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Pitched Baseballs and the Seam Shifted Wake

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PITCHED BASEBALLS AND THE SEAM SHIFTED WAKE

by

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ABSTRACT

Pitched Baseballs and the Seam Shifted Wake

by

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Utah State University, 2020

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An experiment was conducted to investigate how seams and their orientation, relative to the spin axis and flight direction, can alter the formation of a wake around a baseball. Particle Image Velocimetry (PIV) was used to examine the velocity field around an MLB ball in specific orientations and to find the boundary layer separation locations, or the location on the ball where the wake begins to form. Certain seam locations can advance the separation point on one side of the ball, generating a pressure force on the ball and altering its flight path. Using this information as a guide, baseballs were launched 55 feet (a realistic pitching distance) in orientations designed to have an asymmetric separation point. These pitches were 90 mph with spin rates near 1200 rpm and a vertical spin axis, perpendicular to the initial flight direction. A Rapsodo system was used to compare the pitch locations for different seam orientations. The results showed a significant and repeatable difference in the path of the ball depending on the orientation of the seams relative to the spin axis. This effect was found to be larger for baseballs with larger seams.

(76 pages)

PUBLIC ABSTRACT

Pitched Baseballs and the Seam Shifted Wake

Andrew W. Smith

An experiment was conducted to investigate the effect that seams have on the way a baseball moves through the air. An examination of the airflow around a baseball led to the understanding that when seams are in certain areas on the baseball's surface the airflow changes. A subsequent experiment was performed which showed that when these changes in airflow were on one side of the baseball more than the other, the ball moved away from the side with seams. This movement is in a different direction than the movement direction caused by a ball's spin. These experiments were done using balls moving at 90 mph and spinning at 1200 RPM, a baseball tracking system, and a highspeed camera.

For Sterling, Genevieve, and Areti.

ACKNOWLEDGMENTS

Special thanks to Dr. Barton Smith and Austin Parker for taking a chance on hiring me as an undergrad even though I didn't grow up on a farm and to Dr. Lloyd Smith for enabling us to perform the work we did even though it ended up being about something else entirely. I also want to thank Jeff Kensrud for allowing us to use the baseball cannon and Norton Performance for letting us borrow the Rapsodo system. Thanks to Nazmus Sakib for all the time spent letting me think out loud and correcting many of those erroneous thoughts, to John Garrett for helping me with all the tedious stuff, and to my friends Troy and Jaden who helped when they had no reason to. Lastly, and most importantly, Thanks to my wife, Emily for putting up with it all for so long and being so patient. This was only possible because of her.

Andrew W. Smith

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ACRONYMS

FFT	Fast Fourier Transform
LED	Ligth Emitting Diode
MLB	Major League Baseball
Nd:YAG	Neodymium-Doped Yttrium Aluminum Garnet
PIV	Particle Image Velocimetry
RPM	Rotations Per Minute
sCMOS	Scientific Complementary Metal–Oxide–Semiconductor
SSW	Seam Shifted Wake

CHAPTER 1

INTRODUCTION

1.1 Background

A pitcher attempting to fool a batter has been part of baseball since the late 19th century. It took another half century before the physics behind baseball movement became understood at a basic level through scientific inquiry. Since then, the inquiry into baseball movement has continued and investigations into baseball aerodynamics are ongoing. The following are a few of the prominent examples of this research. It is the purpose of this study to further the understanding of baseball movement by providing an understanding of the role that seams can play in baseball aerodynamics.

In 1959, in one of the first works on this subject [3], Carl Selin analyzed, “more than 200 pitches, made by 14 pitchers of baseball teams in the Western (Big Ten) Conference.” Using two high-speed cameras, Selin showed that it was possible for some of these pitchers, by spinning the ball, to generate deflections of up to 18 inches from the non-spinning, ballistic trajectory.

Shortly thereafter in 1959, Lyman Briggs conducted similar research [4] where he initially attempted to measure the effect of a spinning ball that had been launched with an air cannon. The results, when the air cannon was used, were erratic and had spin rates lower than desired and so a new method was attempted. Using a spinning ball in free fall through a wind tunnel, Briggs showed that there is a relationship between spin rate, speed, and the lateral deflection of the ball. This result validated the work done by Selin and others. In addition to the deflection, Briggs also measured the pressure around the ball and compared the result of the baseball to other balls with varying surface characteristics.

In 1990 Robert Adair first published the seminal work *The Physics of Baseball* [5]. While he states that the book is “not meant as a scholarly compendium of research on baseball" it is referenced quite widely in baseball and among scientists studying the sport. The book covers a wide range of baseball topics in some detail. Of note for the purposes of this study are the chapters covering the flight of a baseball and pitching. Adair points to several formulae that predict the flight path of the ball which consider magnus effect in addition to the effects of drag and gravity. Adair does mention seams and how they can affect the flight behavior of the ball but only considers the seams on knuckleballs and only as a source of transition from laminar to turbulent flow .

In 1998 LeRoy Alaways wrote his Ph.D dissertation [6] on the aerodynamics of curveballs. Alaways investigation into the aerodynamics of baseball was done using technology that was relatively new at the time. They experimental setup used 10 cameras positioned to view the ball at different sections of its flight path. The balls were marked with special reflective marks that would allow the cameras to pick up the ball as well as the ball's change in orientation. New software was used to analyze the images and show the ball's spin rate and trajectory and find a corresponding coefficient of lift (C_L). The effect seams may play on the ball's flight behavior is not considered.

Alan Nathan in 2008 conducted further investigation [7] into the relationship between spin, velocity, and deflection. Nathan showed that C_L is dependent on the spin factor ($S = \frac{\omega r}{V}$) for any baseballs that could be pitched in a typical, professional baseball game. Additionally, Nathan showed that, for a given S between 0.15 and 0.25, the C_L is independent of velocity (if the velocity is between 50 mph and 110 mph). This result conflicts with the proposed formula given by Adair.

As computing power and the technology to track baseballs continues to improve research into the finer details of baseball aerodynamics advances. Jeff Kensrud in 2015 showed that the drag on a baseball, and therefore its carry distance, is dependent on the height of its seams [8]. This became a serious issue in 2019 when the MLB experienced a surge in homeruns that was due, at least in part, to the decreased seam height of the baseballs that year. This is also a major step towards understanding the importance that seams can play in the flight of a baseball. Additionally, the cannon developed by Kensrud was a critical piece of equipment that allows for consistent and repeatable pitch parameters with almost no wear on the ball or changing of the ball's surface condition.

In 2018 Kensrud published another paper [1] taking a better look at the effect that seam orientation (2-seam vs 4-seam) and height has on lift and drag. Kensrud found that lift caused by magnus was not affected by the height or orientation of the seams. Drag, however, was affected by both seam height and orientation. This was another huge step forward but was still missing the effect seams might have in directions other than that of the Magnus effect.

All the research shown here, and much else besides, has led to a better understanding of a pitched ball and the ways in which a pitcher can fool a batter. In 2020, it is common for a baseball pitcher to throw a variety of pitches that may have radically different speeds, spin rates, and spin axes (e.g. the axis of a curve ball is nearly opposite to a fastball as it spins in the opposite direction). While some understanding of the curveball and Magnus effect have existed for some time, there is still much that remains unknown about the physics of baseball movement and research continues to produce new results [7] [1]. In particular, this study looks to show what effects seam orientation can have on the trajectory of a pitched baseball.

Conventional pitches, a category into which is placed any fastball (4-seam, 2-seam, sinker, cutter, split finger), the curveball, changeup and slider, have a trajectory that is influenced by gravity and by the Magnus force [9] [6], assuming still air. Knuckleballs, which do not rotate sufficiently fast to generate any appreciable Magus force, are distinct.

The pressure on a moving ball is highest at the front of the ball, which is called the "stagnation point" in fluid dynamics. Meanwhile, a wake forms behind the ball. The start of the wake on each side of the ball is called the boundary layer separation point. This term will be shortened to "separation point" in this study. The pressure on the ball decreases from the stagnation point to the center of the ball and then begins increasing again, assuming separation does not occur. Once separation occurs, the pressure stops changing. In other words, the surface of the ball in the entire wake is at the same pressure which is just under atmospheric pressure.

The Magnus force occurs because the separation point on the retreating side of the ball moves toward the back of the ball while the separation point on the advancing side moves toward the front of the ball. Since the pressure at the separation points is different, a force, the Magnus force, is generated and is perpendicular to the direction of motion and the spin axis.

Understanding that the seams can influence ball movement in flight has existed in baseball for some time. Marshall(2002) [10] claimed, "When air molecules collide with these seams, pressure increases to push the baseballs away from their circles of friction." The circle of friction was defined as the "loop [that] could create a circle that constantly collided with air molecules." While this description is somewhat unclear, it is obvious that Marshall, and likely those he coached, were aware of the effect that seams can have on pitched baseball flight.

Others have noted that the orientation of the ball, relative to its spin axis, can cause a pitch to break differently. Trevor Bauer, an MLB pitcher, said "I began thinking of ways to orient the ball around the axis in 2010. I used to throw two types of sliders in college, one was noticeably flatter and ran more to the glove side, the other ran less and had more depth. I called the first one a circle slider and the second one a dot slider. I'm sure the names are self-explanatory, but they came from my dad. He always caught me, and he noticed that the circle slider appeared to have a circle on the front of the baseball and the dot slider appeared to have a dot on the front of the baseball. As pitch tracking wasn't a thing back then, we agreed that there was a discernible difference in the movement of the two pitches and moved on from there. In... 2015, Kyle Boddy [of Driveline Baseball] and I began discussing laminar flow two seams based on ... [a video by Rodney Cross]. I spent all off-season developing it and getting the axis and orientation correct, and I noticed a massive swinging effect in my first outing of the following year against Houston. I struck out 11 in six innings, many on the pitch we lovingly called the laminar express. It was the first time in my career I'd been able to make a pitch visibly break to the arm side. I wasn't sure the physics were perfectly correct though, as there were some inconsistencies with the observed movement and my understanding of the physics at the time, but the observed movement was what I was after and I moved on from there. As my understanding of the physics was limited, I couldn't think of a way to apply the same principle to another pitch type, though I was sure there was a way. [11]" While this particular pitch is not studied here, it is clear that Bauer understands that orientation relative to the spin axis plays a role in flight behavior.

The Several attempts have been made to quantify the effect that seams can have on a baseball aerodynamics for non-rotating baseballs. Both Higuchi(2012) [12] and Borg(2014) [13] used wind tunnels to investigate the aerodynamics of knuckle balls and estimated the forces the seams could generate.

Wind tunnels offer the advantage of a controlled environment that allows data to be collected over a long period. However, they are subject to pressure changes due to blockage or reflection effects. Wind tunnel studies also require a sting to hold the ball, usually in a fixed relationship to the oncoming flow. To simulate a realistic pitch in a wind tunnel the sting would need to be placed on the axis of rotation on the surface of the ball (the spin pole). This presents two problems; first, the sting is in the oncoming flow area and will disrupt the flow around the entire ball, second, the effect seams have is likely largest near the poles and any sting in that area will obliterate any meaningful results.

In addition to experimental approaches there have been attempts to computationally predict the behavior of baseballs. Himeno (2001) [14] investigated the role of seams on separation at a Reynolds number $Re = \frac{\rho V D}{\mu} = 1 \times 10^5$ (V is the pitch speed, D is the baseball diameter, and ρ and μ are the density and viscosity of air) which corresponds to 45 mph. This is below the "drag crisis" of a baseball [1] and too slow to be relevant to a pitched baseball. The study showed seams causing separation much further forward on the ball than the experimental results from this study.

The major advantage of this experimental study is that all the data were collected on a ball in free flight. Free flight allows the ball's trajectory relative to its axis to change mid-flight as it would in a game environment.

1.2 The Seam Shifted Wake

Most existing models which attempt to predict baseball movement depend solely on lift from magnus and drag. There are, however, many pitches which behave differently than these models predict. This study shows that these differences are due, at least in part, to an effect called the “Seam Shifted Wake.”

Air flow over any surface may be “laminar” (mostly steady, small amounts of mixing and low shear at the surface) or “turbulent” (chaotic, considerable mixing, high surface shear). Generally, a higher relative velocity between the air and a surface increases the probability of turbulent flow. Turbulent flow over a ball results in a later separation than laminar flow since the turbulent boundary layer has more momentum due to increased mixing. Since many sports balls, including baseballs, commonly fly at speeds where flow could be laminar or turbulent, seams can influence the state of the flow and greatly increase the probability that flow on any part of a baseball is turbulent

Cricket balls, which have a band of seams around the equator of the ball, fly at similar speeds and are of similar size to baseballs. It is common for a cricket “bowler” (the equivalent of a baseball pitcher) to use the seams to generate turbulent flow on one side of the ball and laminar on the other [15], resulting in “swing,” or a change in the flight path. This is difficult to do with a baseball because its seams are not in a single band as on a cricket ball.

Baseball pitches change direction either due to gravity or pressure forces on the ball. If the pressure was uniform around the ball, no pressure force would result. However, bluff bodies, such as baseballs, have a complicated pressure fields that will now be discussed with the aid of Fig. 1.1.

This is a PIV dataset (described below) showing a smooth, non-spinning ball with a wire “trip” on its front to ensure the flow is turbulent everywhere. Pressure is highest (P_{stag}) where the air meets the ball at the front and decreases until the minimum pressure (P_{min}) occurs where the surface of the ball is tangent to the flow. From that point until

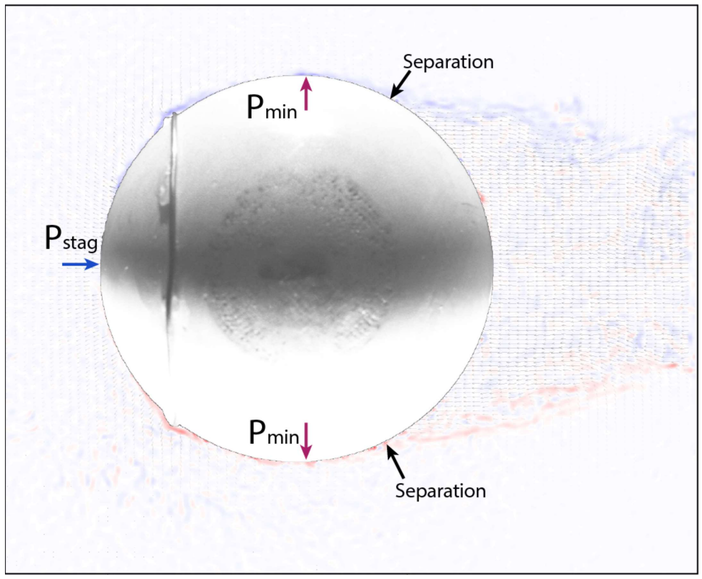

Fig. 1.1: A PIV image of a smooth ball with a wire trip. The vector background is vorticity, red indicating counterclockwise rotation and blue indication clockwise rotation.

separation, the pressure increases. The pressure in the wake is lower than the un-moving air but significantly higher than $P_{\min}$. Since the separation occurs at the same point on both sides of the ball, there is no sideways force due to pressure. Since the pressure is larger on the front of the ball than the back, the ball experiences pressure drag.

