>
<tr>
<td>2.2.1 Test Sting</td>
<td>10</td>
</tr>
<tr>
<td>2.2.2 Sting Base</td>
<td>14</td>
</tr>
<tr>
<td>2.2.3 Rotational Fittings</td>
<td>16</td>
</tr>
<tr>
<td>2.2.4 Test Fairings</td>
<td>20</td>
</tr>
<tr>
<td>2.3 Motor Mount</td>
<td>21</td>
</tr>
<tr>
<td>2.4 Tare Support</td>
<td>24</td>
</tr>
<tr>
<td>2.5 Calibration</td>
<td>26</td>
</tr>
<tr>
<td>2.6 Data Acquisition</td>
<td>30</td>
</tr>
<tr>
<td>2.6.1 Original Method</td>
<td>30</td>
</tr>
<tr>
<td>2.6.2 Revised Method</td>
<td>32</td>
</tr>
<tr>
<td>III. RESULTS</td>
<td>35</td>
</tr>
<tr>
<td>3.1 Calibration</td>
<td>35</td>
</tr>
<tr>
<td>3.2 Initial Testing</td>
<td>38</td>
</tr>
<tr>
<td>CHAPTER</td>
<td>Page</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3.3 Tare Measurements .....................................................................</td>
<td>42</td>
</tr>
<tr>
<td>3.4 Non-Rotating Measurements .....................................................</td>
<td>46</td>
</tr>
<tr>
<td>3.5 Rotating Measurements ................................................................</td>
<td>50</td>
</tr>
<tr>
<td>3.6 Rotational Comparison ..................................................................</td>
<td>52</td>
</tr>
<tr>
<td>3.7 Discussion ....................................................................................</td>
<td>55</td>
</tr>
<tr>
<td>IV. CLOSING REMARKS ..........................................................................</td>
<td>58</td>
</tr>
<tr>
<td>REFERENCES ...........................................................................................</td>
<td>62</td>
</tr>
<tr>
<td>APPENDIX</td>
<td></td>
</tr>
<tr>
<td>A. CAD Drawings ..................................................................................</td>
<td>63</td>
</tr>
<tr>
<td>B. Frontal Area of an Ellipsoid at Angle of Attack ............................</td>
<td>74</td>
</tr>
</tbody>
</table>


LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Data Acquisition Timeline</td>
<td>34</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Seam Incision</td>
<td>8</td>
</tr>
<tr>
<td>2. Ball Mount</td>
<td>8</td>
</tr>
<tr>
<td>3. Insertion of Ball Mount</td>
<td>8</td>
</tr>
<tr>
<td>4. Hole for Aluminum Rod</td>
<td>8</td>
</tr>
<tr>
<td>5. Ball Mount Adjustment</td>
<td>9</td>
</tr>
<tr>
<td>6. Ball Complete with Mount</td>
<td>9</td>
</tr>
<tr>
<td>7. 9” Flexible Drive Cable</td>
<td>12</td>
</tr>
<tr>
<td>8. Test Stings</td>
<td>13</td>
</tr>
<tr>
<td>9. Angle Adjustment Base Mount</td>
<td>15</td>
</tr>
<tr>
<td>10. Mount to Force Balance</td>
<td>15</td>
</tr>
<tr>
<td>11. Ninety-Degree Base Mount</td>
<td>16</td>
</tr>
<tr>
<td>12. Flexible Drive Cable with Fittings</td>
<td>17</td>
</tr>
<tr>
<td>13. Collar Front</td>
<td>19</td>
</tr>
<tr>
<td>14. Collar Aft</td>
<td>19</td>
</tr>
<tr>
<td>15. Complete Test Apparatus</td>
<td>19</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>16. Aerodynamic Fairings</td>
<td>20</td>
</tr>
<tr>
<td>17. Motor Mount Attachment to Force Balance</td>
<td>22</td>
</tr>
<tr>
<td>18. Motor Mount Arm</td>
<td>23</td>
</tr>
<tr>
<td>19. Motor Attachment to Arm</td>
<td>24</td>
</tr>
<tr>
<td>20. Ceiling Track System</td>
<td>25</td>
</tr>
<tr>
<td>21. Telescoping Arm</td>
<td>25</td>
</tr>
<tr>
<td>22. Mount of Track and Telescope</td>
<td>25</td>
</tr>
<tr>
<td>23. Rotating Pin</td>
<td>25</td>
</tr>
<tr>
<td>24. Calibration Apparatus</td>
<td>27</td>
</tr>
<tr>
<td>25. Lift Pulley</td>
<td>28</td>
</tr>
<tr>
<td>26. Lift Calibration Set-Up</td>
<td>28</td>
</tr>
<tr>
<td>27. Drag Pulley</td>
<td>29</td>
</tr>
<tr>
<td>28. Drag Calibration Set-Up</td>
<td>29</td>
</tr>
<tr>
<td>29. Load Cell Calibrations</td>
<td>37</td>
</tr>
<tr>
<td>30a. Experimental Data Points at 0 Degrees AoA for Ball B</td>
<td>40</td>
</tr>
<tr>
<td>30b. Experimental Data Points at 60 Degrees AoA for Ball B</td>
<td>41</td>
</tr>
<tr>
<td>31a. Experimental Lift Tare Data</td>
<td>44</td>
</tr>
<tr>
<td>31b. Experimental Drag Tare Data</td>
<td>45</td>
</tr>
<tr>
<td>32a. Experimental Lift Data at 0 RPM</td>
<td>48</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>32b.</td>
<td>Experimental Drag Data at 0 RPM</td>
</tr>
<tr>
<td>33.</td>
<td>Experimental Lift and Drag Data at 360 RPM</td>
</tr>
<tr>
<td>34a.</td>
<td>Influence of Spin on Ball A</td>
</tr>
<tr>
<td>34b.</td>
<td>Influence of Spin on Ball B</td>
</tr>
<tr>
<td>35.</td>
<td>Lift and Drag Coefficient Comparison</td>
</tr>
</tbody>
</table>
NOMENCLATURE

English Symbols

a Length of Semi-Major Axis of an Ellipse
A One press of “Take Data Point” Button
c Length of Semi-Minor Axis of an Ellipse
CD Coefficient of Drag
CL Coefficient of Lift
q Dynamic Pressure
S Reference Area
SJ One Burst of Data
V Velocity
x Cartesian Coordinate Direction
y Cartesian Coordinate Direction
z Cartesian Coordinate Direction

Greek Symbols

α Angle of Attack
CHAPTER I
INTRODUCTION

The research of various shapes and geometries has been of interest to theoretical and experimental aerodynamicists for quite some time. Most shapes investigated would fall under the categories of either sharp or blunt objects. The differences in these objects are mainly based on the body fineness ratio, L/D (length to diameter ratio), and the leading edge contour of the body. However, since the beginning of the supersonic flight era, most research revolved around sharp bodies with lesser amounts of research towards blunt bodies.

A blunt body of particular interest is a spheroid. A spheroid is an ellipsoid in which two of the three axes are equal and has the equation of the form

\[
\frac{(x^2 + y^2)}{a^2} + \frac{z^2}{c^2} = 1
\]

Eq. 1
In contrast, an ellipsoid is defined so that all three axes may have different lengths. A spheroid is a quadric surface in three dimensions that is obtained by rotating an ellipse about one of its principal axes. If the ellipse is rotated about its major axis, the surface is called a prolate spheroid. If the minor axis is chosen, the surface is called an oblate spheroid.

