An Investigation into the Aerodynamic Effects Resulting from Scuffing a Baseball

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An experimental investigation was undertaken to quantify the effect scuffing (localized roughness) has on the aerodynamic forces developed on a baseball. The parametric study varied both the size of the scuffed area and the severity of the scuff. Roughening the surface with sandpapers of varying grit varied the severity of the scuff. Sandpaper grits from 40, 80, and 120 were tested over three different sized areas (0.16 in^2, 0.32 in^2, and 6.15 in^2). Force data was collected from a stationary baseball at two different orientations (two-seam and four-seam) in a subsonic wind tunnel with a three-component sting balance. The freestream velocities studied were those that are typical of a pitched baseball (80 mph $\leq V_\infty \leq$ 100 mph). This corresponds to Reynolds numbers, based on diameter, of 1.8 x 10^5 to 2.2 x 10^5. As suspected, the data shows the side force generated increased with increased area of scuffing. The effect of scuff severity was less intuitive. Greater side force measurements resulted from baseballs scuffed by 80-grit sandpaper, which was not the coarsest tested. The largest change in the side force resulted from scuffing a 6.15 in^2 area with 80-grit sandpaper. The side force coefficient observed in this case was 0.15 and corresponded to a 50% increase over the baseline (un-scuffed) baseball. Of the two orientations tested, larger changes in side force were realized when the baseball's seams were upstream of the scuffed area. Lastly, the drag coefficient was shown to be insensitive to most scuffs. The investigation suggests scuffed baseballs can produce lateral movement of up to 1.75 in.

Nomenclature

V_∞	Freestream Velocity, mph
U_∞	Freestream Velocity, ft/s
C_D	Drag Force Coefficient
C_S	Side Force Coefficient
S	Side Force, lbs
D	Drag Force, lbs
ρ_∞	Freestream Air Density, slugs/ft^3
A_F	Projected Frontal Area, ft^2
X_S	Horizontal Movement, in
ΔX_S	Horizontal Movement over Baseline, in
m	Mass of a Baseball, slugs
T_o	Pitch Travel Time, sec

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I. Introduction

Baseball dates from back before the civil war era when games were played on sandlots. It was not until 1871, however, that the first professional baseball league was formed. The game had few rules, especially those concerning the baseball itself. The ball was constructed out of rubber wrapped with strings covered by horsehide. In 1872, a size restriction was placed on the ball and then in 1910 a cork core was implemented. In 1931, the baseball was improved by implementing rubber around the cork core and raised stitches, which provided a more balanced ball and gave pitchers more control over the spin of the ball. In 1974, the final major change was replacing the horsehide with cowhide cover, which was done for economic reasons.[1] Today, tight regulations are placed on the production of Major League Baseballs, as it is understood that geometric differences can greatly affect the aerodynamic forces on the baseball, and thus, the trajectory and speed of a pitch.

Understanding the physics of flow past a sphere is foundational to the understanding of the forces generated on a baseball (Figure 1). Aerodynamic forces develop from asymmetrical distributions of predominantly surface pressure, but also shear stress.[2] A sphere experiences bluff body separation at moderate Reynolds numbers causing pressure differences between the front half and the back half which brings about a drag force. Below Reynolds numbers of approximately 300,000, a sphere is subjected to laminar boundary layer separation on the front half of the surface which causes a large wake to form, and ultimately, a large drag coefficient (Figure 2a). Above approximately Re = 300,000, the laminar boundary layer naturally transitions to a turbulent boundary layer. The transition to turbulence increases the mixing within the boundary layer and, as a result, increases the momentum close to the surface. This allows the flow to better withstand the adverse pressure gradient over the back portion of the ball and, as a result, to separate relatively late compared to a laminar boundary layer,[8] which decreases the extent of the wake region and greatly reduces the drag coefficient (Figure 2b). When the flow pattern is symmetric about the upper and lower portions of the sphere a side force is not developed. Asymmetries in this transverse direction can be induced by either rotation[3] or altering the surface.[4] When rotation generates a side force it is more commonly referred to as a Magnus force.[5]