Knuckleball pitches are thrown with minimal spin [16]. It has long been held that knuckleballs break randomly because seams on the front of the ball may cause flow to become turbulent (thus delaying separation) on some parts of the ball while other parts remain laminar. Two prominent baseball scientists have published books that make this claim. Both Adair(2002) [5] and Cross (2011) [17] point to the flow regime (laminar or turbulent) as the main effect seams have on the flight behavior of a ball. This study will suggest an alternative explanation: that seams near a plane perpendicular to the ball's direction of motion and passing thought center of the ball cause the wake to form early on one side of the ball compared to the other. In this sense, the effect is like the Magnus effect, in that it is due to asymmetric separation points, but it stems from the seams rather than spin.

Fig. 1.2: A PIV image of an MLB baseball moving left at 90 mph with an imbalanced wake. The separation on the seam on the top of the ball is forward of the separation on the bottom of the ball causing an imbalanced pressure field on the ball. This ball will have additional down force due to the asymmetry of the wake.

Fig. 1.2 shows a pitch with an asymmetrical wake. The asymmetrical wake is due to the seam on top advancing the location of separation. The question is, can the ball be thrown in such a way as to have appreciable magnus effect (from enough spin) and an additional force from the seams like that of a knuckleball. The purpose of this study is to show that seams can cause a change in the separation points of a spinning baseball, and that for certain ball orientations relative to the spin axis, this effect can persist for most of a rotation of the ball and therefore cause the ball to alter its path. This effect is called the "Seam Shifted Wake". It will be demonstrated that the symmetry between the separation location on the two sides of the ball can be broken by seams on a baseball. If this situation can be maintained during the majority of the flight of the ball, the ball will change direction as a result. This will open a new avenue for pitchers to further fool batters at the plate.

CHAPTER 2

METHODS AND EXPERIMENTAL SETUP

The study consists of two parts: air velocity measurements near the ball and ball trajectory measurements at full pitching distance. In both cases the ball was pushed at a speed of 90 mph with a linearly accelerated pneumatic cannon. At an elevation of 4500 ft and at a temperature of 70°F the resultant Reynolds number of the pitches is 1.79×10^5. All references to the coordinate system are based on the system shown in Fig. 2.1

2.1 Air Velocity Measurements Near the Ball

Two-component planar PIV measurements unobtrusively provide the velocity field around the baseball in free flight. The primary purpose of these measurements is to identify the points where separation occurs. Note that the PIV measurements show the flow field on a slice through the center of the ball.

The velocity field is used to compute vorticity, which is the curl of velocity. The PIV results are presented as vorticity contours shown over velocity vectors. Vorticity is used in this study because this quantity makes the separation point easy to identify. Since vorticity has a sign, both positive and negative vorticity (colored blue or red) are present in the separated flow. The sign of vorticity is not important to this study, so the color can be ignored by the reader. For the PIV dataset figures, the image of the ball from the raw PIV data is superimposed on the vector/velocity field to ensure that the orientation of the ball is accurate.

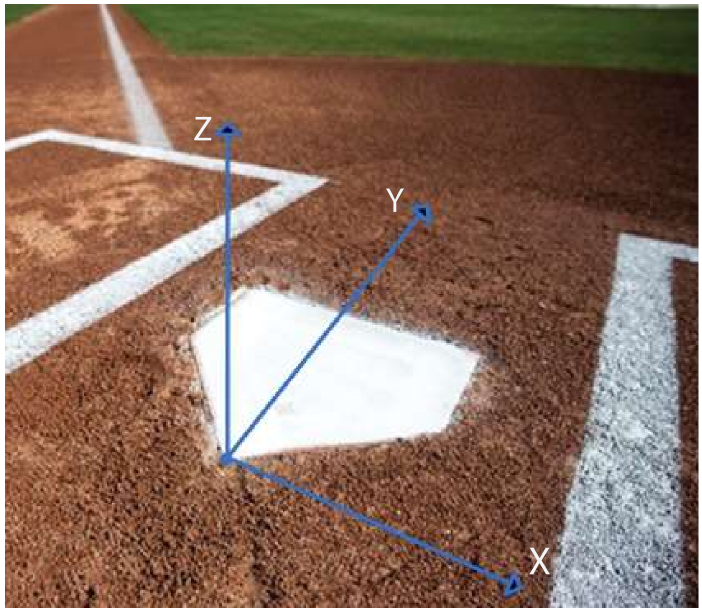

Fig. 2.1: Coordinate system used in this study which has the origin at the corner of home plate. Positive x is to the catcher's right, positive y is toward the pitcher, and positive z is up.

2.1.1 Hardware

The PIV system (Fig. 2.2) consists of two opposing pairs of Nd:YAG lasers and a 16-bit sCMOS camera. The interogation area is seeded with theatre fog using a PeaSoup fog machine located near the test area. The fog is mixed with the air using a 10 in. fan positioned to not disturb the interrogation space. A custom-built pneumatic cannon is used to launch the ball into the test section. A pair of LED lasers and photo transistors serve to trigger the system when the ball blocks both LED lasers simultaneously. A three inch thick foam pad, attached to a heavy rubber mat is hung to stop the ball which is then returned down a ramp to base of the cannon. This ball-return system allows for the repeated firing of the same ball with minimal delay.

2.1.2 PIV Data Capture

When the PIV system is triggered the two laser sheets overlap to generate a single light sheet. This light sheet illuminates the theatre fog particles in a single plane. Each time the lasers pulse the camera will record an image. This process is done twice in rapid succession

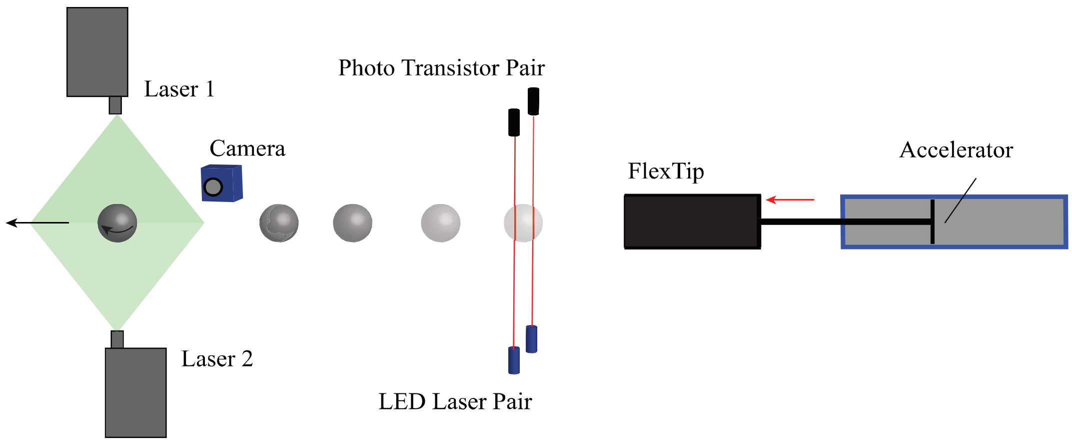

Fig. 2.2: Schematic of the PIV set up. The cannon launches the ball through the system with a vertical spin axis and, when the ball blocks both LED lasers, the PIV system is triggered capturing an image pair of the ball and the air in the vertical plane.

($dt \approx 10$ μS) to create a pair of images showing the same place separated by a small amount of time. The two laser pairs are positioned on opposite sides of the ball to illuminate the seed particles in the shadows of the ball. The laser plane is oriented vertically and along the direction of ball flight and illuminates the equator of the ball.

2.1.3 Analysis

The Computer software, provided by LaVision, is used to analyze the images. LaVision's software uses a spacial cross corolation algorithm to produce velocity fields from the data. LaVision's code allows for multiple passes and window shifting. The velocity data gathered with the PIV system were only used to identify the boundary layer separation locations. A masking feature sets the pixels to zero in regions thought to be the baseball so that they cannot contribute to the correlation. Since the baseball is brighter than nearly all the particles, a intensity threshold is set so that the outside of the ball is set to zero. Following processing, additional post-processing can be done to eliminate any bad vectors.

After the data have been processed and the images of the balls have been superimposed on the vector fields, each of the images are checked to see if separation occurred on a seam. All the images are analyzed and those which have separation on the seams are compared to those that do not. The analysis is done to find the angle between the minimum pressure

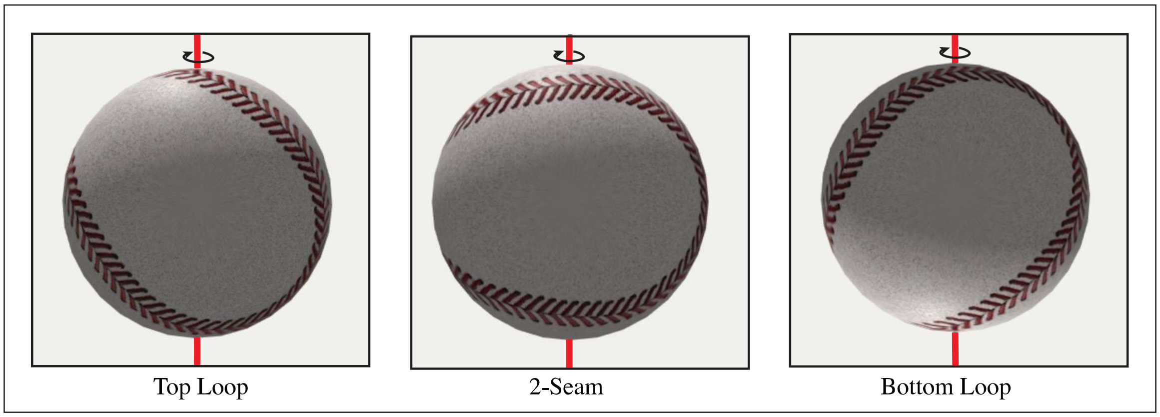

Fig. 2.3: The three seam orientations used in this study. The “Top Loop” orientation has a seam that is always near the top spin pole. The “Bottom Loop” has a seam that is always near the bottom spin pole. The 2 seam has no seam is near a spin pole. The Top Loop orientation is so named because a pitched spinning ball will appear to have a red loop spinning about the top pole. Similarly, the Bottom Loop appears to have a red loop spinning about the bottom pole.

location of the ball (where the flow is parallel to the surface) and the seam. The interrogation space is close enough to the cannon that the ball’s trajectory is still horizontal so minimum pressure locations are at the top and bottom of the ball. A digital, on-screen, protractor is used to measure the angle from the top and bottom of the ball to the location where separation occurs. A note was made to indicate if the separation occured on a seam.

For an SSW to occur, the average separation locations must be different one one side than the other over the course of a full rotation. This will often occur if the seams are oriented so that they occur near the spin pole on one side and not on the other. The seams on the “horse-shoe” part of the ball have no seams on the opposite side of the ball from them. Placing this “horse-shoe” section on or near the spin pole presents likely orientation candidates for the SSW. Two of these orientations (the top loop and the bottom loop) are shown in Fig. 2.3.

2.2 Ball Trajectory Analysis at Full Pitching Distance

2.2.1 Data Acquisition

For the pitched-ball portion of the study, A Rapsodo 1.0 system [18] is used to 1)

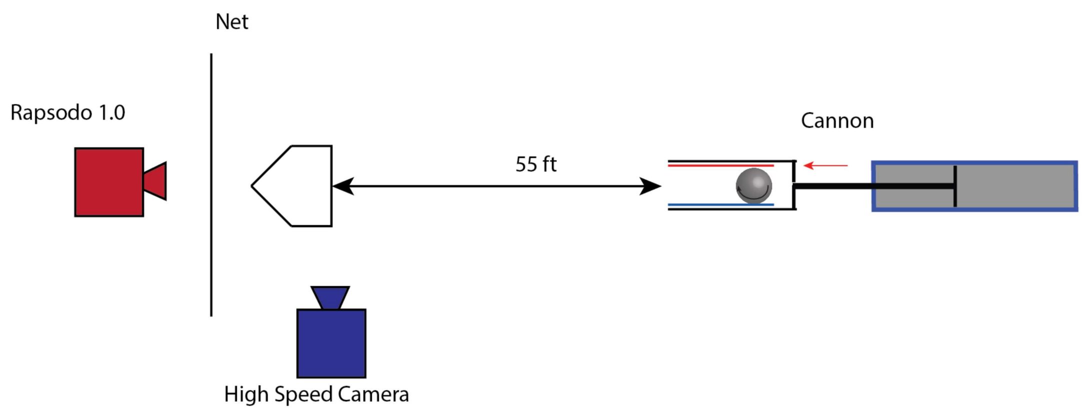

Fig. 2.4: Setup for the ball flight experiment. The cannon incorporated a "flex tip" that imparts spin on the ball by means of opposing high and low friction surfaces. The ball travels 55 ft (a typical pitch distance) where both a high speed camera and the Rapsodo system captured data on the ball as it crosses the plate. This same cannon has been used in other studies [1, 2].

find the pitch location and 2) confirm the speed, axis, and rotation rate of the pitch. To generate a spinning ball, a tip is added to the cannon with high and low friction materials on opposing sides (Fig. 2.4) [19]. These induce spin as the ball leaves the tip. The axis of rotation can be easily modified by rotating the tip around the piston's axis.

The orientation of the seams is dependent on the initial position of the ball. Figs. 2.5-2.6 show the position of the ball in the flex tip for the 2 seam pitch from the front and top respectively. The seam effects on the 2 seam pitch are symmetric and cancel out. Figs. 2.7-2.8 show the position of the ball in the flex tip for the Top Loop orientation from the front and top respectively. The seams for the Top Loop orientation are prevalent on the top of the ball throughout an entire revolution of the ball while the bottom of the ball only has seams nearby intermittently. Seam effects do not cancel out and a net force down is generated.