Of these types of spheroids, more research is centered on a prolate spheroid, which is similar to the shape of a cigar. More research is centered about this shape because it is more ideal for applications such as airships than an oblate spheroid. Most past and present existing airships have been designed with streamline hull forms based on a prolate spheroid to reduce drag on the hull. In contrast, an oblate spheroid would have greatly increased drag.

Hoerner\(^1\) has documented some empirically derived formulas that are often used in preliminary design applications that give acceptable approximations for drag coefficients for a range of fineness ratios. However, Hoerner also gives these approximations in terms of drag area, which is the drag force divided by dynamic pressure. The quantity of drag area is just as acceptable as the drag coefficient itself. This quantity arises from the fact that the reference area for drag coefficient is difficult to compute, especially for bodies at an angle of attack greater than zero. Since the surface area is difficult to compute, Hoerner developed empirical equations based on the volume of prolate spheroids to the two-thirds power instead of the surface area and named this quantity the volumetric drag coefficient.
Dorrington\textsuperscript{2} used Hoerner’s empirical formulas for the volumetric drag coefficient to estimate the coefficient of several airships shaped as prolate spheroids. Dorrington discovered that the volumetric drag coefficient was a function of fineness ratio. These two works show the importance of drag in the design of airships based on prolate spheroids.

Other works by Chesnakas and Simpson\textsuperscript{3} and Simpson and Wetzel\textsuperscript{4} are concerned with flow separation on prolate spheroids. Separation is responsible for a significant fraction of the drag of such bodies.

The research of various shapes and geometries has been of interest to sports enthusiasts for a short time. The importance of sports engineering has increased in the past decade as the demands for the performance of athletes has intensified. This intensity in research has also included the equipment that the athletes use, such as rugby balls which resemble prolate spheroids.

In 1994, Mississippi State University (MSU) conducted experimental aerodynamic research on footballs. The main purpose of the project was to measure and analyze the lift and drag of footballs with different surface textures. These balls were run through a series of tests with varying flow speed, angle of attack, and ball rotation rates.

Seo, Kobayashi, and Murakami\textsuperscript{5} conducted a recent experimental aerodynamic study on the application of rugby balls. The investigation was similar to the MSU football project with respect to the same variables. More importantly, the authors also
used the volume of the spheroid rugby ball in order to calculate the drag coefficient in the manner of Hoerner and Dorrington.

All three works -- Hoerner, Dorrington, and Seo et. al. -- use the parameter of volume to the two-thirds power in order to obtain the reference area for drag coefficient. Although this method was proved to be accurate by Dorrington and Hoerner, it does not necessarily provide an accurate representation of the most important surface area when the object is oriented at a large angle of attack.
CHAPTER II
EXPERIMENTAL DETAILS

2.1 Ball Mount

Each rugby ball had to be assembled with a mount in order to spin the ball longitudinally. The previous football experiment in the early 1990’s provided guidance for an effective method to mount the ball for spinning. The rugby balls in this experiment were mounted identically to the footballs with a few variations such as location of the mount and method of mount insertion.

The footballs had a circular plywood disk inserted into them. An aluminum shaft was bolted to the plywood disk by way of a ¼ x 20 bolt. However, entry was gained in the laces of the football where rugby balls do not have a similar source of entry. Therefore, several tests were undertaken to determine the best method for gaining entry into the rugby ball.

The best way determined to enter the rugby ball was to make an incision on one of the four main seams on the ball as shown in Figure 1. Several tests were conducted in order to determine the best location to make the incision. Initially, it was determined that the incision should be made at the flattest potion of the ball so that sewing the seam
back together would become relatively easy since at that location there is the least amount of curvature on the ball. This initial test was successful; however, each subsequent test had the incision further from the center of the ball. Finally, after several tests, it was determined that the location of the seam was independent of the ball’s curvature. The seams on the balls were sewn back to its original shape no matter where they were located. Therefore, the location of the seam was arbitrary. However, for aerodynamic purposes, the seam needed to be as far aft on the ball as possible such that the freestream velocity sees as little of the seam as possible. This was the driving factor in the location of the seam.

In the football experiment, after the mount was positioned, the laces on the ball were sewn back together. However, the rugby ball seams were cut to gain access into the ball. Therefore, the balls were sewn back together using Spiderwire®. The original holes were used to sew the seam back together. Several stitching patters were tested until the best pattern was determined which was a cross-stitch pattern similar to shoe laces. The wire was pulled tight until the two panels were joined once again. However, the stitching wasn’t enough. To ensure that the seam was back to its original shape, 6-minute epoxy was used to complete the joining process. In the end, the sewing allowed for easier gluing.

The plywood disks that were used in the football experiment were modified and adapted to fit inside the rugby balls. The original shape and size were maintained,
however, the curvature of the edges was adjusted to contour the curvature of the rugby balls since they are square-like in cross-sectional area, where as a football is more elliptical. The plywood disks were made of 5/16” plywood and cut to 3” in diameter. The inner circle of the plywood disks was 2 7/16” where the difference from the inner and outer diameter was the result of curvature of the rugby ball. The center of the plywood disk was drilled such that a ¾”, ¼ x 20 bolt could be attached. The bolt was then glued to the disk with 6- minute epoxy to ensure that the bolt remained true to the disk. The bolt was then mounted to a ½” diameter aluminum shaft that was 3 3/4” long. The aluminum shaft was tapped and threaded so that it could screw onto the ¼ x 20 bolt. This mount is shown in Figure 2 and an isometric and 3-view drawing is shown in Appendix A.

The incision in the seam of the rugby ball was made long enough such that the plywood mount with the aluminum shaft could be inserted into the rugby ball, Figure 3. Next, a hole was drilled into one end of the rugby ball, Figure 4, such that the aluminum shaft could slide through and then the mount was butted up against the end of the ball such that the curvature of the plywood disk met the curvature of the rugby ball, Figure 5. Inside the rugby balls, two of the four main panels converge together and are sewn making one of the four main seams. When the two panels are combined, it creates a large ridge inside the balls. Therefore, notches had to be cut out of the plywood disk to accommodate those ridges. Each notch was 3/8” wide and 5/16” long such that each
ridge would sit comfortably into the notch. Each ridge was centered on the notches to ensure that the entire mount was butted up against the curvature of the ball.

Figure 1. Seam Incision
Figure 2. Ball Mount
Figure 3. Insertion of Ball Mount
Figure 4. Hole for Aluminum Rod
Inside the rugby balls was a bladder used to inflate the rugby ball. After the mount was inserted into position, the bladder was inflated so that the ball would take shape. However, the bladder didn’t take up the entire interior since the mount was added. In the previous football experiment, expandable insulation foam was added to fill up the gap between the plywood disk and the tail of the ball. Therefore, the same procedure was used to fill the empty space in the rugby balls. It was also particularly important to make the aluminum shaft align with the centerline of the rugby ball, as the shaft would act as the primary rotational link between the flexible drive shaft and the rugby ball. If the shaft were not aligned with the ball’s centerline, then a rotating imbalance would occur when the ball was rotating.