Ball rotation[6–9] or surface roughness[10] can modify the pressure distribution, establishing changes to drag and side forces which change the trajectory. There have been numerous studies on how seam height and spin affect the flow over a baseball. These studies have concluded that higher seamed baseballs have a greater Magnus force, which creates a greater drop in the trajectory of the baseball when thrown with spin.[9,11,11,12] The seam produces an overall roughness that helps reduce the critical Reynolds number which marks the transition between laminar and turbulent boundary layer separation. Scuffing a baseball has the same effect as the seams in roughing the surface of the ball.[12] The movement of a knuckleball works on this principle. The knuckleball is thrown with very limited rotation. The position of the seams relative to the freestream velocity cause separation to occur at different positions on the surface which brings about asymmetries, as studied by Borg.[13]

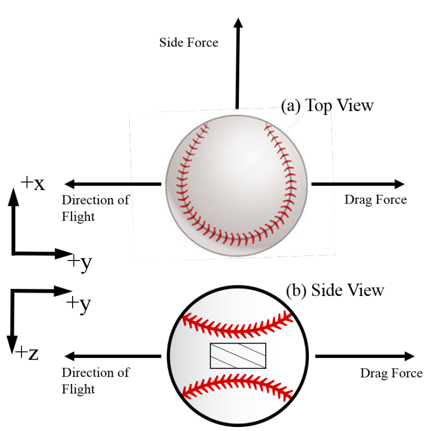

Figure 1: Schematic depicting the aerodynamic forces on a baseball (a) top view and (b) side view

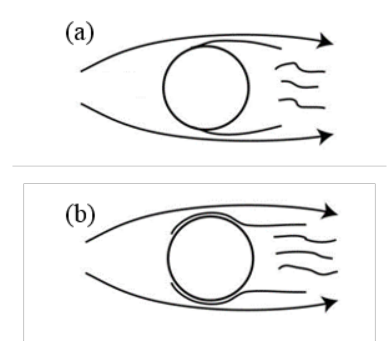

Figure 2: Separation point transition regions with increasing Reynolds number

The current study examines a stationary ball and the forces that are apparent at MLB pitch velocities of 80 mph - 100 mph, which corresponds to Reynolds numbers based on ball diameter of 1.76 x 10^5 - 2.2 x 10^5. The purpose of the study was to quantify the side force generated from a scuff on a stationary baseball. This study is seen as a first step in quantifying the effect of scuffing on a pitched baseball which would also be subjected to rotational effects.

II. Experimental Setup

A. Apparatus

Experiments were conducted in a subsonic open return wind tunnel (model AerolabEWT). The wind tunnel is a suction type tunnel capable of velocities in excess of 145 mph through a 12 in x 12 in x 24 in test section. The turbulence levels of the system are less than 0.2%. The freestream velocity of the wind tunnel was monitored using a pitot static probe placed upstream of the model. The static and stagnation pressure were measured by a Scanivalve DSA3217 pressure scanner. The unit has a full scale range of ±10 in of water and a static accuracy of ±0.20%.

B. The Model

Measurements were acquired on official MLB baseballs (model ROMLB). These baseballs are manufactured and distributed by Rawlings. The balls consist of a round cushioned cork center wrapped tightly in wool and polyester/cotton yarn, which is covered by stitched cowhide. The balls weigh between 5 and 5.25 ounces and measure between 9 and 9.25 inches in circumference. A hole was drilled into the baseballs and press fit into a custom support mount which attached to a three-component sting/balance as shown in Figure 3. The balls were oriented on the balance in either a two-seam grip or a four-seam grip. The scuffs were generated on the side of the baseball and were of varying area and roughness. The areas tested were 0.16 in^2, 0.32 in^2, and 6.15 in^2. The 0.16 in^2 and 0.32^2 areas were chosen as they represent areas seen from pictures of game balls which appeared to be scuffed during play. The 6.15 in^2 area was then tested to place an upper bound on the data as this area is much larger than any that would be plausible during gameplay. To test the severity of the scuff, varying roughnesses were produced by implementing sandpaper scratches of varying grit. Three different roughnesses were tested from either 40 (coarse), 80, or 120 (fine) grit sandpaper. Three swipes or rubbing of the area with the thumb were done to fill in the required areas with a scuff. The baseball orientation, scuff placement, and scuff areas are depicted in Figure 4 and Figure 5.