2.2.2 Analysis

The Rapsodo 1.0 system uses a radar to trigger the system and to measure release velocity and multiple images of the ball as it arrives at the plate combined with a machine

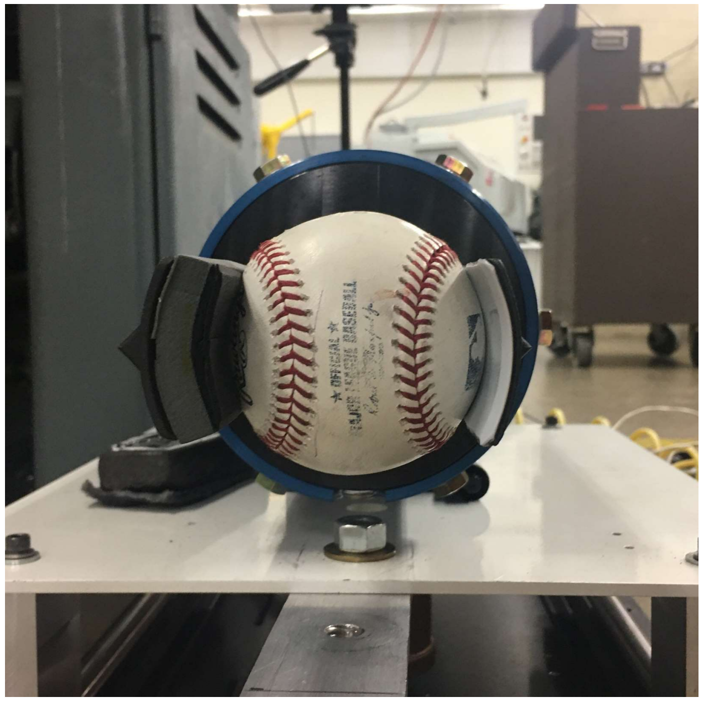

Fig. 2.5: MLB baseball in the flex tip in the 2-seam orientation as viewed from the front. Seam effects for this orientation cancel.

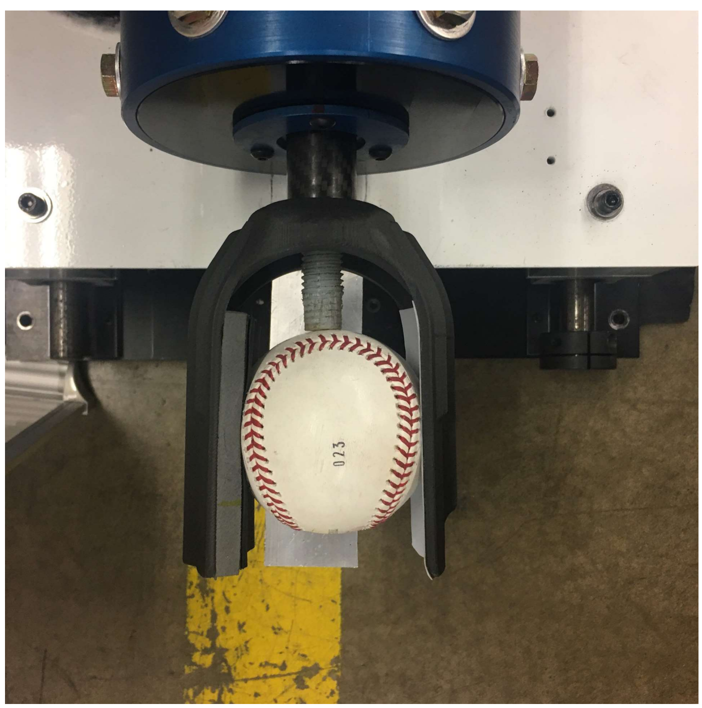

Fig. 2.6: MLB baseball in the flex tip in the 2-seam orientation as viewed from the top. Seam effects for this orientation are equal on both sides and result in no force on the baseball.

Fig. 2.7: MLB baseball in the flex tip in the Top Loop orientation as viewed from the front. Seam effects for this orientation are equal on both sides and result in no force on the baseball.

Fig. 2.8: MLB baseball in the flex tip in the Top Loop orientation as viewed from the top. Seam effects for this orientation cause advanced separation on the top of the ball resulting in a downward force.

Table 2.1: The seam heights of the baseballs used in this study. The average value is based on a collection of 72 unused 2019 MLB baseballs.

Geometry	Average	High Seams	Low Seams
Seam Height (in.)	$0.031 \pm 9.0 \times 10^{-4}$	$0.035 \pm 8.2 \times 10^{-4}$	$0.025 \pm 6.9 \times 10^{-4}$
Difference from Avg	0%	12%	-19%

vision algorithm to find the spin rate and spin axis of the ball. The application for the device runs on a tablet, and this can also be used to acquire video of the pitch from directly behind the cannon. The accuracy of the Rapsodo pitch location is verified using the matching photos of the pitch arrival acquired with the app. The ball is also recorded by a separate high-speed camera as it crosses the plate. The uncertainty of the rapsodo was found to be smaller than the random uncertainty of the mean.

This study used two MLB baseballs, both unused from the 2019 season. One ball with seams larger than the average of six dozen 2019 balls and another with seams smaller than the average as measured before and after the tests using calipers. The baseball diameters were measured in 20 locations, 12 on the leather and 8 on the seams. The difference between the average of the seam diameters and the average of the leather diameters was divided by two to find the average seam heights. Note, the seam heights were unchanged by the flex-tip after firing. The seam heights of the balls used along with the average of the of the 72 2019 balls are show in Table 2.1. Each pitch had a similar velocity, spin rate, and spin axis. Each ball was launched with two different orientations 12 times each.

CHAPTER 3
RESULTS

The air velocity field over a non-spinning baseball at 90 mph is shown in Fig. 3.1. Of interest for this research is the wake of the ball, which is easily found in locations of large velocity vectors and vorticity (red or blue), and where the wake starts on each side of the ball (the blue or red streak leaving the rear of the ball). The separation (marked with an arrow) has occurred a similar distance from the front of the ball resulting in a similar pressure distribution on the top and bottom of the ball. As a result, the wake is quite straight. The seams have had no effect on this case, and it is used as a baseline.

By advancing the separation point on one side of the ball relative to the other, an unbalanced pressure distribution and a corresponding force can be induced. The conventional means of making this change is the Magnus effect on a spinning ball, and these effects occur on any kind of spinning sphere. An example on a baseball is shown in Fig. 3.2. The ball, which is traveling to the left, has backspin which causes the separation point beneath the ball to move toward the front while the separation point on the top of the ball moves toward the back. This results in a pressure difference and, therefore, a force upward on the ball.

While the Magnus Effect has been studied for many decades, a novel finding of the present study is that baseball seams can cause early separation, independent of spin. An example is shown in Fig. 3.3. In this case, the seam on top of the ball is near the plane perpendicular to the ball direction, which is called the Hemisphere Plane. The separation point on the top of the ball is considerably further forward than the separation point on the bottom of the ball, resulting in a larger very-low-pressure zone on the bottom of the ball than on the bottom of the ball. This pressure difference across the ball causes a downward force. The wake deflects upward as a result. This effect is called a Seam Shifted Wake. Note that the deflected wake looks similar (although opposite in this case) to the wake of the

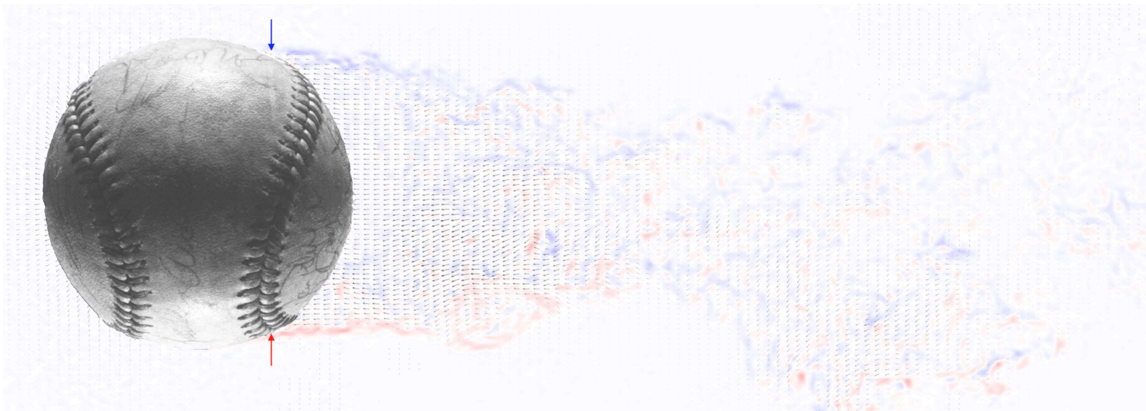

Fig. 3.1: Baseball traveling at 90 mph. In this case, the separation points (marked with arrows) form at a similar point on both sides of the ball and there is no sideways force on the ball.

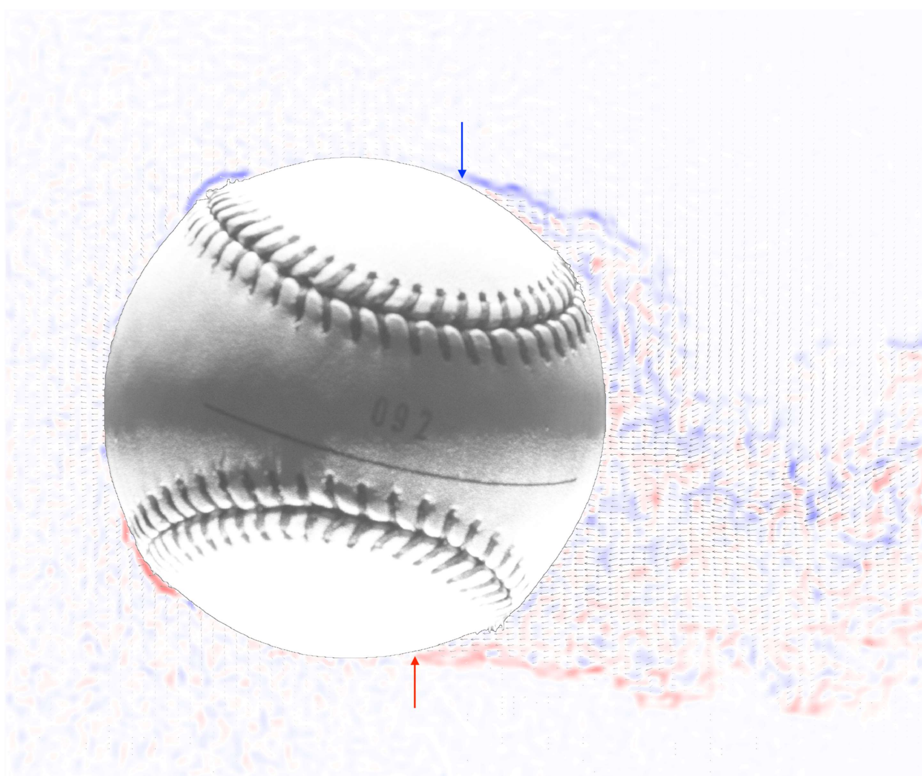

Fig. 3.2: A PIV dataset of a baseball traveling at 90 mph to the left and spinning clockwise at 2000 RPM.

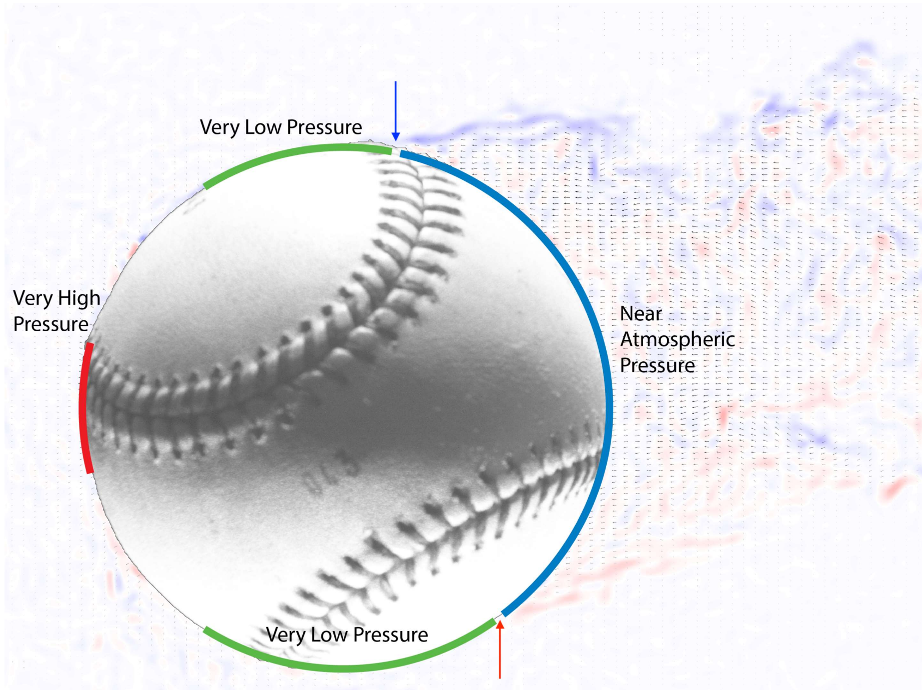

Fig. 3.3: A PIV dataset of a non-spinning SSW baseball traveling at 90 mph to the left. Note that the very-low-pressure region on the bottom is larger than the very-low-pressure region on the top which results in a higher pressure on the top of the ball.

spinning ball in Fig. 3.2. In both cases, a pressure force results from asymmetric separation.

To investigate this behavior, dozens of non-spinning baseballs in various orientations were fired through the PIV system. The map in Fig. 3.5 was developed based on these data. It shows that, in most cases, if a seam is perpendicular to the flow direction and resides in a region 6° in front of the hemisphere plane to 18° behind it, the separation point will correspond with the seam location. If no seam exists in those locations, the flow will typically separate somewhere from 18° to 30° beyond the hemisphere plane.When no seam is near the hemisphere plane the separation location is likely unsteady and may be affected by surface characteristics, 3D flows, etc.

Six of the images used to find the map are shown in Fig. 3.4. The raw image of the ball has not been superimposed on the vector data, so images have velocity vectors and vorticity values on the interior of the ball. The green circles indicate locations where separation was advanced by the seam and the blue circles show where separation occurred on the leather.

For each 4-seam shot, two data points were collected as seams are on both the top and the bottom. All data sets used for the development of the separation map can be found in the appendices.

The same study showed anecdotally that, for a baseball spinning in the plane of the page, the map of Fig. 3.5 rotates somewhat in the direction of spin. The amount of rotation is an area of ongoing research. Based on these results, the attention of this study is on a plane perpendicular to that in which Magnus effect occurs and a "quasi-static assumption" is made with respect to the seam effects, which states that the behavior of a spinning baseball at each instance in time is similar to a non-spinning ball in the same orientation. The effect of spin, that is the Magnus effect, remains unchanged.

While seams can clearly alter the forces on the ball at an instant in time, pitched baseballs are nearly always spinning. Referring again to Fig. 3.3, if this ball were spinning in the clockwise direction, after 1/4 of a turn, the lower seam would cause an early separation and the wake would tilt downward. For this 4-seam orientation, the wake will change from one side to the other 4 times during a rotation. However, the mass of a baseball is too large for any appreciable change in trajectory at that high frequency. The key to Seam Shifted Wake pitches is to allow the deflection to remain on the same side of the ball for the majority of a rotation.

While there are likely many orientations that can produce a Seam Shifted Wake on a spinning pitch, the study must work within some constraints. First, while the cannon and flex tip can project a ball with a wide range of spin and any desired tilt (a common description of the axis in the $x - z$ plane), it cannot impart a spin component in the y direction, commonly called "gyro" spin. Therefore, all pitches in this study are launched with no gyro.