A hole was drilled in the rugby ball near the exit of the aluminum shaft. Expandable foam, which hardens when it contacts with air, was sprayed into the rugby ball. While this procedure was taking place, the ball was mounted on a lathe where the
aluminum shaft was placed in the chuck and the free end was butted up against a rotating pin. This would ensure that the aluminum shaft and the ball were aligned and would stay aligned after the foam completely dried. The lathe was spun at 32 RPM for 30 minutes to make sure that the foam was evenly distributed inside the rugby ball. After 24 hours, the foam was dry and the ball was taken off the lathe and the excess foam was removed. The foam acted as gap filler but more importantly, the foam acted as an adhesive, binding the ball to the mount such that the two stayed true to each other.

2.2 Test Apparatus

2.2.1 Test Sting

The rugby balls were to be tested at four angles ranging from zero degrees to ninety degrees angle of attack in increments of thirty degrees. In the initial design phase, two possible options for test stings were available. The first was to make one sting that would translate and rotate to achieve the desired angles. The second was to make individual stings for each angle that would need to be changed before testing a new angle.

The subsonic wind tunnel force balance requires that the center of applied force of any model be positioned at a specific place in the test section. This location is the point of the force balance calibration, which coincides, with the center of the test
section. A hole is located on the top plate of the force balance, which indicates this center location. Since the test section is 36 inches in height, the center of applied force of any model must be placed 18 inches above the floor of the test section. This was a main factor in deciding which method should be used. If one sting were made, it would have to translate vertically and also rotate to accommodate angle changes so that the rugby ball would remain at the same center location in the test section. Therefore, a separate test sting was made for each of the four angles.

Next, the shape and material selection of the test stings was addressed. However, the shape and material of the sting were functions of the type of rotational device used in the longitudinal mode of spinning. The sting had to be large enough to accommodate the device. An internal device rather than an external device was selected to reduce the number of objects in the flow field. The previously mentioned football experiment used a bicycle speedometer cable to rotate the balls. However, since rugby balls are larger and weigh more than footballs, a more rigid cable was thought to be needed. After researching online catalogues and commercial retailers, a 9” flexible drive cable for hand drills was selected. This flexible drive cable was flexible enough to allow drilling into awkward locations. Since these cables were only 9” long, several would need to be linked together into order to connect the rugby ball to the motor for spinning. This flexible drive cable is shown in Figure 7.
After determining the device used for rotation, the shape and material selection could then be addressed. The most important factor in material selection was the fact that the largest outer diameter of the flexible cable was 0.725 in. Any test sting would need to have an inner diameter sufficient to accommodate the cable. Also, since multiple cables were linked together, the sting would also have to accommodate the four inches of cable that was not flexible. Therefore, the sting would also need ample room such that when it was bent, the linkages could also fit inside the sting. The cheapest and most rigid material found was ¾” electrical conduit. This size conduit had an inner diameter such that the flexible cable could fit and also had ample room for non-flexible linkages, if bent less than forty degrees.

In order to determine the shape of each test sting, a template was made before bending each pipe. Before making a template, the length from the center of the ball to the end of the pipe was required. As described before in the mounting of each ball, the
aluminum shaft would be the main linkage between the ball and the flexible drive cable. Therefore, the length from the center of the ball, which was mounted to the aluminum shaft to the end of the sting, was ten inches. Then, a template was drawn on plywood. First, the center of the force balance and the location eighteen inches above that point were drawn. Next, a protractor was used to draw a ten-inch line at each angle. Then a curve was drawn for each sting. A conduit pipe bender was used to bend each sting to shape. After each sting was bent, the cables were linked together to ensure that the non-flexible portions did indeed fit inside the stings. The stings for each angle are shown in Figure 8 and Appendix A.
2.2.2 Sting Base

Now that the test stings were made, they had to be linked to the upper plate of the force balance. Therefore, an adjustable base was designed that could rigidly hold each sting at its required angle. The base was made out of solid aluminum and had holes to match mounting holes in the upper plate of the force balance. Attached to the lower base were two vertical aluminum parts that held the angle adjustment mechanism in place. These vertical parts had a curved slot to allow for the mechanism to move freely and bolts that locked the mechanism in place. The angle adjustment mechanism had a hole drilled out to the same diameter as the outer diameter of the stings. This hole was where each sting mounted to the base. This mechanism was cut into two equal pieces after the hole was drilled and two bolts were attached to the upper part of the rotating mechanism. After the sting was placed into the hole, these two bolts were tightened, squeezing the two identical parts together and locking the sting into place. Once the sting had the desired angle, the mechanism was locked into place by the bolts on the vertical part. The flexible drive cable exited through the angle adjustment mechanism and then through the U-shaped lower plate of the base to reach the motor and its mount. This rotating base is shown in Figure 9 and 10 and a 3-view drawing is shown in Appendix A.
The only angle that could not be tested with the angle adjustment base mount was ninety degrees. The ninety-degree angle of attack test sting, which is a vertical pipe, could not be rotated to the desired angle of attack with this mechanism. Therefore, another base was used to test the balls at ninety degrees. Since a vertical test sting was common to tests in this wind tunnel, the necessary base already existed. This base, shown in Figure 11 and Appendix A, has three bolts that mounted to the upper plate of the force balance and an extruded circular base that plugged in the hole on the upper plate. The ninety-degree sting was slipped over the top of this mount and fastened with a hose clamp.
2.2.3 Rotational Fittings

Now that the test stings and their associated rotating base had been designed and built, the next task was to design and build a rotating mechanism to ensure that the rugby balls would rotate without vibration. Since flexible drive cables were used, the best design option was to make fittings for one flexible drive cable to fit inside each sting. The intent was to build a single cable with fittings that could be changed out between stings. The flexible drive cable along with fittings is shown in Figure 12 and Appendix A.
This picture shows several pieces that were each important for a specific purpose. This flexible drive cable can be broken down into 3 main parts. Part A was a collar with an outer diameter that matched the inner diameter of each test sting. This part allowed the flexible cable to fit inside each sting snugly. Part B was another collar. Since the brass coupling on the original flexible drive cable had a significant amount of play, this collar was added to make another contact point with each sting. Since Part A and the collar on Part B had the same outer diameter, this allowed for two contact points inside each sting, which eliminated the play in the brass coupling. What is not shown in the figure above, beneath the collar in Part B, are the fittings that attached to the flexible cable. The end of the flexible drive cable that normally locked into hand drills also locked into the beginning of the next cable, thus allowing the linkage of cables. A fitting was made to fit into the flexible cable to grip the rugby ball. This fitting was made out of a tool steel spade bit. The head of the spade bit was cut off and the
remaining portion was threaded to a \( \frac{1}{4} \times 20 \) die. This portion was then glued with epoxy onto the flexible cable. While the epoxy cured, the flexible cable was held in a lathe to ensure it was longitudinally aligned with the brass coupling. Finally, Part C was added. Part C was the same aluminum rod used to mount each ball. This rod was threaded on the fitting in Part B along with a \( \frac{1}{4} \times 20 \) nut. The rod and nut were tightened against each other and then glued together using epoxy. The original design called for using the aluminum rod used to mount each ball. After some initial tests, Part C still had a significant amount of play which induced a rotating imbalance when the ball was attached and rotated. An aluminum collar was then added for more stability. This aluminum collar, shown in Figure 13, 14, and Appendix A, had a roller bearing at one end with an inner diameter of \( \frac{1}{2}'' \) to accommodate the aluminum rod, and at the other end had an inner diameter which corresponded to the outer diameter of each test sting. Expansion slots were cut into the end that attached to each test sting, allowing the collar to slip over the pipe. After the collar was mounted over the test sting, the exposed portions were clamped down to the stings using a hose clamp. This collar was mounted to each test sting to give extra stability to the entire test apparatus. The complete test apparatus is shown in Figure 15 and Appendix A.
Figure 15 shows the aluminum rod exiting the aluminum collar along with the hose clamp and test sting. Immediately, one should notice that the aluminum rod has a female connection just like the ball mount described earlier. Instead of mounting the rod to the test apparatus, now the rod was detached from the ball, leaving the ¼ x 20 bolt to be screwed onto the extruding rod in Figure 15.
2.2.4 Test Fairings

Finally, to complete the test apparatus, fairings were constructed to help eliminate the lift and drag forces on the test stings. Fairings were made of 2024-T3 sheet aluminum and then sized proportionally to fit each test sting. The fairings were bent to allow for a steep angle on the leading edge and were wide enough so as not to interfere with each sting. The fairings are shown in Figure 16 with the fairing for zero degrees angle of attack on the left and the fairing for sixty degrees angle of attack on the right with the median angle fairings in the middle.