Figure 3: Experimental set up with baseball mounted to force balance inside of wind tunnel

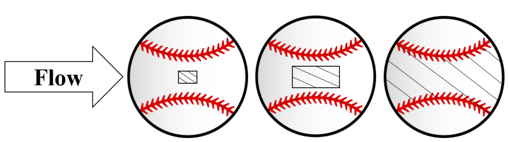

Figure 4: Schematic depicting varying scuff areas and placement with a two-seam fastball orientation

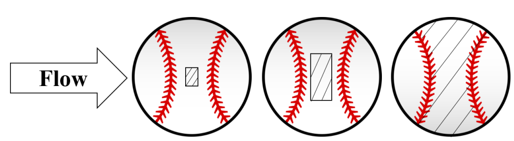

Figure 5: Schematic depicting varying scuff areas and placement with a four-seam fastball orientation

C. Force Measurements

The baseballs were mounted on a three-component force balance to measure drag and side (transverse) forces. For each baseball, the tests were run at 80 mph and then increased by 5 mph until 100 mph was reached and then reduced to 80 mph again at the 5 mph increments to eliminate hysteresis. For every test run performed, the baseball was taken off the sting balance and remounted to mitigate systemic errors. Several cases, such as the baseline, used two different baseballs to check the repeatability of the data. Side and drag forces are non-dimensionalized by the dynamic pressure and the projected frontal area through,

$$C_S = \frac{S}{\frac{1}{2}\rho_\infty U_\infty^2 A_F}, \tag{1}$$

$$C_D = \frac{D}{\frac{1}{2}\rho_\infty U_\infty^2 A_F}, \tag{2}$$

where ρ_∞ is the freestream air density, U_∞ is the freestream velocity, and A_F is the projected frontal area. The Aerolab three-component internal strain gage force/moment balance is capable of reading a side force of 25 pounds, an axial force of 10 pounds and a pitching /yawing moment of 50 inch-pounds. The data collection was handled through a National Instruments (NI) data acquisition (DAQ) system (NI-9237) with a NI-CDAQ-9174. The information was transmitted from the balance to the DAQ and then via USB cable to the computer to be used in conjunction with LabVIEW software. The uncertainty in side force coefficient was calculated to be near 6.2%.

III. Results and Discussion

A. Side Force

Side force data was collected and analyzed on baseballs which had various orientations (two-seam or four seam), scuffed area, and scuffed roughness. Presented first is the measured side force coefficient at varying pitch velocities (between 80 mph and 100 mph) and scuff areas (0, 0.16 in^2, 0.32 in^2, and 6.15 in^2) for both the two-seam (Figure 6) and four-seam (Figure 7) orientations. These figures show the data which corresponds to scuffs created by 80-grit sandpaper. The data show that the side force coefficient is independent of pitch speed. When focusing on the two-seam orientation, it can be seen that, as expected, the greatest side force ($C_S \approx 0.1$) was generated by the 6.15 in^2 scuff followed by the 0.32 in^2 area ($C_S \approx 0.05$). The 0.16 in^2 scuff showed no effect over the baseline ($C_S \approx$ -0.02). Interestingly, the four-seam orientation showed different results as both the 0.16 in^2 and 0.32 in^2 scuffs had no effect on the side force measurements, yet the large 6.15 in^2 scuff produced the greatest effect of either orientation ($C_S \approx 0.15$). It is the authors belief that reason for this difference stems from the location of the seams. In the four-seam orientation, the seam is upstream of the scuff while in the two-seam orientation they are at the sides. The increased surface roughness in the scuffed area is expected to modify the boundary layer and its separation point. If the seam is directly upstream of this scuffed region, the boundary layer would already be disturbed and the ability of the scuff to modify the separation point is drastically reduced. This is the reason only the large scuff produced an effect in the four-seam orientation. In the two-seam orientation, the boundary layer is not affected by a seam prior to being exposed to the scuff. In this orientation, the much smaller 0.32 in^2 scuff in addition to the 6.15 in^2 scuff generated side forces not present in the baseline flow field. This is important to note as the 0.32 in^2 scuff is of a size which could be produced by a pitcher attempting to gain an unfair advantage.