A simple candidate for a Seam Shifted Wake with no gyro spin component is an orientation that is termed "Looper" and is shown in Fig. 2.3. The name comes from the seam looping around the pole as the ball spins. For most of the rotation, that seam remains within the angles that cause early separation as shown in Fig. 3.5.

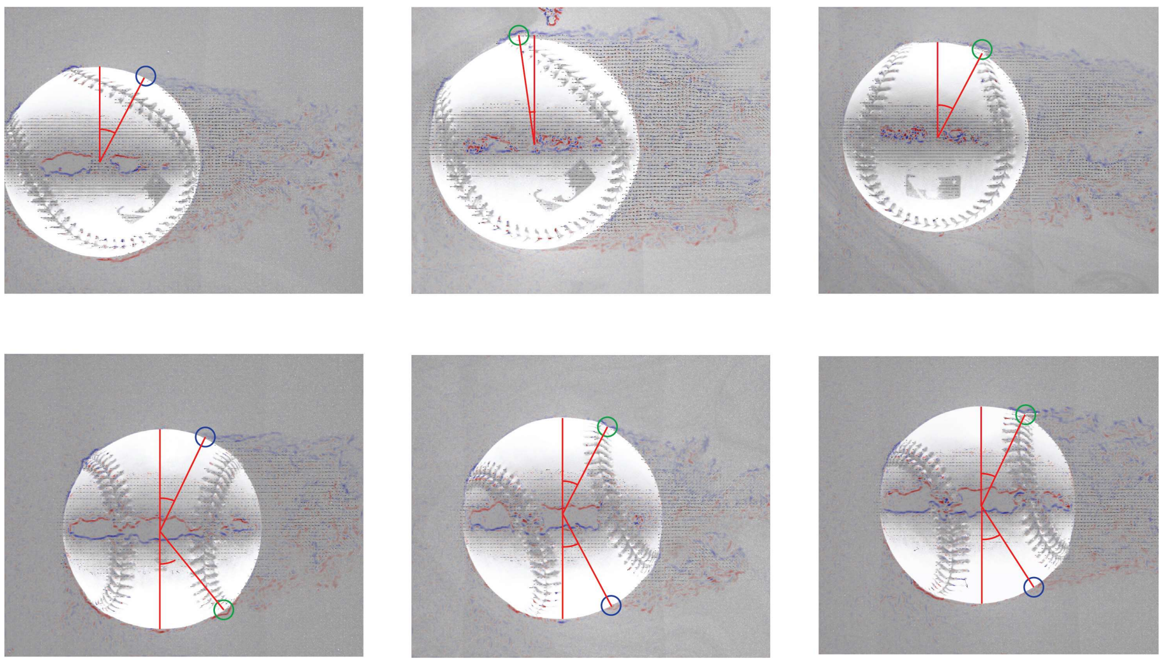

Fig. 3.4: 36 images of 2-seam orientations and 24 images of 4 seam orientations were analyzed to create Fig. 3.5. The 4-seam data have seams on top and bottom in every shot and so two data points can be collected from each shot. All images are of baseballs moving left at 90 mph. These data have not had the raw image of the ball superimposed on the PIV data, so vector arrows and vorticity values are visible on sections of the interior of the ball. There are three 2-seam orientations and three 4-seam orientations shown with the corresponding angles at which separation occurred shown. The separation points on seams are shown with green circles while separation on the leather is shown with blue circles. The PIV software was programmed to ignore areas that were two bright. There is a section of data missing from the top middle figure, which was too bright, but this missing data has no impact on the analysis.

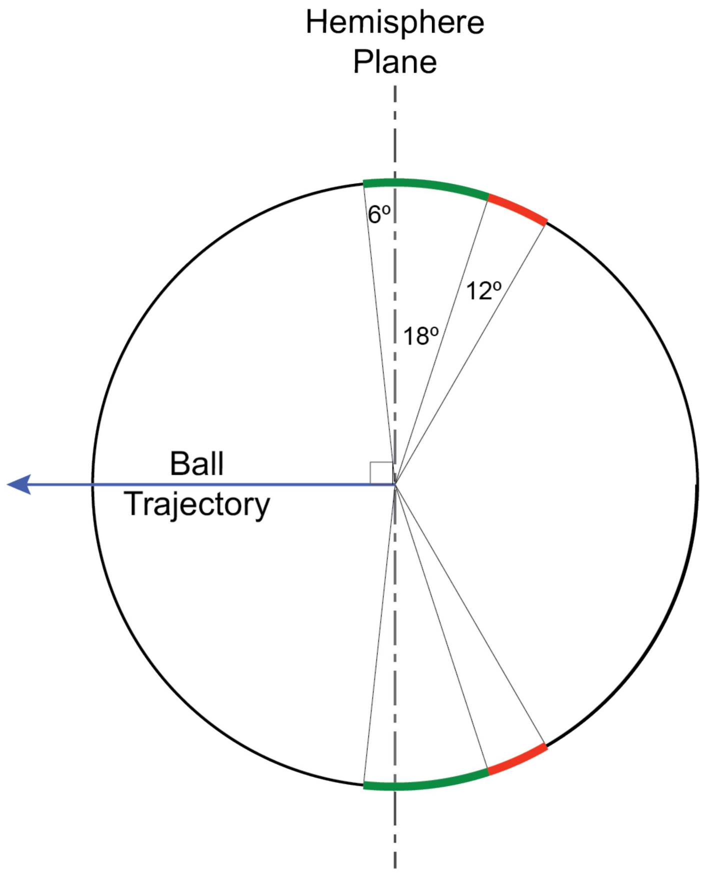

Fig. 3.5: Map showing the location of separation based on the locations of seams relative to the plane through the center of the ball and perpendicular to the flow direction (i.e. the Hemisphere Plane). The green section shows locations where the presence of a seam can advance the separation and produce a Seam Shifted Wake. The red section indicates where the separation occurs for a turbulent flow when no seam is present near the hemisphere plane of the ball. Seams have little effect on other parts of the ball.

While the spin axis was the same for all pitches, different orientations (relative to the spin axis) and seam heights were used. Three orientations were tested as shown Fig. 2.3. Two of the orientations (called Top Loop and Bottom Loop) are designed to generate seam effects. The third, which is a standard 2-seam orientation, should not experience such effects and will be used as the baseline.

The tests consisted of 12 pitches each in the Top-Loop and Bottom-Loop orientations for two baseballs with different seam heights. Additionally, 5 pitches in the 2-seam orientation form a baseline. The cannon was adjusted to fire level from an elevation 6 feet above home plate. All pitches had a vertical axis and spun between 1100 and 1200 RPM, causing about 15 inches of horizontal movement from the Magnus effect in the negative x direction. The cannon was aimed so that, despite this horizontal movement, the average 2-seam orientation pitch arrived near the middle of the strike zone. The arrival location of the average 2-seam pitch is taken as the origin of the cartesian pitch location.

To gain an understanding of how this pitch travels as it spins and to ensure that the desired orientation was achieved, several images from the high-speed camera are overlaid in Fig.3.6. The baseball shown arriving at the plate higher (larger z location) is the Bottom-Loop orientation and the baseball arriving at the plate lower (smaller z location) is the Top-Loop orientation. For a spinning ball, the Top-Loop orientation would appear to an observer to have a red loop around the top pole while the Bottom- Loop orientation would appear to have the loop around the bottom pole. The Top-Loop orientation is closer to the camera than the Bottom-Loop orientation and so appears to be larger. Since substantially less than one revolution is completed within this field of view, these images cannot be used to confirm the RPM as reported by the Rapsodo unit.

The pitch location results are shown in Fig. 3.7. As expected, the Seam Shifted Wake causes the Top-Loop pitch to break downward while the Bottom-Loop breaks upward relative to the baseline pitch. The vertical displacement difference between the average of the Top-Loop orientation and the average of the Bottom-Loop orientation was 9.3 inches for the ball with the larger seams.

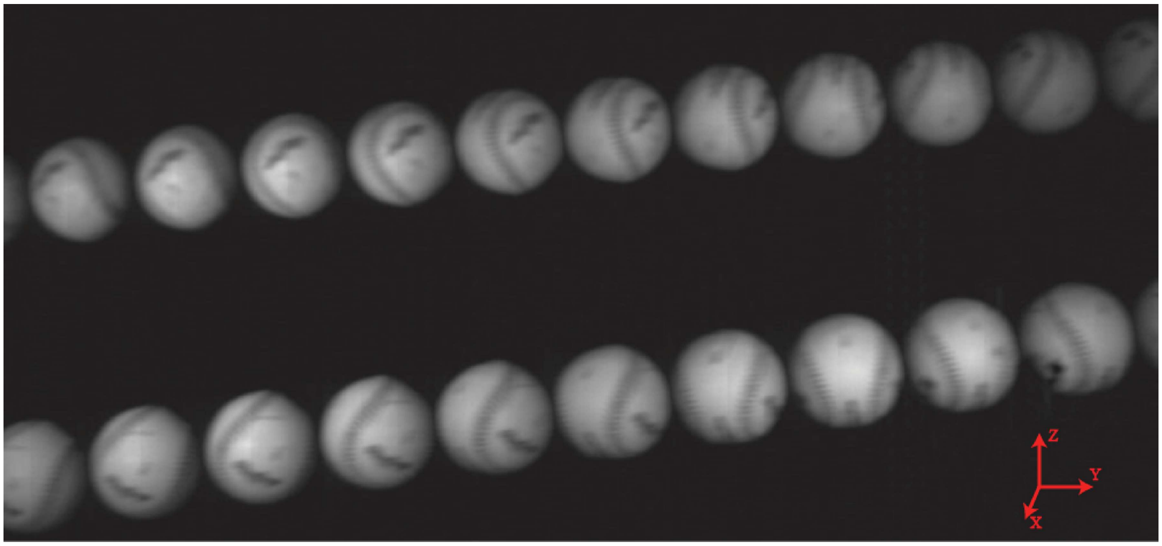

Fig. 3.6: Images captured by the high-speed camera showing the approach of the baseball to the strike zone. The Bottom Loop orientation is the higher of the two image sets shown. The Bottom-Seam orientation has the seam consistently near the bottom of the ball which cause the ball to arrive at the plate higher than the Top-Seam orientation. Note, y is positive to the right z is positive up and x is positive out of the page, towards the camera.

The uncertainty bands represent 95% confidence intervals based on the individual pitches and Student's t distribution [20]. The small number of baseline samples results in a very large uncertainty for the baseline. Note that this may account for the small asymmetry in the results (the top loop seems to break more than the bottom loop) but has no impact on the difference in the break generated by the two orientations.

The change in horizontal position was unexpected. An attractive explanation is that as each ball's trajectory becomes downward, part of its spin no longer contributes to the Magnus effect. Note that the pitches that dropped less also had more horizontal movement and vice versa. However, for the trajectory of these pitches, this effect would be orders of magnitude smaller. It is possible that the horizontal movement is due to interaction between the seams and Magnus effect, invalidating the quasi-static assumption. Further work in this area is needed.

Given the role of the seams on this effect, it is not surprising that the seam height matters. The ball with a 35% larger seam height experienced about 20% more break in both directions.

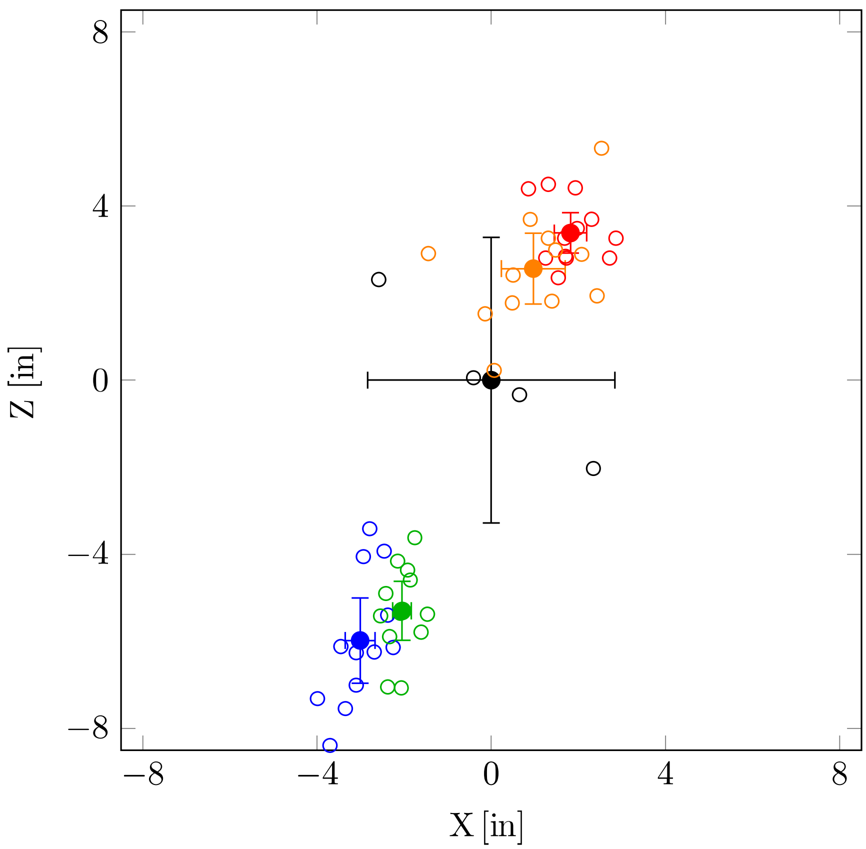

Fig. 3.7: Pitch locations as measured by Rapsodo 1.0. Open symbols are individual pitches while closed symbols are the average of pitches of that type. Three orientations were tested with 2 baseballs. Red and Blue use the ball with the larger seams while the Orange and Green use the lower-seamed ball. The Blue and Green are the Top-Loop orientation while the Red and Orange are in the Bottom-Loop orientation. Black is the 2-seam baseline case which used the baseball with lower seams. The uncertainty bands are the 95% uncertainty of the mean values.

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS FOR FURTHER WORK

An experiment was conducted that allowed for consistent and repeatable Particle Image Velocimetry (PIV) measurements of a baseball in flight. A PIV setup was used to test hundreds of non-spinning baseballs in various orientations. A map was developed from the results which showed that boundary layer separation will advance to occur on a seam which between 6° forward of the hemisphere plane and 18° behind it. In cases where no seam is present in that region, boundary layer separation tends to occur 18° to 30° behind the hemisphere plane. The boundary layer separation on a spinning ball rotates somewhat in the direction of spin.

Seam orientations relative to spin axis and flight direction were analyzed to find orientations where boundary layer separation was persistent near one spin pole and absent or nearly absent on the other. Such orientations create a persistent Seam Shifted Wake and net force away from the pole with seams. The orientation selected was the Looper which has seams frequently near the spin pole on one side and is mostly void of seams near the other.