Figure 16. Aerodynamic Fairings
2.3 Motor Mount

The rugby balls needed to be spun over a range of 200 RPM to 600 RPM. In the football project, a Dremel tool was used to spin the footballs. Since the longitudinal rotation of a football is far greater in game play than a rugby ball in game play, a motor was needed to obtain slower rotational rates than what a Dremel tool would deliver. Of course, a Dremel tool would provide low rotational speeds but at the cost of poor resolution. Additionally, a rugby ball weighs more that a football, so the torque required for spinning the rugby balls was also considered.

A motor that provides rotational rates in the range indicated above with the necessary torque is commonly found in hand drills. A standard corded electric drill with a torque handle was selected as the drive mechanism. This drill was chosen for two reasons. First, the drill’s detachable handle allowed for an easy way to firmly mount the drill in the force balance. Second, the drill had a locking mechanism such that a person would not have to hold the trigger for the entire length of each rotational test. Instead of using the trigger switch to control speed, a separate variable AC power supply, or Variac, was used.

For the proper use of the subsonic wind tunnel force balance, the stings had to be attached to the upper plate of the force balance. Therefore, to avoid introducing external forces to the balance from the motor, the motor mount also had to be mounted to the same plate. The force balance had such attachments to the upper plate for an
angle of attack mechanism used in scaled wing and aircraft model tests. This mechanism was mounted on the underside of the upper plate. Since this experiment didn’t use that mechanism, it was removed, freeing those attachments. Therefore, a motor mount arm was made to attach to those points. This is shown in Figure 17.

The motor mount arm had to be sufficiently rigid in bending and torsion to avoid excessive and harmonic vibrations. Therefore, the arm was made out of a hollow steel square tube. The motor mount was a welded combination of three individual parts. The first part was a flat plate that had three holes, each threaded to a \( \frac{1}{4} \times 20 \) bolt. These holes screwed into the same holes on which the angle of attack mechanism was mounted. The second part, which was welded to the flat plate, was 11 inches long at an angle of 40 degrees from the horizontal. This angle was required in order to avoid disrupting other components in the force balance. The third part, which
was cut and bent from the second part, was welded back together to the second part.
This part was 10.6 inches long at an angle of 140 degrees from the second part and was
also nearly parallel to the first part, the flat plat attachment point to the force balance.
This arm is pictured in Figure 18 below and a 3-view is shown in Appendix A.

![Figure 18. Motor Mount Arm](image)

Since the last flexible drive cables for the four angles didn’t exit the pipe in the
force balance at the same location, the motor had to be able to translate. Therefore a slot
was cut in the third part to allow this translation. The slot was 7.6 inches long, 0.5
inches wide, centered on the arm. A bolt was placed through the slot, head facing down,
and then threaded into the attachment point for the drill’s handle. A spacer was placed
on the top of the arm, between the arm and drill, to level the drill. This is shown in
Figure 19 below.
2.4 Tare Support

Tare measurements were obtained using an apparatus designed and constructed by Gaetan. Since the rugby ball would change orientation for each desired angle, the tare apparatus had to accommodate this change. Therefore, the apparatus was designed to translate horizontally and vertically. The apparatus translated horizontally by a track mounted on the top of the wind tunnel test section shown in Figure 20. Vertical translation was obtained from a telescoping aluminum shaft inside a hollow aluminum shaft shown in Figure 21. The telescoping shaft was held into place by two set screws mounted on the hollow shaft. These two parts, track and hollow shaft, were mounted together using L-brackets shown in Figure 22. Finally, a rotating pin was made in order to obtain the desired angle after the track and telescope were locked into place, which is
shown in Figure 23. A full design analysis, including CAD drawings, was reported by Gaetan.

Figure 20. Ceiling Track System
Figure 21. Telescoping Arm

Figure 22. Mount of Track and Telescope
Figure 23. Rotating Pin
2.5 Calibration

Calibration of the subsonic wind tunnel force balance was required to ensure accurate calibration slopes. The last recorded calibration was completed prior to the football project. A calibration required the determination of voltage slopes for lift force, drag force, side force, and moment. A calibration was required to determine if the original slope values applied to this specific experiment.

The subsonic wind tunnel force balance was comprised of 6 load cells; two loads cell for lift, and one for drag, one load cell for side force, a dummy cell for rolling moment, and a sixth load cell for pitching moment. No allowance is made for the measurement of yawing moment. These loads cells contained strain gages, which output a voltage as a function of applied force. For this experiment, interest was only in the lift and drag forces, therefore, only these forces were calibrated. The wind tunnel control program input voltages from the load cells, subtracted a zero reference voltage, and then multiplied the voltages by the calibration slope in order to determine the actual force.

The force balance was designed such that the calibration slope was independent of test sting shape. This was the main objective in performing this calibration, to determine if shape was indeed independent of calibration slope.

This calibration was only performed at 30 degrees. Since it would be difficult to calibrate the test sting with the ball attached to the test sting, a modification was made. A solid aluminum shaft, ½” in diameter, was threaded by a ¼ x 20 die and then screwed
into the aluminum shaft which was the main rotation device that extruded out of each pipe. This aluminum shaft was cut to the length of the rugby ball. Then, a hole was drilled in the aluminum rod at the location where the center of gravity of the ball would be located. String was tied through this hole and the other end of the string was attached to a weight through a pulley. This apparatus is shown in Figure 24.