The effect of changing the scuff roughness is next analyzed through Figure 8 and Figure 9. These figures again show the side force coefficient for varying pitch speeds yet the data presented varies the sandpaper grit (40, 80, and 120) used to generate the scuff. All data corresponds to the maximum 6.15 in^2 scuffs for either the two-seam (Figure 8) or four-seam (Figure 9) orientation. For these maximum scuff cases, it was determined that all roughnesses tested altered the baseline flow. Surprisingly, the greatest side force occurred when 80-grit sandpaper was used even though it was neither the roughest nor the finest studied. The side force coefficients were measured at approximately 0.1 and 0.15 for the two-seam and four-seam orientations respectively. The effect of roughness on the smaller sized scuffs were tested but did not result in noticeable changes and have been omitted for brevity.

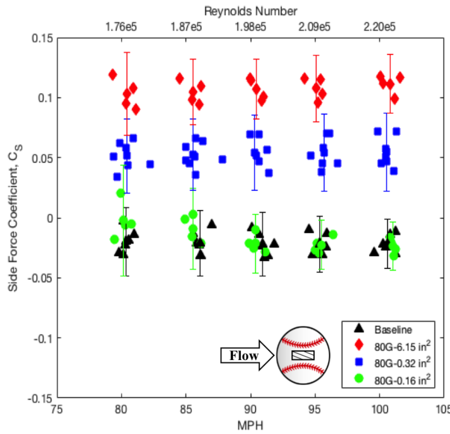

Figure 6: Effect of area on lift coefficient for 80-grit scuff in two-seam orientation

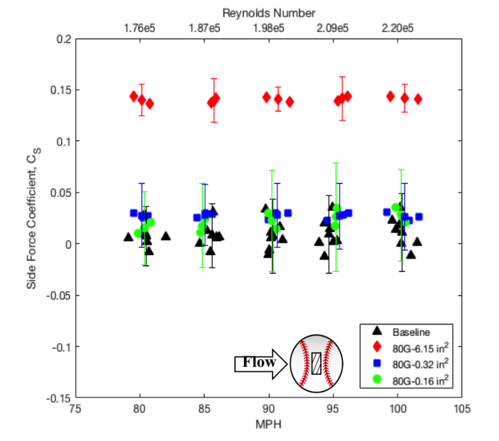

Figure 7: Effect of area on lift coefficient for 80-grit scuff in four-seam orientation

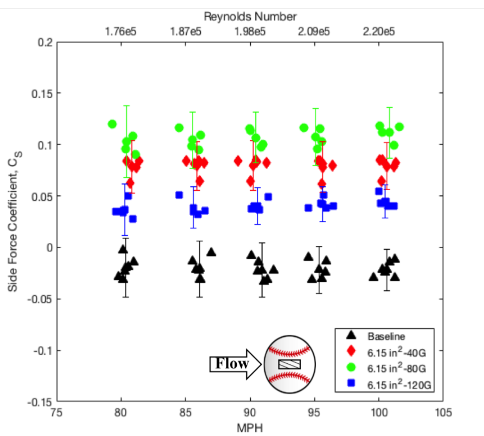

Figure 8: Effect of grit on lift coefficient for 6.15 in^2 scuff in two-seam orientation

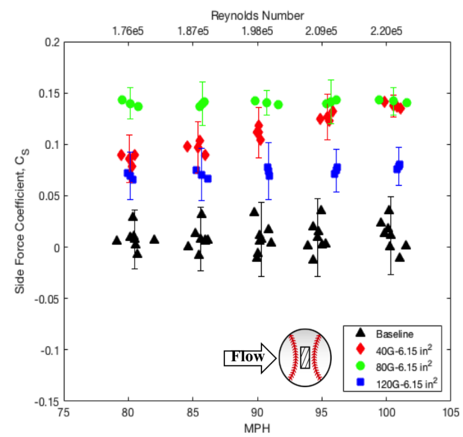

Figure 9: Effect of grit on lift coefficient for 6.15 in^2 scuff in four-seam orientation

Many studies have been performed on the effect of spin on lift coefficients. Due to the nature of this experiment using a non-rotating baseball, comparisons of lift coefficients can be made at very small spin parameters. Based on the research done by Alaways,[14] at spin parameters less than 0.1 for a four-seam fastball, side force coefficients can be seen from slightly above 0.2 down to 0.0 with no spin. Research on knuckleballs conducted by Borg[13] had similar results for non-spinning baseballs. Side force coefficients ranged from 0.2 to slightly below 0 in his experiments for the Reynolds number range of 1.6 x 10^5 to 1.8 x 10^5. Our findings show that a stationary ball with a scuff generated a side force coefficient between 0.1 and 0.15, which are on the same order as knuckleballs or low spin rates.