The effect of the Looper orientation on a baseball at 90 mph and around 1200 RPM on a vertical spin axis was tested. The study demonstrated that the Looper orientation will cause the ball to break approximately 4.3 ± 0.7 inches away from the side with the loop over a 55-foot flight. There is also additional break induced in the direction normal to the axis, and this is found to add or subtract from the break induced by Magnus at this rotation speed. To the knowledge of the researchers, this is the first demonstration of ball orientation affecting movement on a spinning baseball and the first time it has been shown that the seams are the reason that orientation can matter.

The understanding gained by this work opens a wide range of future work about the effect that seams can have on the flight behavior of a baseball. While the results are valuable the work done is only a small and imperfect part of what can be profitably studied. This study looked at the effect of seams for a given speed and spin rate for a small number of seam orientation. The effect that seams can have is dependent on several parameters and a significant amount of research is needed to be done before the effect of seams is fully understood. Subsequent studies on how the Seam Shifted Wake (SSW) is affected by the height of the seams should be conducted. Additional studies to fill the entire parameter space should also be done especially the effect of gyro on the SSW. Many other studies could use the same setup as the one presented here with minor changes being made as necessary. A ball launching system capable of generating pitches with gyro would be advantageous for future work.

This study shows some preliminary work on the effect of seam height on the force generated by the SSW. Further study is required to show to what extent the seam height plays a role. Ball trajectory measurements at full pitching distance for balls with varying seam heights could be done to find how the force varies with seam height. Additionally, PIV analysis of baseballs with varying seam heights could be done to find out how boundary layer separation is affected by seam height.

In order to more completely understand the SSW, a series of experiments should be done which generate boundary layer separation maps (Fig. 3.5) that show how the separation points on seams change as spin, spin rate, and pitch speed change. Of immediate interest is the effect that gyro (the y component of spin) has on the effect of the SSW. Any future work on the effects of gyro would require a cannon that can generate it (unlike the one used in this study). With such a cannon all the above work could be repeated with varying amounts of gyro.

All work in this subject could be combined to produce an accurate model to predict baseball flight paths that would take into consideration the effect of seam height, seam orientation, spin rate, spin axis, and pitch velocity.

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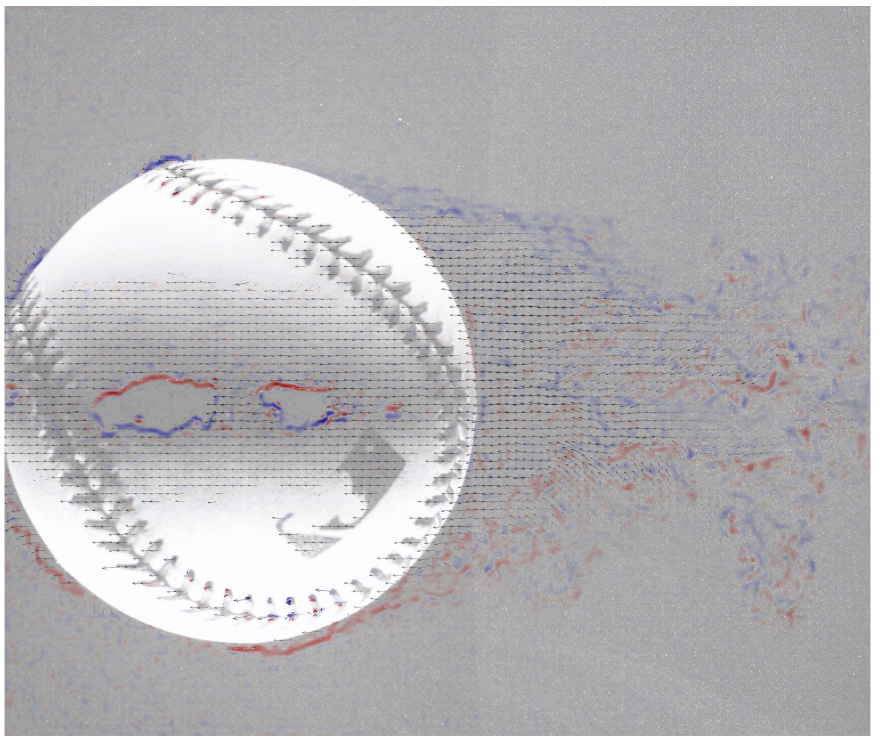
APPENDICES

APPENDIX A

All 2-Seam PIV data sets used to define the boundary layer separation map.



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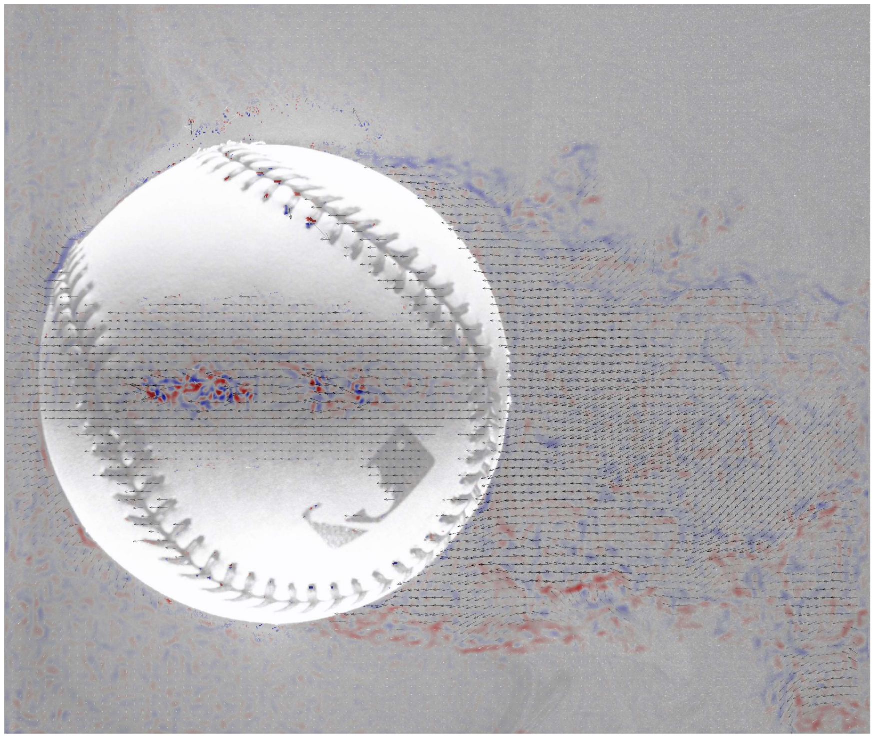

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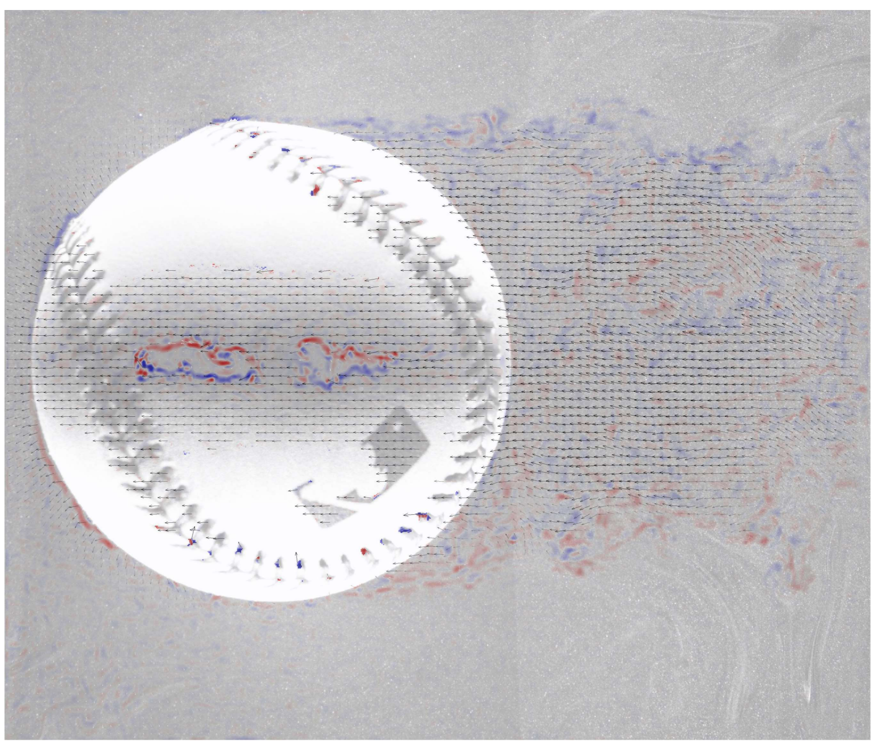

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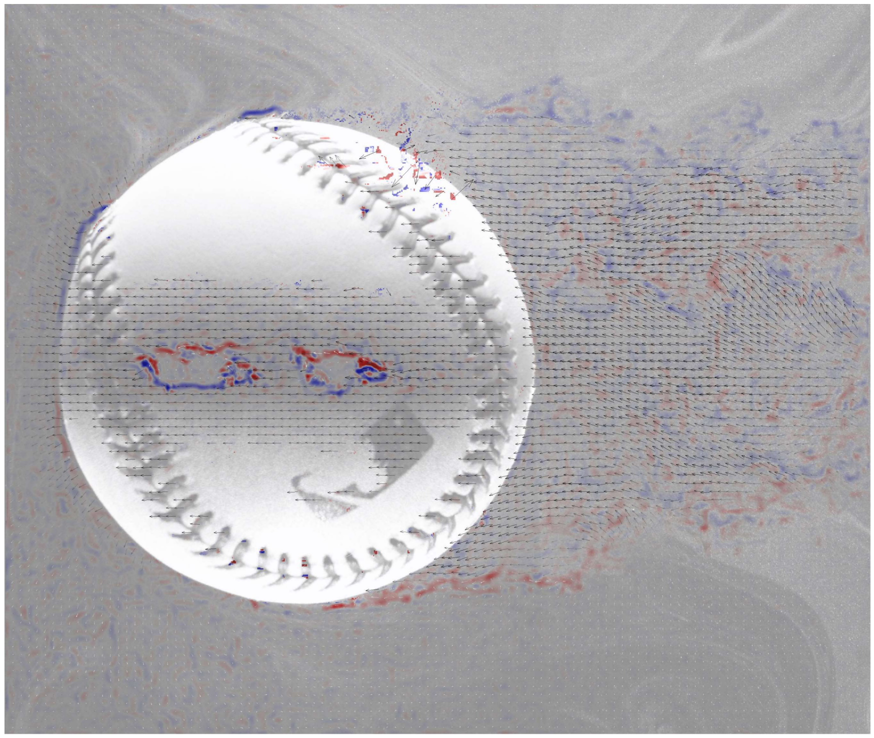

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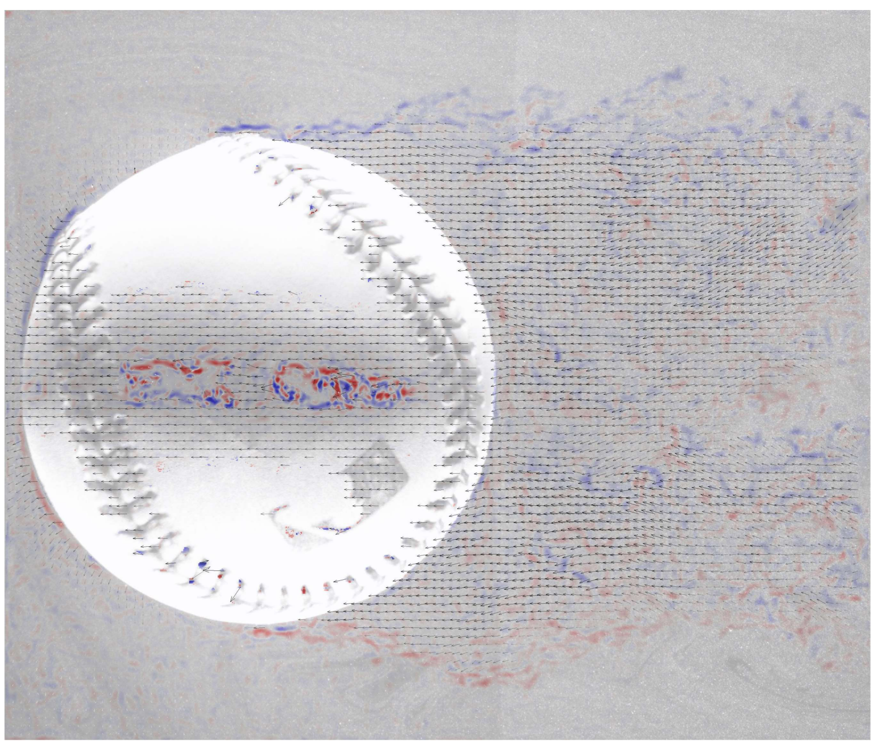

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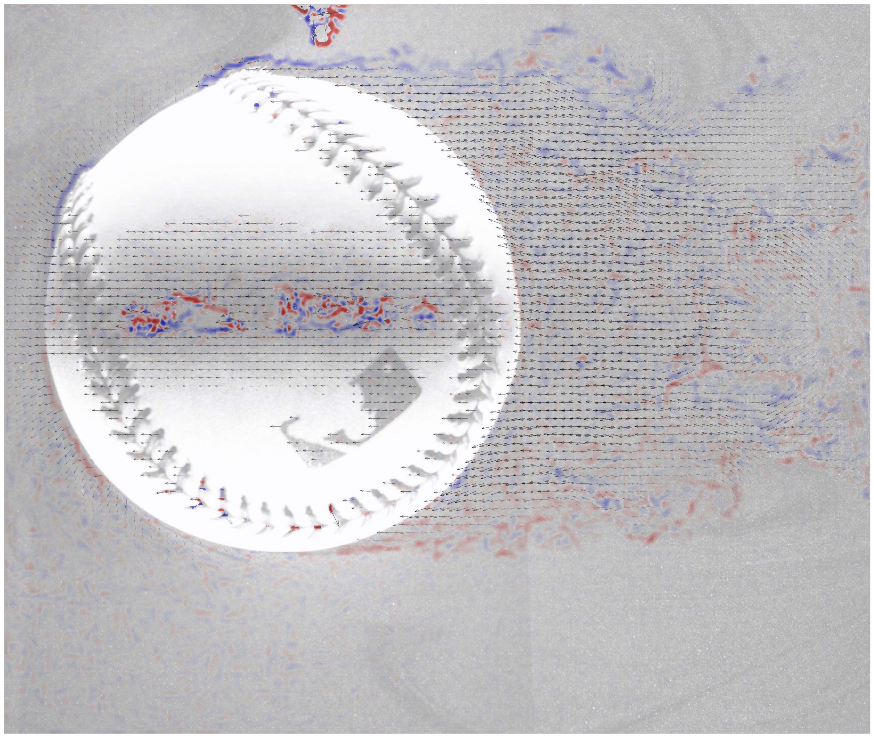