![Figure 24. Calibration Apparatus](image)

In order to determine the lift calibration slope, a pulley was mounted on the ceiling of the wind tunnel directly above the center of the force balance and thus above the hole in the solid aluminum shaft. This is shown in Figure 25. The string attached to the aluminum shaft was threaded through the pulley and weights were hung from the other end of the string, which is shown in Figure 26.
The following figures, 27 and 28, show the drag calibration setup. A pulley was mounted to the floor of the test section directly behind the test sting. Again, the string attached to the aluminum shaft was threaded through the pulley and weights were hung from the other end of the string.
A basic program was written in LabVIEW to obtain lift and drag voltages from the wind tunnel force balance. The program sampled at 10,000Hz. Each time the “take data” button was pushed; an average voltage value was read from an indicator after one second of time. Each time an additional lead weight was added to the tray, the voltage was sampled and recorded. The lift weight was incremented by 0.25 pounds and drag weight was incremented by 0.06 pounds. The different increments for lift and drag weights were done because the drag force is much less than the lift force for this given experiment based upon initial force measurements. Voltages were recorded for increasing and decreasing weight, to check for hysteresis in the system.
2.6 Data Acquisition

2.6.1 Original Method

The force balance was designed such that the lift, drag, and dynamic pressure could be obtained over time. Instead of obtaining an average value of these quantities, a time history could be obtained. A time history was desirable over an averaged value since it would allow for the tracking of any phenomenon associated with this experiment. The output signals, high and low voltage, for each quantity were obtained and used as the input into LabVIEW through an NI 6024E data acquisition board connected to a PCB-68 wiring board. A program was written in LabVIEW to obtain these quantities. Data were taken at a rate of 10,000 Hz for 1 second of time. After investigating the time histories, some unusual phenomena were observed. First, while the average values of these quantities were adequate, the actual signal had some problems. There were several distinct AC noises in each signal coming from unidentified sources. Also, the signal appeared to be chopped such that only a certain portion of the signal was obtained. The signal appeared to be sinusoidal in fashion, however, only the top portion was displayed. Also, the noise sources could not be determined or isolated. It was noted that there was considerable EMF associated with the power supplies, unshielded ballasts of fluorescent light fixtures, and unshielded wires in the vicinity. Later in the testing, the power supply for the load cells was found
to be defective. This could have been the source of the problem. Whenever oscilloscope
leads were connected, the phenomena was minimized or completely eliminated. This
phenomenon did not appear to effect the measurements made with the tunnel control
system. Rather, the phenomenon seemed to be associated with the only parallel
connections to the 6024E. A decision was made to conduct tests using the existing
computer DACS system as was done in the past.

If the time histories are available, the following is the proper procedure of
analysis. There are two considerations for the measurements. First there should be a
sufficient number of measurements per cycle in order to observe the highest relevant
frequency. This requires a high enough sampling rate. The second consideration is that
measurements should be taken over a sufficient number of cycles in order to capture the
lowest relevant frequency. This requires a long enough sampling time. Simply stated,
the high frequency needs enough points and the low frequency needs enough cycles to
characterize its motion. There are a few guidelines for estimating the high and low
frequencies. The first is a shedding frequency which leads to the determination of the
Strouhal number. The second is to estimate the natural vibration frequencies of various
hardware components. Also, flow frequencies as a result of blade passage, time for the
flow to make one transit of the entire wind tunnel, and sound waves are to be
determined. Finally, a Fourier transform is used to identify these frequencies. An
average over a sufficient number of the lowest relevant frequencies is also required.
2.6.2 Revised Method

Therefore, after the previously discussed electronics problems, it was determined instead to obtain voltage readings from the primary wind tunnel control computer. Of course, the disadvantage of this method was the inability to obtain a detailed time history of forces. The wind tunnel control computer had a pre-existing program written in LabVIEW to control the wind tunnel and also to acquire data. Data were acquired from the force balance via a LabVIEW Sub-VI in the main program and a digital multiplexer connected to a precision digital multi-meter. A LabVIEW Sub-VI is a subroutine in the main program. This sub-vi allowed the user to obtain data by simply pressing a button named “Take Data Point.” The data were acquired in the hierarchal format shown in Table 1. The digital multi-meter read a group or “burst” of 24 samples from a given channel at a rate of 2,000 Hz, computed an average for this burst and passed it on to the LabVIEW program. For each press of the “Take Data Point” button (a “press”) the LabVIEW program cycled through the various channels and acquired 15 of these averages for each of lift and drag, 4 of these averages for dynamic pressure, 30 for side force, 15 for pitching moment and 4 for temperature. The LabVIEW program took these data (which were averages themselves) and averaged them to produce a final number for lift, drag, dynamic pressure, etc. Equations 2 and 3 show the averaging computations. A total of approximately eight seconds was required to obtain the final results from one press. Without extensive programming, neither the
values of individual samples nor the values for individual burst averages were available. The lowest level at which data could be accessed was the “press”, which was the result from Eq. 3.

Five or ten presses constituted a sequence, which took approximately 80 seconds to acquire. A test was composed of six sequences. The sequences were separated by anywhere from 1 to 24 hours.

\[ S_j^\prime = \left( \frac{1}{24} \sum_{i=1}^{24} S_i \right)_j \]  
Eq. 2

\[ A = \frac{1}{15} \sum_{j=1}^{15} S_j^\prime \]  
Eq. 3
Table 1. Data Acquisition Timeline

<table>
<thead>
<tr>
<th>Type of Data Acquisition</th>
<th>Description/Relationships</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 sample</td>
<td>1 discrete measurement from 1 channel</td>
</tr>
<tr>
<td>1 burst</td>
<td>24 samples</td>
</tr>
<tr>
<td>1 press or “click”</td>
<td>15 bursts (lift and drag)</td>
</tr>
<tr>
<td></td>
<td>4 bursts (q)</td>
</tr>
<tr>
<td>1 sequence</td>
<td>5 or 10 presses</td>
</tr>
<tr>
<td>1 test</td>
<td>6 sequences</td>
</tr>
</tbody>
</table>

Even though time histories do not exist, there are a few procedures that can be carried out to make certain that the measured mean equals the analytical mean. The best method was to create particular waveforms with known means. These waveforms should be of several types which included pure sine waves, a sum of sine waves, square waves, etc. These waveforms should be allowed to vary in the same frequency ranges as the hardware itself. In order to make the measured mean equal to the analytical mean, the number of bursts per press must be adjusted. In the LabVIEW Sub-VI in the main wind tunnel control program, the number of bursts is an input. However, these initial values are arbitrary. Also, avoiding parallel unshielded wires and ensuring that the power supplies are not saturated should also ensure cleaner signals.
CHAPTER III

RESULTS

Two balls were tested at several different wind tunnel speeds and rotational rates. The test matrix included speeds of 0, 10, 20, and 30 m/s, rotation rates of 0, 250, and 500 RPM, and angles of attack of 0, 30, 60, and 90 degrees. Tests were conducted at 0 m/s and 0 RPM to see what type of response the force balance had without a load applied, either in translation or rotation.

3.1 Calibration

The published calibration slopes used in the main wind tunnel control program were 1953.45 lbf/Volt for lift and –593.25 lbf/Volt for drag. Figure 29 displays the plot for the lift and drag slope calibration.

Both figures display the measured points and a trend line to the data. The equations are displayed for each trend line along with the R-squared values. The R-squared values are close to 1, indicating a good fit to the data. For lift, the calibration slope obtained was 1952.1 lbf/Volt. Comparing this slope to the published value, a percent error of 0.07% was obtained. Similarly for drag, a percent error of
0.05% was obtained. These percent errors are exceptionally reasonable. The curve-fits above also indicate that hysteresis was not present in the force balance system for lift and drag since the data points for increasing and decreasing lift and drag lie directly on top of one another.
Figure 29. Load Cell Calibrations

Data Points = Open Square ;  Regression = Solid Curve
3.2 Initial Testing

At this time, a note must be made about a few important steps taken in order to improve the measured data. First, before each wind tunnel test, the electronics involved with the use of the force balance were allowed to warm up for 20 minutes. Since the force balance contains sensitive electronics that are susceptible to circuit heating up to a steady state condition, a proper warm-up schedule was recommended. A few of these electronics are the load cell power supply and the supply power to the entire balance itself. Second, the recording devices were reset between wind tunnel tests. This ensured that the recording devices would obtain zero values before each test. Third, a new wind tunnel program was compiled to save six significant digits instead of three significant digits. The original wind tunnel program only kept three significant digits in the saved data files. More significant digits were necessary in order for precision. Finally, a check was made that ensured all the switches on the main breaker panel in Patterson Laboratory were on.