To gain an estimate on the horizontal movement produced by the measured side forces, a rudimentary dynamic analysis was employed where displacement was quantified through,

$$X_S = \frac{S}{2m} T_o^2 \tag{3}$$

where m is the mass of a baseball, and T_o is the time it takes for a pitch to travel to home plate (60 ft 6 in). This formula is derived under the assumption that the displacement, X_S, is much smaller than total distance traveled by the ball. The values shown in Table 1 and Table 2 are the average lateral movement, X_S, across all velocities tested, 80 - 100 mph, as well as the movement over the baseline, ΔX_S. The cases in Table 1 and Table 2 were chosen based on the roughnesses that yielded the highest C_S values, and the areas, 0.32 in^2, that would be most realistic in actual gameplay. By comparing the two tables, the four-seam orientation had the greatest lateral movement for the max area cases investigated. The greatest movement was the 80-grit max area scuff with C_S=0.15, X_S=1.78 in, and ΔX_S=1.73 in. The larger scuffed regions produced the most movement. The two-seam orientation produced the greatest movement, X_S=0.72 in, for the smaller area compared to the four-seam orientation, $X_S = 0.18$ in. All positive displacements correspond to movement away from the scuffed region. The movement deduced from the data validates accounts from former Major League Baseball pitcher Dirk Hayhurst, who stated, "The first thing to know about a scuffed ball is that, once scuffed, the ball will break in the opposite direction of the scuff."[15]

	Average Movement (in)	ΔX_S (in)
Baseline	-0.20	
6.15 in^2 80-grit	1.27	1.47
6.15 in^2 40-grit	1.00	1.19
0.32 in^2 80-grit	0.72	0.92

Table 1: Lateral movement for the two-seam fastball

	Average Movement (in)	ΔX_S (in)
Baseline	0.05	
6.15 in^2 80-grit	1.78	1.73
6.15 in^2 40-grit	1.40	1.35
0.32 in^2 80-grit	0.18	0.13

Table 2: Lateral movement for the four-seam fastball

B. Drag

Drag force data was collected and analyzed in the same manner as the side force data. In the side force discussion, it was seen that the two-seam orientation with 80-grit scuffs most affected side forces with small 0.32 in^2 areas. The corresponding drag force coefficients are presented in Figure 10. Of note, though side forces were produced, the drag coefficients were determined to not be statistically different from the baseline case. This suggests that, when pitched, these scuffed baseballs would incur side movement without decreasing the forward pitch velocity.

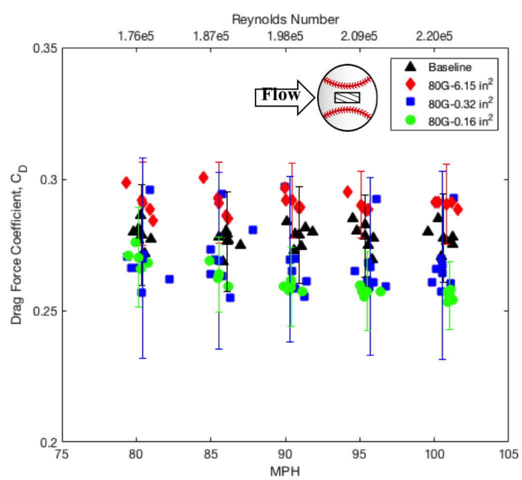

Figure 10: Effect of area on drag coefficient for 80-grit scuff in two-seam orientation