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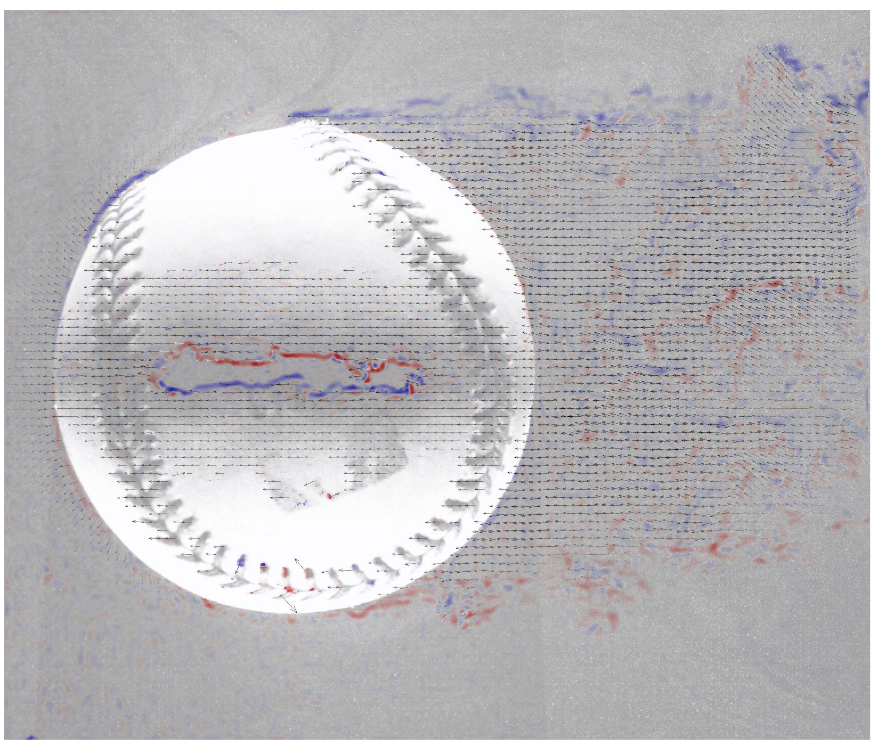

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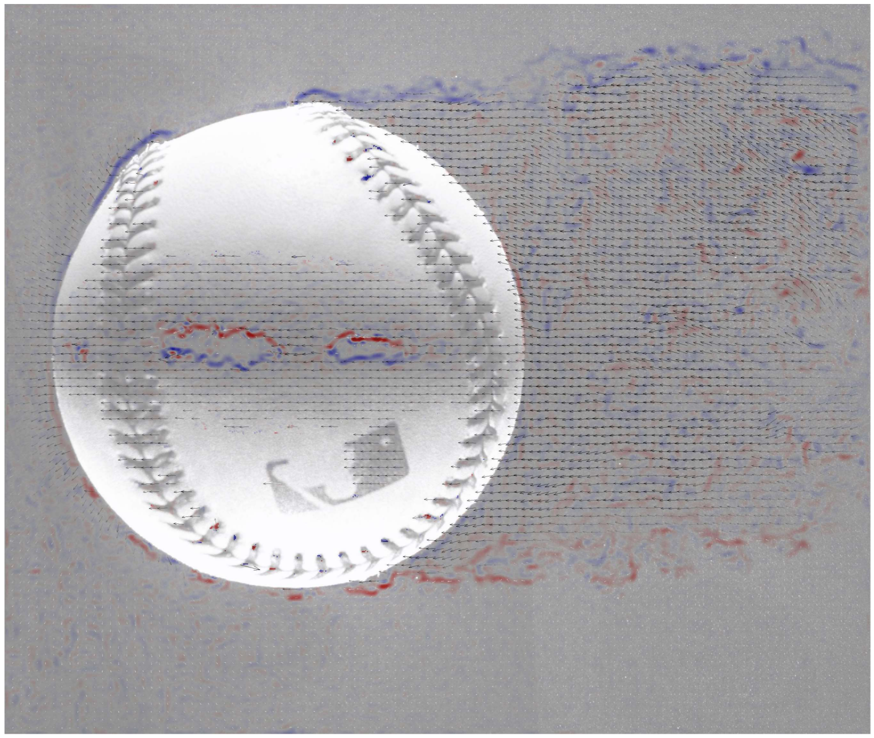

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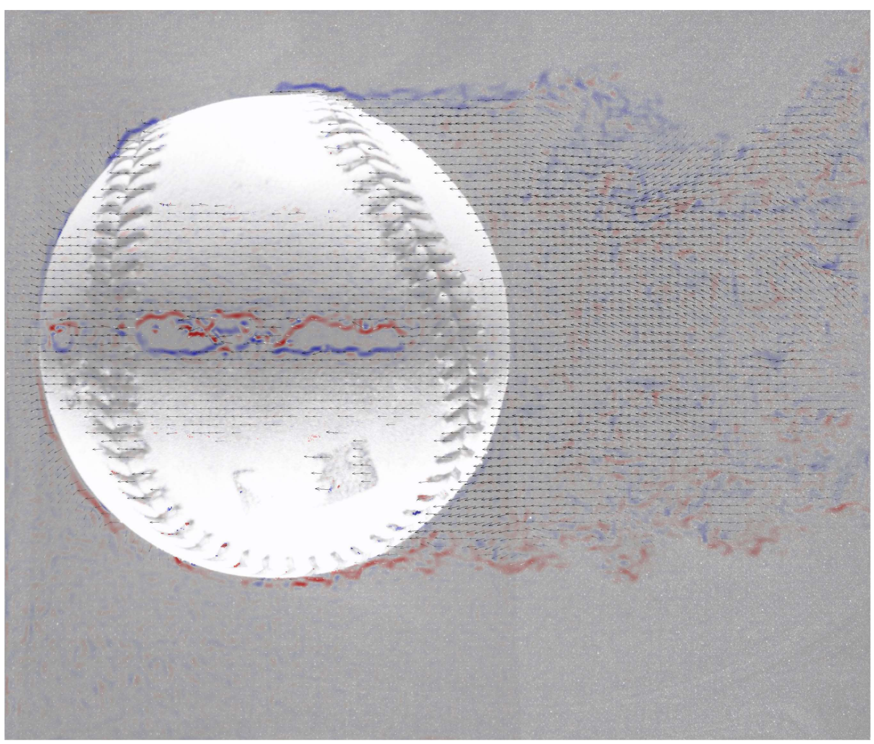

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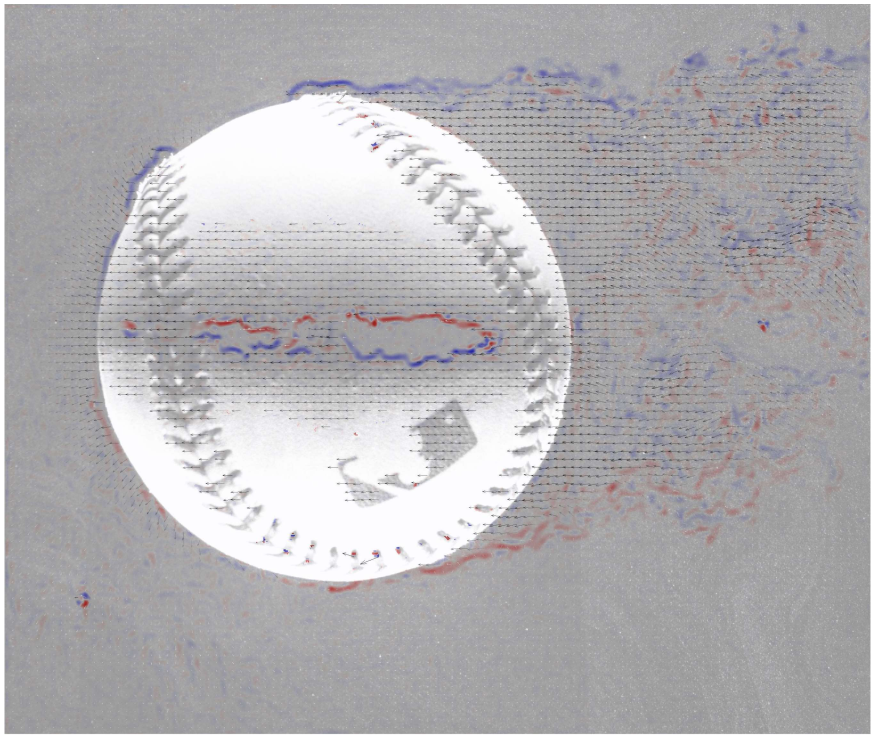

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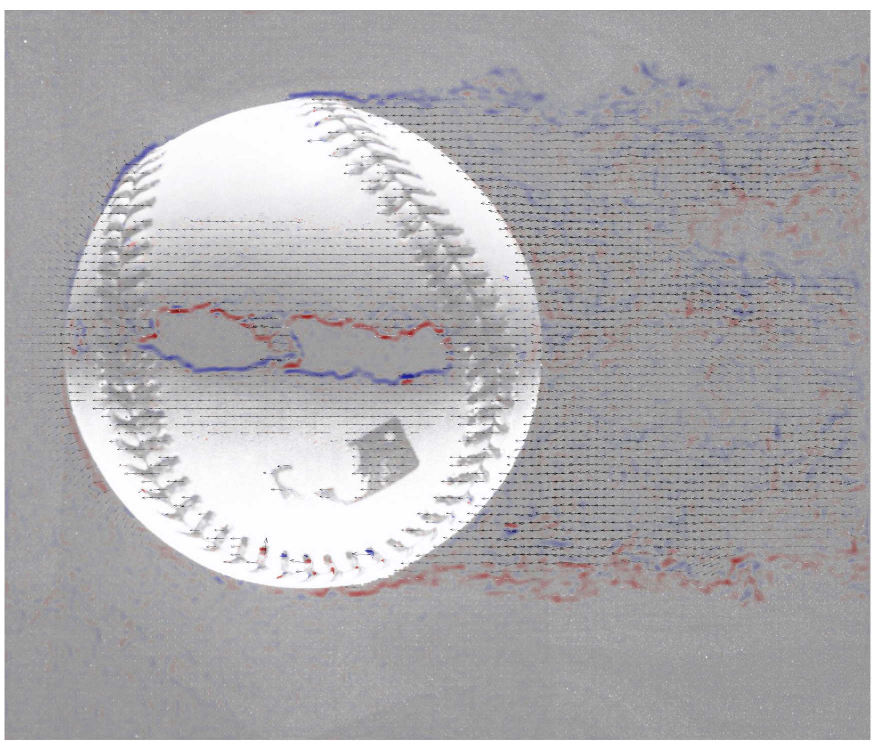

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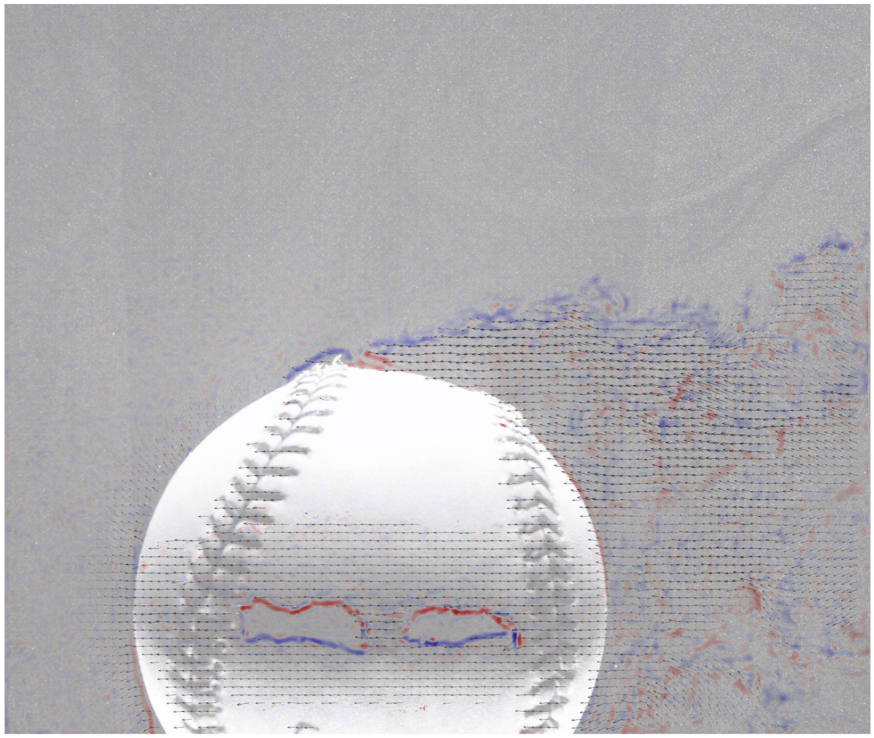

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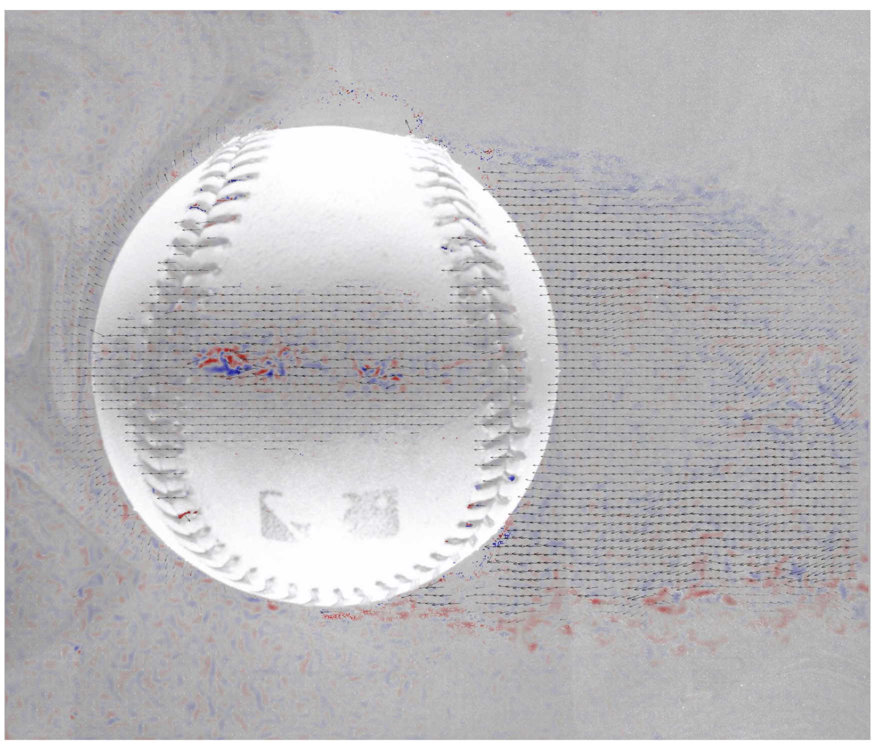