Initially, data were taken in the following manner. The wind tunnel control program allowed the user to take data and save the measurements in an array. This array was to be saved as a comma-delimited file for future data manipulation. In order to determine the repeatability of the force balance measurements, the initial tests required ten individual presses of the “Take Data Point” button for each wind tunnel speed and rotational rate.
Figure 30 shows the results of these initial tests, which are the total forces on the ball and mount combination; i.e., tare forces were not removed. For each given wind tunnel speed and rotational rate, the lift and drag were recorded ten times and placed in this figure. The time interval between successive recordings was approximately eight seconds, so that it took approximately eighty seconds to complete one sequence. Each sequence was acquired a total of three times. Sequences were repeated at varying intervals from one hour to one day. The results are presented in Figure 30 as lift and drag areas, \( C_L S \) and \( C_D S \), to help minimize the effect of the varying airspeed in the test section (~2%). An exception was made for the 0m/s and 0 RPM data. The magnitudes of the lift and drag areas are not particularly important at this moment, but what is important is to note the variability of the tests, especially for the rotating cases.
Figure 30a. Experimental Data Points at 0 Degrees AoA for Ball B

Solid Line = Lift Area  ;  Dashed Line = Drag Area
Figure 30b. Experimental Data Points at 60 Degrees AoA for Ball B

Solid Line = Lift Area ; Dashed Line = Drag Area
There are several key observations that should be made about Figure 30. There were rather large temporal variations in lift and drag even when the tunnel motor was running at idle, and the ball was not rotating. Increasing the rotation rate at idle increased the variations, with 250 RPM being worse than 500 RPM. This larger variation occurred since 250 RPM was closer to the natural frequency of the force balance system, which was approximately 5 Hz. Of the forces measured, lift and drag, the lift showed a larger variation than the drag. It is also important to note that increasing the wind tunnel speed did not change these trends, but did lower the amplitudes. For drag, it is particularly important to observe that its variation at higher speeds was relatively small.

3.3 Tare Measurements

After the initial force investigation, tare measurements were taken for each ball at each angle of attack. For these measurements, the lift and drag were recorded only five times and stored into an array, instead of the previous ten. The decision to reduce time spent on data acquisition was based on the observation that the average values for lift and drag for each of the three independent sequences were approximately the same values (~5%). Reduction in the number of individual data recordings greatly reduced the time of each test, and subsequent wear and tear on the system.
Each sequence was acquired a total of six times. This number was doubled from the initial tests because the tare measurements did not require the ball to rotate. It was also increased because the number of recordings was reduced.

The tare data, Figure 31, are presented as lift and drag areas as a function of angle of attack. Range bars are included to show the variability of the six independent sequences. The upper bar represents the maximum measured value and the lower bar represents the minimum measured value out of the six sequences. The curves between the range bars is the average of the six sequences. It should be noted that these indicated ranges do not represent any statistical or mathematical analyses. The ranges are strictly displaying the spread of data.

Figure 31a shows the lift area as a function of angle of attack. One key observation is the relatively large variations at each angle for either ball and the influence of the ball type is buried within the data spread or “noise”. The drag area shown in Figure 31b shows the opposite trend in variations as compared to the lift area. There are relatively small variations for a given velocity and angle of attack. However, the influence of the ball type is also located “in the noise”.
Figure 31a. Experimental Lift Tare Data

Ball A = Solid Curve, Solid Square    ;    Ball B = Dashed Curve, Open Square
Figure 31b. Experimental Drag Tare Data

Ball A = Solid Curve, Solid Square ; Ball B = Dashed Curve, Open Square
3.4 Non-Rotating Measurements

After obtaining the tare measurements, each ball was tested at zero RPM. The same sequences used in obtaining the tare measurements were used from this point forward. The lift area and drag area are shown in Figures 32a and 32b, respectively. It should be noted that the forces in these plots are for the ball only; the tare has been subtracted. Since the tare data and the data at zero RPM both have variations, which are not shown, the range bars in these plots have a slightly different meaning than what is shown in the tare data plots. In Figures 32a and 32b, the upper bar represents the maximum value of zero RPM data minus the minimum value of tare data. The lower bar represents the minimum value of zero RPM data minus the maximum value of tare data. These range bars were done in this manner to represent the “worst case” scenario. The solid and dashed lines represent the average data at zero RPM minus the average tare data. Again, it is important to note that six sequences of data were taken. The maximum and minimum values are taken from six values.

Figure 32a, which shows lift area data, shows a non-zero lift area at zero and ninety degrees. There is virtually no change in the average lift area from zero degrees to thirty degrees for the two higher speeds. This is a surprising result. However, a change does occur at the lowest speed. There is nearly a fifty percent variation in lift area at zero degrees for all the speeds, which reduces to approximately ten percent at sixty degrees and 30m/s. Also, there appears to be no significant influence of the ball type, except perhaps at ninety degrees.
In Figure 32b, which shows drag area data, it can be immediately observed that the variations at each condition are much smaller than for lift. Drag area increases by only a small amount going from zero to thirty degrees. There is a larger increase in drag area going from thirty to sixty degrees, which coincides with the large increase in lift shown in Figure 32a. There is only a very small difference between ball types at each speed between zero degrees and sixty degrees. The only noticeable difference in ball type occurs at ninety degrees.
Figure 32a. Experimental Lift Data at 0 RPM

Ball A = Solid Curve, Solid Square ; Ball B = Dashed Curve, Open Square
Figure 32b. Experimental Drag Data at 0 RPM

Ball A = Solid Curve, Solid Square ; Ball B = Dashed Curve, Open Square
3.5 Rotating Measurements

After obtaining a rather large set of data for the non-rotating cases, an investigation was performed of rugby balls in longitudinal spinning. The rotational data were taken only at a velocity of 20m/s. Only one speed was used for two main reasons. The first reason was to obtain a better grasp of game-play conditions where 10m/s was too low and 30m/s was too high for typical game-play conditions. The second reason was to cut down the number of wind tunnel tests. The lift and drag areas at 20m/s and 360 RPM are shown in Figure 33. There are no obvious differences between these plots and the corresponding zero RPM case (Figure 32) except for the drag of ball A at ninety degrees angle of attack. The lift area variations are not particularly large and the drag area variations are very small. These observations are important when one is interested in the mechanics of the system. The digital multiplexer samples at a rate of 2,000 samples per second. For each press of the “Take Data Point” button, 15 samples were taken for drag and lift within the LabVIEW data acquisition program. For a rotation rate of 360 revolutions per minute, the ball rotated 15.2 degrees per press, meaning a small amount of rotation per press. This implied that oscillatory and movement forces might appear in the data. The small variations in Figure 33 suggest that there is not much vibration in the system.
Figure 33. Experimental Lift and Drag Data at 360 RPM

Ball A = Solid Curve, Solid Square ; Ball B = Dashed Curve, Open Square
3.6 Rotational Comparison

Finally, an investigation was performed in comparing rotation and non-rotation for each ball at game-play conditions, 20m/s. The influence of spin for ball A and ball B are given in Figures 34a and 34b, respectively. A few observations were made from these plots. Most significantly, the rotation of a rugby ball did not produce any significant change in ball forces except for the drag and possibly the lift of ball A at ninety degrees angle of attack. This phenomenon is highlighted by the ovals in Figures 34a and 34b. Once again, it should be noted that these plots are the results of six sequences acquired alternately for each ball.
Figure 34a. Influence of Spin on Ball A

0 RPM = Solid Curve, Solid Square ; 360 RPM = Dashed Curve, Open Square
Figure 34b. Influence of Spin on Ball B

0 RPM = Solid Curve, Solid Square ; 360 RPM = Dashed Curve, Open Square
3.7 Discussion

In general, the force balance system works well. However, a few limitations exist. First, accurate measurements at low velocity were difficult to obtain. Second, care must be taken to avoid exciting the natural frequency of the force balance. Obviously, testing cannot occur at these frequencies, limiting the data above 300 RPM. Also, the time histories of lift and drag could not be measured due to a possible electrical problem as stated in the experimental details chapter.