Figure 11 shows the drag coefficient after varying pitch speeds for different scuff regions. The data corresponds to roughest scuff (40-grit) in the four-seam orientation. The drag coefficient varied from approximately 0.25 - 0.35 over a range of Reynolds numbers from 1.76 x 10^5 to 2.2 x 10^5 as scuff area changed for the 40-grit scuff in the four-seam orientation. The data presented is consistent with what was collected by Mehta and Pallis,[8] as well as Achenbach.[4] Drag coefficient data was observed to range from 0.3 to 0.35 (Reynolds numbers of 1.5 x 10^5 to 1.7 x 10^5) and 0.2 to 0.25 (Reynolds numbers of 1.25 x 10^5 to 1.85 x 10^5) for each study respectively. The smaller areas, 0.16 in^2 and 0.32 in^2, had little impact on C_D compared to the baseline. The only noticeable impact was caused by the maximum area scuff. The two-seam orientation did not show any identifiable differences among the different area cases compared to the baseline results. Results similar to the 40-grit maximum areas were collected for the 80-grit cases in both four-seam and two-seam orientations.

When reviewing the 6.15 in^2 scuff in the four-seam orientation (Figure 12), it can be seen that in order for a change in C_D to occur, there needs to be a very rough scuff. The 120-grit scuff did not experience a change from the baseline scuff, while the 80-grit and 40-grit increased C_D.

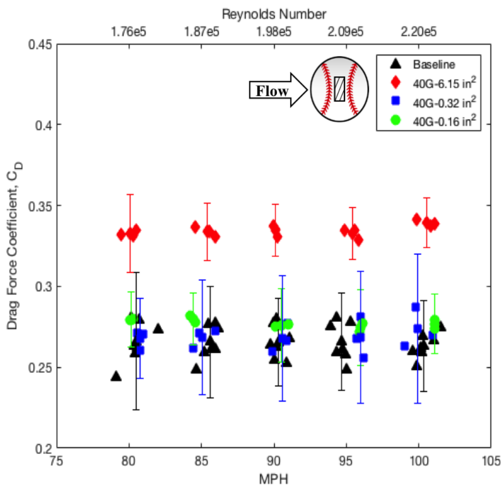

Figure 11: Effect of area on drag coefficient for 40-grit scuff in four-seam orientation

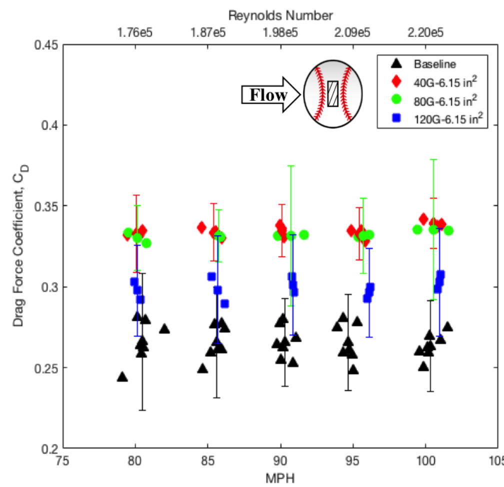

Figure 12: Effect of grit on drag coefficient for 6.15 in^2 scuff in four-seam orientation

IV. Conclusion

A study was performed to quantify the aerodynamic forces generated by scuffed baseballs. The findings suggest that minimally sized scuffs (<0.32 in^2) had no measurable effect to the baseline flow field. Once a scuff area was at or above 0.32 in^2, a change in side force was seen for the two-seam orientation but not for the four-seam orientation. This is attributed to the seams of the baseball modifying the boundary layer prior to the scuff, thus minimizing its effect. The largest side coefficients measured were for the maximum area 6.15 in^2 scuffs produced by 80-grit sandpaper. The measured values were $C_S \approx 0.15$ and $C_S \approx 0.1$ for the four-seam and two-seam orientations, respectively. This was interesting as the 80-grit sandpaper outperformed both the courser 40 grit sandpaper and the finer 120 grit sandpaper.

Ultimately, the lateral movement of the baseball is important to a pitcher. A simplified analysis estimated an added movement of 0.92 in to a two-seam fastball for a 0.32 in^2 scuff (which is a size representing game play scuff). In addition, larger scuffs were examined to determine an upper bound on the induced motion. The upper bound was estimated to be 1.7 in. All movement was determined to be in the direction opposite the scuffed region. It should be emphasized that data was collected on a stationary baseball and future research should be conducted on scuffed spinning baseballs to supplement the work presented.

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