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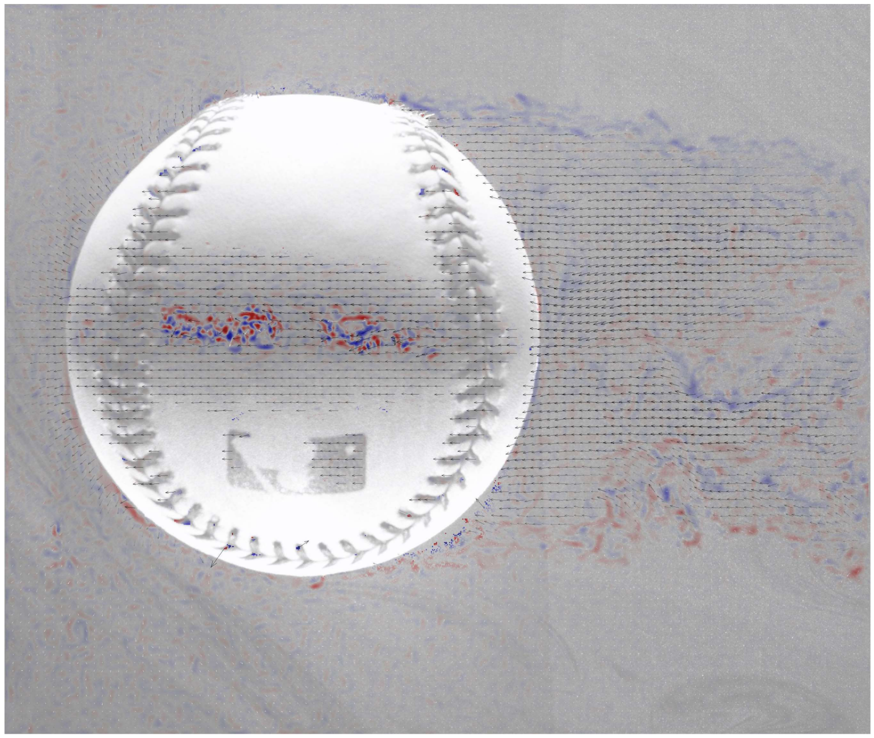

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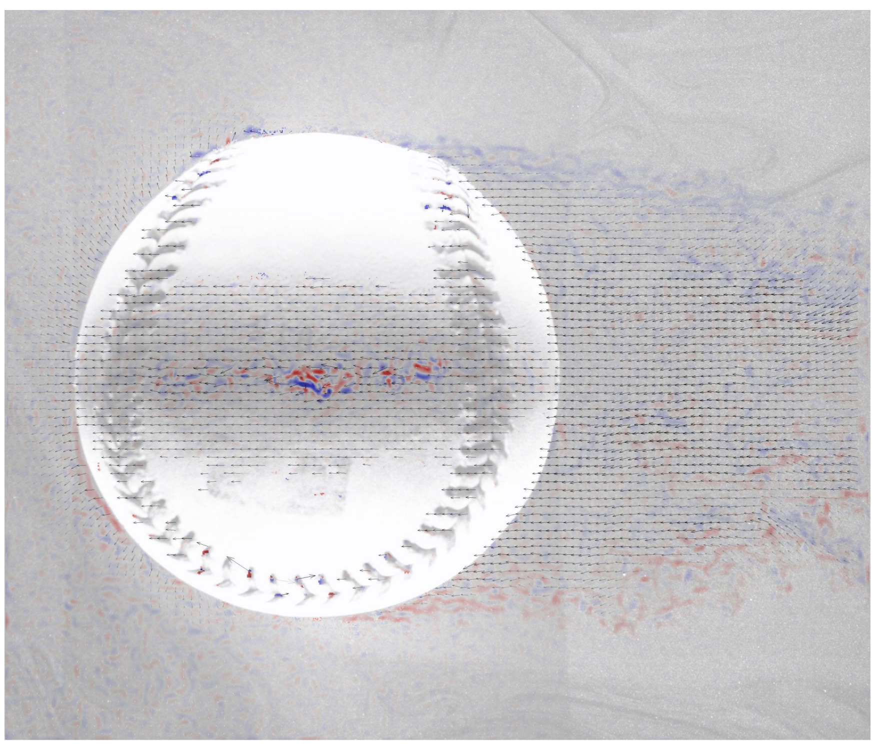

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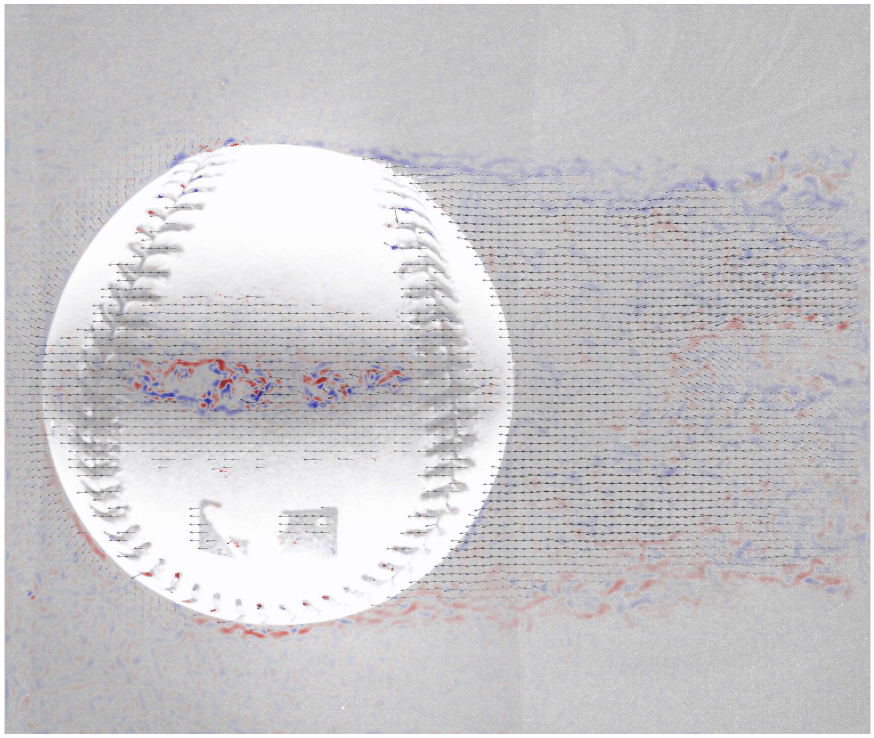

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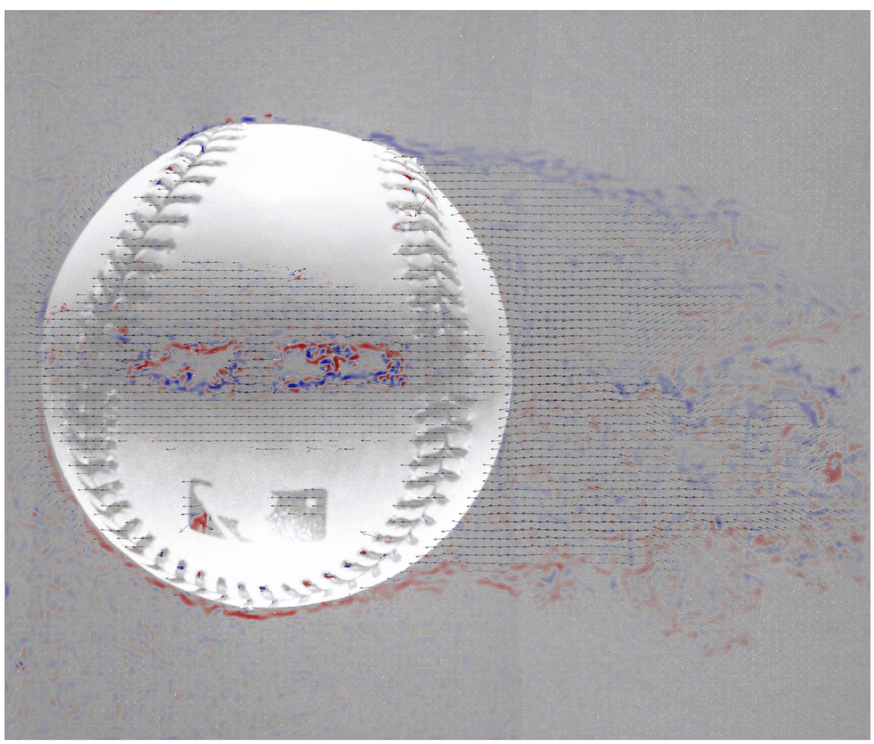

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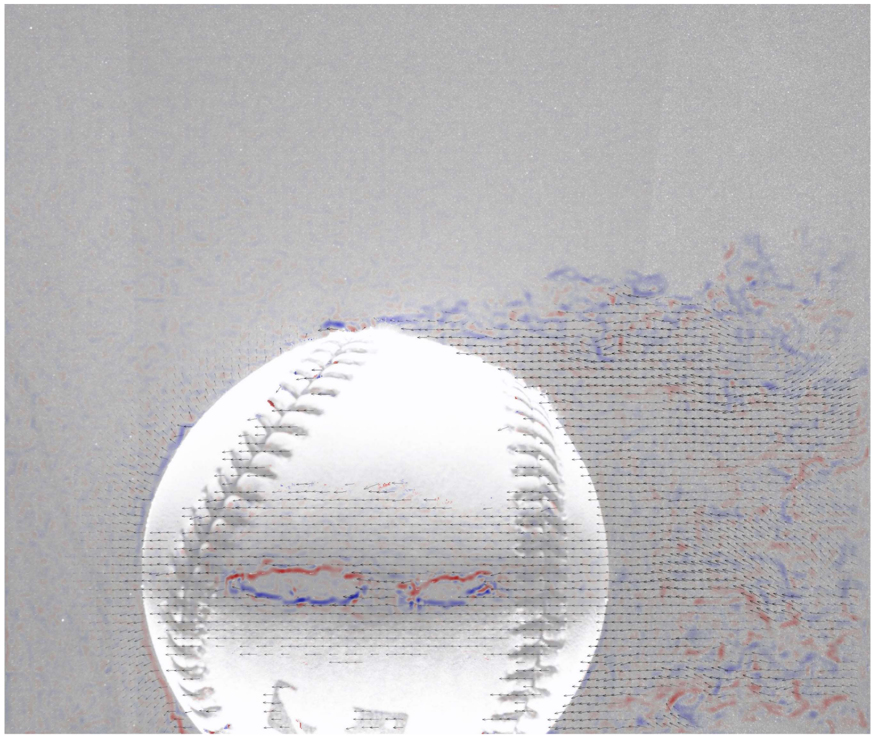

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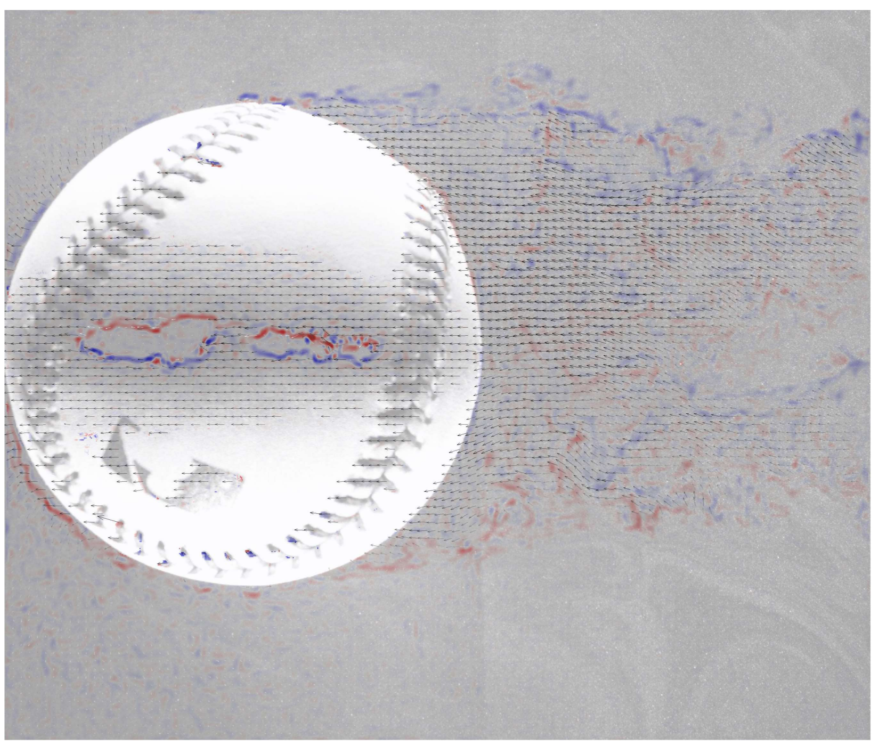

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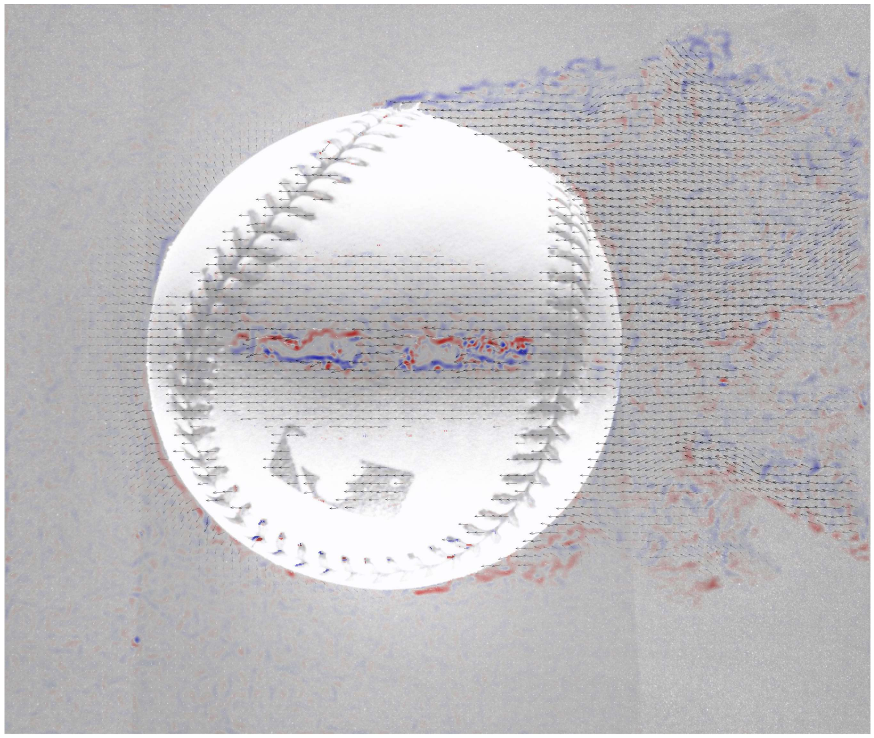