There are some results of testing that are difficult to explain. The most important is the fact that there is lift greater than zero at zero and ninety degrees angle of attack. An explanation of this phenomenon is upflow induced by the mount or fairing. The fairing used for this angle of attack was different than the fairings discussed in section 2.2.4. A typical vertical fairing was used for ninety degrees angle of attack. Since this fairing was vertical instead of sloped, it may have induced an upflow, which would explain additional lift at that particular angle. An additional source of lift could have been flow through the balance into the test section if the cover was not properly installed on the balance. Also, there could be a difference in the “lifting” area for each case.

A few phenomena that go unexplained for the moment are the virtually constant lift from zero degrees to thirty degrees angle of attack, and the effect of spinning at ninety degrees shown in Figure 34a. Normally, when increasing the angle of attack of a
body, the lift should increase until stall has occurred. However, when the angle of attack was increased thirty degrees, only a small amount of change in lift occurred. It would be logical for the lift curve slope to be a constant between zero and sixty degrees angle of attack. However, a different slope exists between zero and thirty degrees and between thirty and sixty degrees. The experiment conducted by Seo et. al. depicted the logical solution to this problem. The data from their experiment, shown in Figure 35, included a greater lift coefficient at thirty degrees than zero degrees but also a nearly linear region from zero degrees to sixty degrees. It should be noted that their data is an average from three different wind tunnel speeds; therefore, the data is not at a particular wind speed. The authors stated that this was a reasonable assumption because when the lift force is divided by the dynamic pressure, the magnitudes of the lift coefficient become nearly identical. The data obtained from this project for each ball was manipulated to account for their assumptions and plotted against their data in Figure 35.

It should be noted that the magnitudes of the forces of the tare measurements are relative to magnitudes of the ball forces. In other words, if the ball forces and the tare forces were plotted together, the forces are within the same range. This fact does not indicate an immediate concern; however it comes as an unexpected result. It would be expected for the ball forces to be greater than the tare forces.

In Figure 35, the lift and drag coefficients were computed using the volume of each ball to the two-thirds power to calculate the reference area. An alternative method to calculate the reference area is shown in Appendix B.
Figure 35. Lift and Drag Coefficient Comparison

Seo et. al. = Solid Curve ; Ball A = Dashed Curve ; Ball B = Dotted Curve
CHAPTER IV
CLOSING REMARKS

Prolate spheroids have a particular interest to aerodynamicists and sports engineers alike. Aerodynamicists are interested in these shapes in order to obtain a better understanding of forces but also flow separation. Sports engineers are interested in these shapes since equipment in a few different sports resembles these shapes. To either group, this type of shape is important in order to investigate drag but also to optimize performance, in either airships or athletes.

Most importantly, this project developed a system for measuring aerodynamic forces on rugby balls. Although an actual system for measuring forces was previously developed by way of a force balance, this project developed a method to quickly connect to the force balance in order to measure forces for an array of variables. A method for preparing the balls for mounting was obtained after a few iterations. The final method was quick but also had enough rigidity to withstand spinning at high angles of attack and airspeed. A test apparatus was developed which fixed the ball at a specific angle of attack but also allowed the ball to rotate longitudinally without a
rotating imbalance. A motor mount was developed to reduce the number of variables introduced to the system. Finally, a calibration on the system was conducted which proved to be accurate and precise.

Data acquisition was an important variable throughout this project. The original method called for the time histories of lift and drag to be obtained. However, after undesirable results, this method was not used. Fortunately, a secondary method was available through the wind tunnel control program. Although the secondary process of data acquisition showed an extensive array of data, it still cannot be compared to an array of time histories. Time histories track phenomenon associated with this type of experiment while an averaged data set could possible skip some valuable information.

The results of this experiment show a few common and expected aerodynamic phenomena but also a few that are unexpected and difficult to explain. The most important expected phenomenon is visible in the plots of lift as a function of angle of attack. These plots are expected since these they most resemble typical plots for airfoils. A $C_L$ versus $\alpha$ plot for a typical airfoil shows a steady increase in lift until the airfoil reaches a specific angle of attack where the slope changes sign. That specific angle is referred to as the stall angle. This pattern was also observed in the data that was obtained for the rugby balls. It appeared that the stall point most likely occurs at nearly sixty degrees angle of attack. It is uncertain that stall occurred at sixty degrees since the
test angles were in increments of thirty degrees. In order to determine the stall angle, more testing would be needed at angles such as forty-five and seventy-five degrees.

Another expected result is that the drag increases as angle of attack increases. The drag is expected to increase with angle because as the angle increases, the drag reference area also increases thus resulting in a higher drag force.

The most important unexpected phenomenon occurred when the lift force did not increase at the same rate from zero to thirty degrees as from thirty to sixty degrees. It would be more expected if the lift curve slope were found to be constant from zero to sixty degrees. Upon initial investigation, the most likely cause of this phenomenon could be the lack of resolution in the force balance system. However, this explanation is false as the calibration plots indicated that this is not the cause. In the calibration plots, the magnitudes of the forces were less than the forces seen in the tests and the force balance was not being overloaded. Even with the lower forces, the calibration still showed a very accurate slope compared to the published values for both lift and drag without hysteresis. Therefore, the resolution could not be the culprit for such a phenomenon.

Another unexplained phenomenon is the difference between the rotating and non-rotating case for Ball A at ninety degrees, which is shown in Figure 34a. However, Figure 34b does not indicate this difference at ninety degrees for Ball B. At this moment, it is not quite understood why this phenomenon exists. Also, video was taken
and a mass imbalance was not observed, i.e., there was no excessive vibration.

The entire system has some uncertainties that remain to be investigated. The most important uncertainties lie within three main sources. The first source is that the airflow may not be aligned with the rugby balls, especially at zero and ninety degrees. The second source is the upwash due to the support and fairing. Both of these sources would induce a change in forces, especially in lift. The third source is possible changes in force balance calibration and flow tests. These changes include mechanical interference or electrical problems. A few minor sources include asymmetries in the balls and flow leaking from below the test section.

Although a few phenomena are unexpected and difficult to explain, the developed system is a well developed method for testing any model of any shape.
REFERENCES


APPENDIX A

CAD DRAWINGS
Part Name: Ball Mount
Scale: 3:1
Drawn By: Matteo Gaetan
Date: May 26, 2006
Mississippi State University
Rugby Ball Project
Part Name: Zero Degree Test Sting
Scale: 6:1
Drawn By: Matteo Gaetan
Date: May 26, 2006
Mississippi State University
Rugby Ball Project
Bottom view

Isometric view

Part Name: Thirty Degree Test Sting
Scale: 5:1
Drawn By: Matteo Gaetan
Date: May 26, 2006
Mississippi State University
Rugby Ball Project
Part Name: Sixty Degree Test Sting
Scale: 3:1
Drawn By: Matteo Gaetan
Date: May 26, 2006
Mississippi State University
Rugby Ball Project
Part Name: Flexible Drive Cable with Fittings
Scale: 4:1
Drawn By: Matteo Gaeta
Date: May 26, 2006
Mississippi State University
Rugby Ball Project
APPENDIX B

FRONTAL AREA OF AN ELLIPSE AT ANGLE OF ATTACK
The ellipsoids of concern here are of the prolate spheroid class, being axisymmetric, with the major axis coinciding with the axis of symmetry, as shown in Fig. 2.1. The frontal area of this object is the cross-sectional area projected into the direction of the free stream. It is computed by the integral over the body of the projections of elemental surface areas such as depicted in Fig 2.2 and defined by

\[ \mathbf{e} \cdot \mathbf{n} \, dA \]  

(2.1)

Here \( \mathbf{e} \) is the unit vector of the velocity, \( \mathbf{n} \) is the unit outward normal vector to the ellipsoid and \( dA \) is a differential area element of the body surface.

The unit outward normal is

\[ \mathbf{n} = \cos(\nu) \mathbf{i} + \cos(\phi)\sin(\nu) \mathbf{j} + \sin(\phi)\sin(\nu) \mathbf{k} \]

where \( \nu \) is the angle of the normal with respect to the axis of the body and \( \phi \) is the azimuthal or “roll” angle about the axis shown in Fig. 2.3. For this analysis the ellipsoid will be fixed in space and the approach flow will vary in direction. The approach flow unit vector, which is at an angle of attack \( \alpha \), is

\[ \mathbf{e} = \cos(\alpha) \mathbf{i} + \sin(\alpha) \mathbf{j} \]

No sideslip is assumed. The dot product is then

\[ \mathbf{e} \cdot \mathbf{n} = \cos(\alpha)\cos(\nu) + \sin(\alpha)\cos(\phi)\sin(\nu) \]  

(2.2)

It is now a matter of determining the angle \( \nu \) and the elemental area \( dA \). The equation for the ellipsoid is

\[ \left( \frac{x}{a} \right)^2 + \left( \frac{r}{b} \right)^2 = 1 \]  

(2.3)

The coordinates and axes are defined in Fig. 2.4. The angle the normal vector makes with the major axis is perpendicular to the tangent

\[ \nu = \tau + \frac{\pi}{2} = \tan \left( \frac{dr}{dx} \right) + \frac{\pi}{2} \]  

(2.4)

where
\[
\frac{dr}{dx} = -\left(\frac{b}{a}\right)^2 \frac{x}{b} \left(1 - \left(\frac{x}{a}\right)^2\right)^{\frac{1}{2}}
\]

Equations (2.4) and (2.5) provide the angle of the normal vector.

A differential element of the surface has an area

\[dA = ds \, r \, d\phi\]

The arc length \(ds\) is

\[ds = \left(dx^2 + dr^2\right)^{\frac{1}{2}} = dx \left[1 + \left(\frac{dr}{dx}\right)^2\right]^{\frac{1}{2}}\]

The area is then

\[dA = \left[1 + \left(\frac{dr}{dx}\right)^2\right]^{\frac{1}{2}} r \, dx \, d\phi \]

with the slope, \(dr/dx\), given by Eq. (2.5). This area is used in Eq. (2.1) and integrated to give the total area.

The integration of (2.1) is only carried out, however, over the windward side of the body, which is the side where the dot product is less than or equal to zero. In general, there will be a region at the front of the body \((\nu \sim \pi)\) where the integration will go completely around the axis, i.e. \(0 \leq \phi \leq 2\pi\). Further aft, however, part of the body will be on the leeward or “shadow” side and the dot product will be positive. This region must be excluded from the integration. The demarcation is the curve on which the dot product is zero. Setting the right hand side of Eq. (2.2) equal to zero and solving for \(\cos(\phi)\) gives

\[
\cos(\phi) = -\frac{\cos(\alpha) \cos(\nu)}{\sin(\alpha) \sin(\nu)} = -\frac{1}{\tan(\alpha) \tan(\nu)}
\]
Near the nose of the body the magnitude of \(\cos(\phi)\) is greater than 1 and \(\phi\) is imaginary. This means that the integration will go completely around the axis. Further aft \(\phi\) becomes real and there are two meaningful results—the principal value of \(\phi (= \phi_1)\) and \(2\pi\) minus the principal value (= \(\phi_2\)). The integration takes place between these two values. Finally near the base of the body \(\phi\) becomes imaginary again. This region is in the shadow and is not used. Figure 2.5 demonstrates the integration limits on \(\phi\).

The integration was implemented here by finite summations. The surface was subdivided into small panels of size \(\Delta \phi \Delta x\). In the streamwise direction 500 equal length segments were used so that \(\Delta x = L/500\), where \(L\) is the body length. In general, not all 500 segments were used however, because the base or tail region of the body was completely in shadow. In the azimuthal direction, near the nose where the integration went from \(\phi = 0\) to \(\phi = 2\pi\), 1° increments were used, i.e., \(\Delta \phi = 1^\circ\). In the region where the integration went from \(\phi_1\) to \(\phi_2\), 100 equal size azimuthal segments were used i.e., \(\Delta \phi = (\phi_2 - \phi_1)/100\). The final equations used were

\[
A_1 = \sum_{i=0}^{360} \sum_{j=0}^{i_{\text{nose}}} -\left(\frac{b}{a}\right)^2 \frac{x_j}{b} \left(1 - \left(\frac{x_i}{a}\right)^2\right)^{1/2} \Delta \phi \Delta x \left[\cos(\alpha)\cos(v_j) + \sin(\alpha)\cos(\phi_i)\sin(v_j)\right]
\]

\[
A_2 = \sum_{i=0}^{100} \sum_{j=i_{\text{nose}}}^{i_{\text{base}}} -\left(\frac{b}{a}\right)^2 \frac{x_j}{b} \left(1 - \left(\frac{x_i}{a}\right)^2\right)^{1/2} \Delta \phi_j \Delta x \left[\cos(\alpha)\cos(v_j) + \sin(\alpha)\cos(\phi_i)\sin(v_j)\right]
\]

\[A = A_1 + A_2\]

The area for a prolate spheroid 28.3 cm long and with a maximum diameter of 18.1 cm was determined for angle of attack ranging from 0° to 90°. (These dimensions match production rugby balls.) The results are shown in Fig. 2.5 as the ratio to the area based on volume \(2/3\), which for this geometry is 44.4 cm². There is clearly a significant difference between the projected area and volume \(2/3\) at large angles of attack. Because the flow is dominated by separation at large angles of attack, the projected area may be more physically meaningful for these cases.
Figure 2.1  A generic prolate spheroid.

Figure 2.2  Unit vectors.
Figure 2.3  Unit normal vector angles.

Figure 2.4  Cylindrical coordinates.
Figure 2.5  Azimuthal integration limits.

Figure 2.6  Results for a rugby ball.