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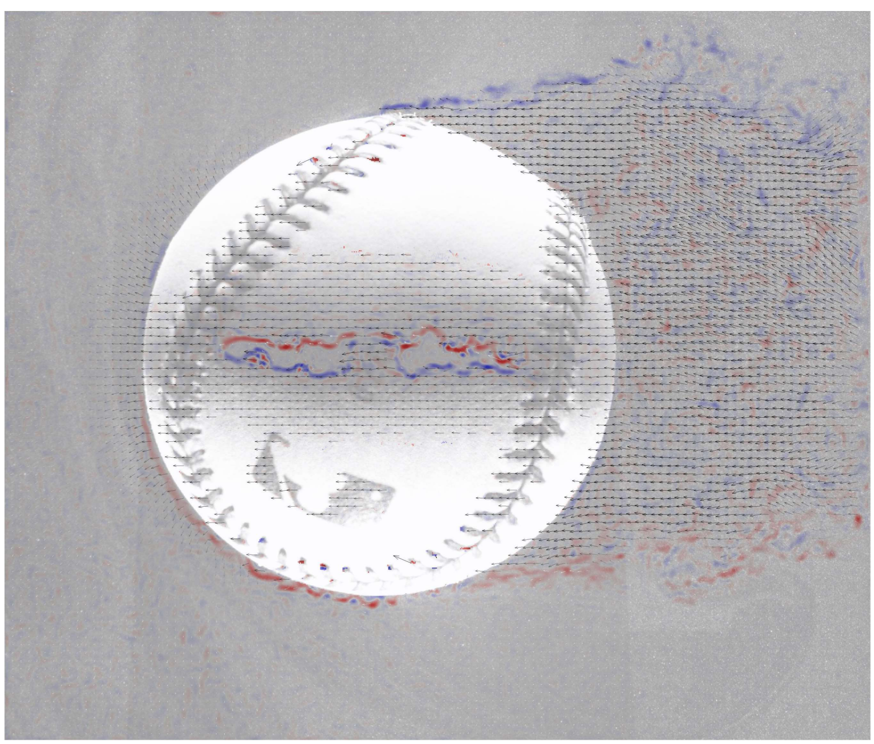

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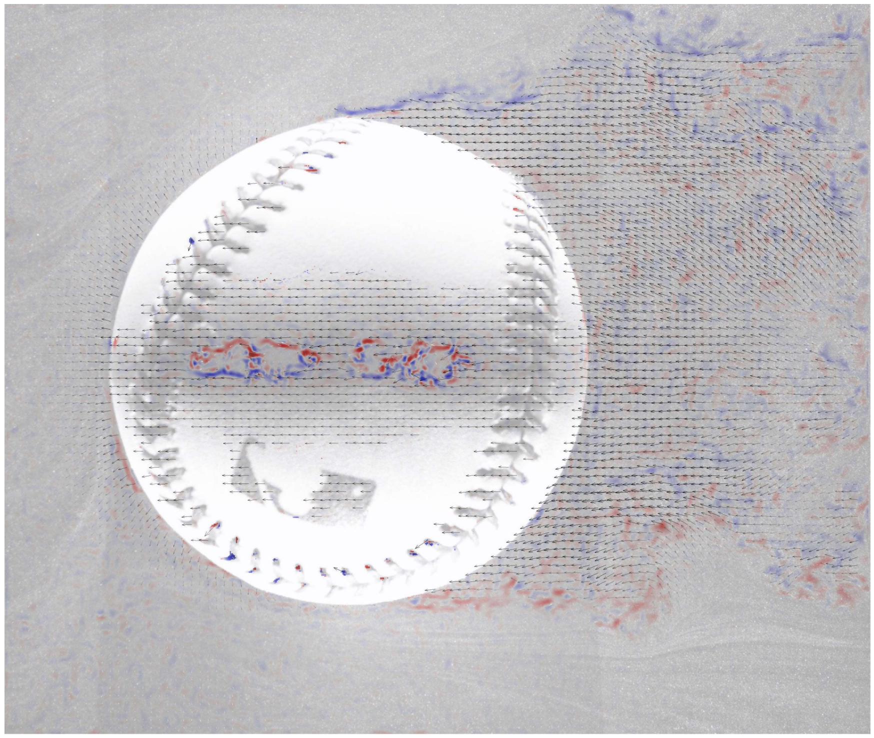

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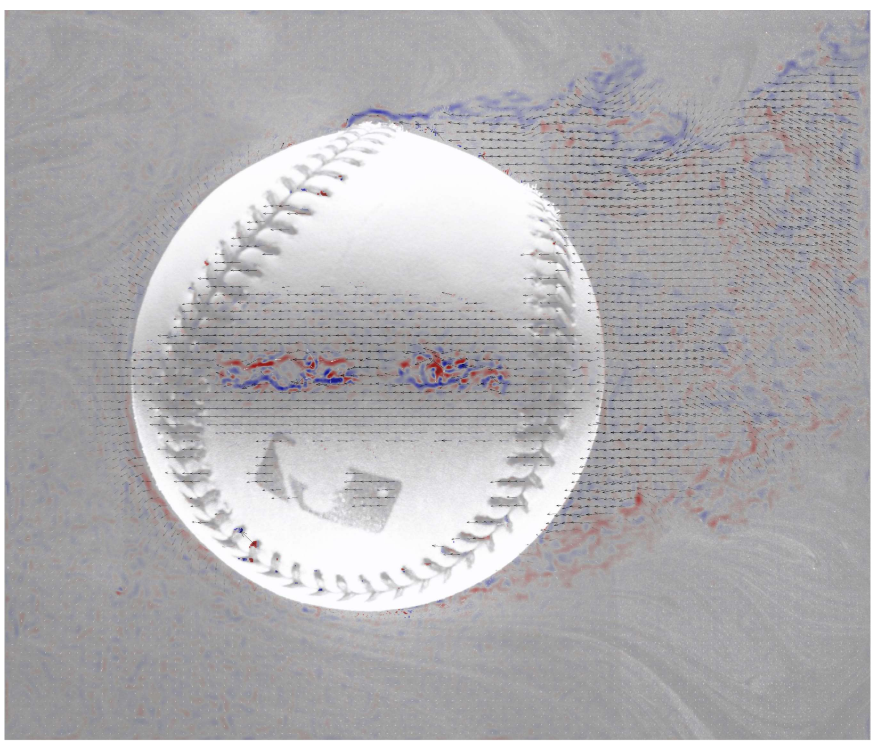

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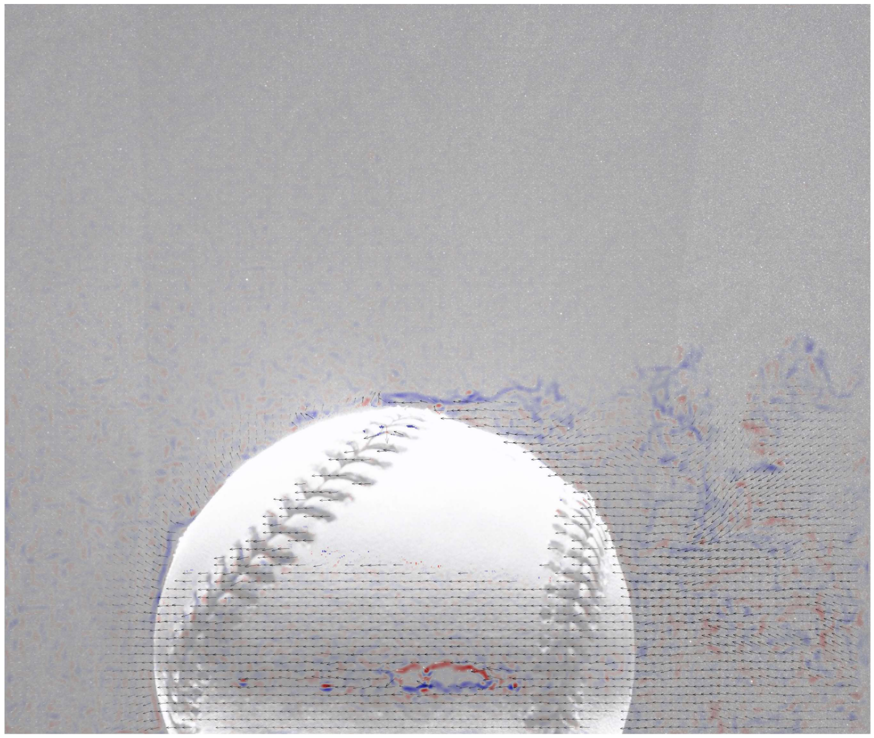

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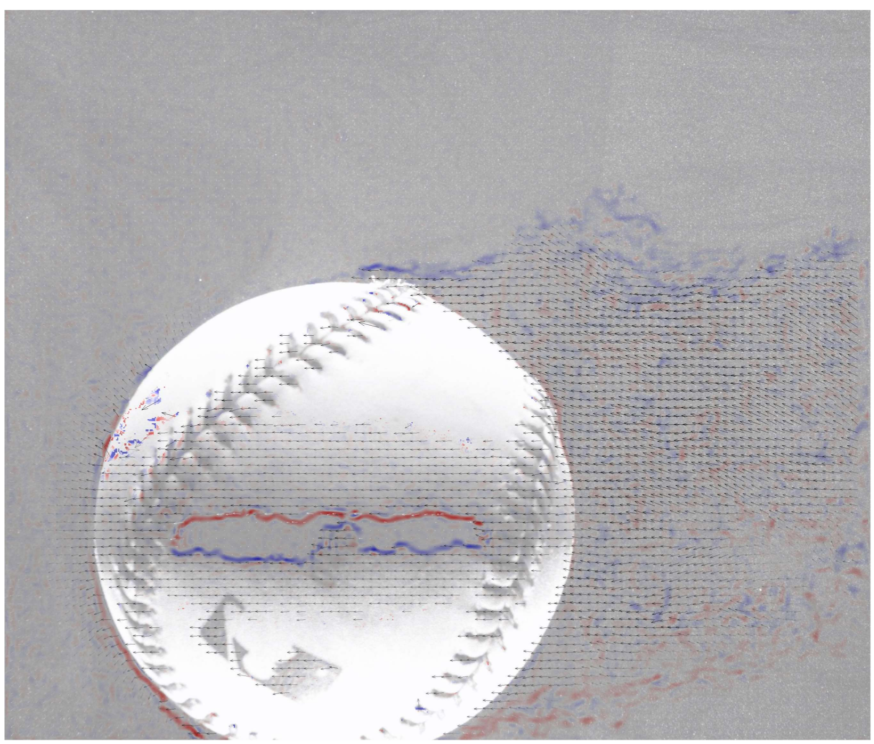

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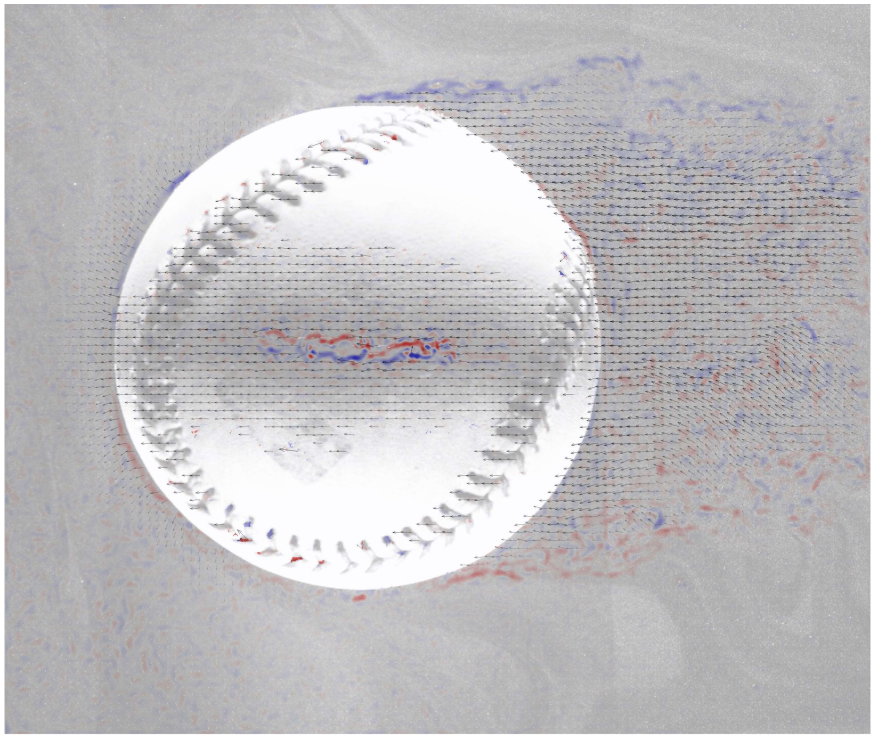

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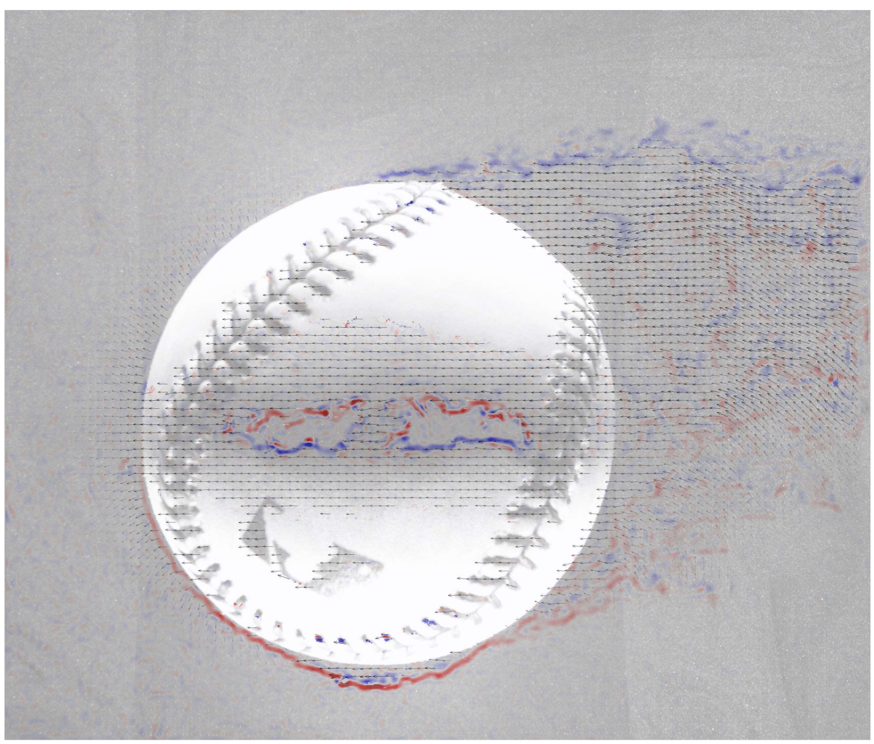

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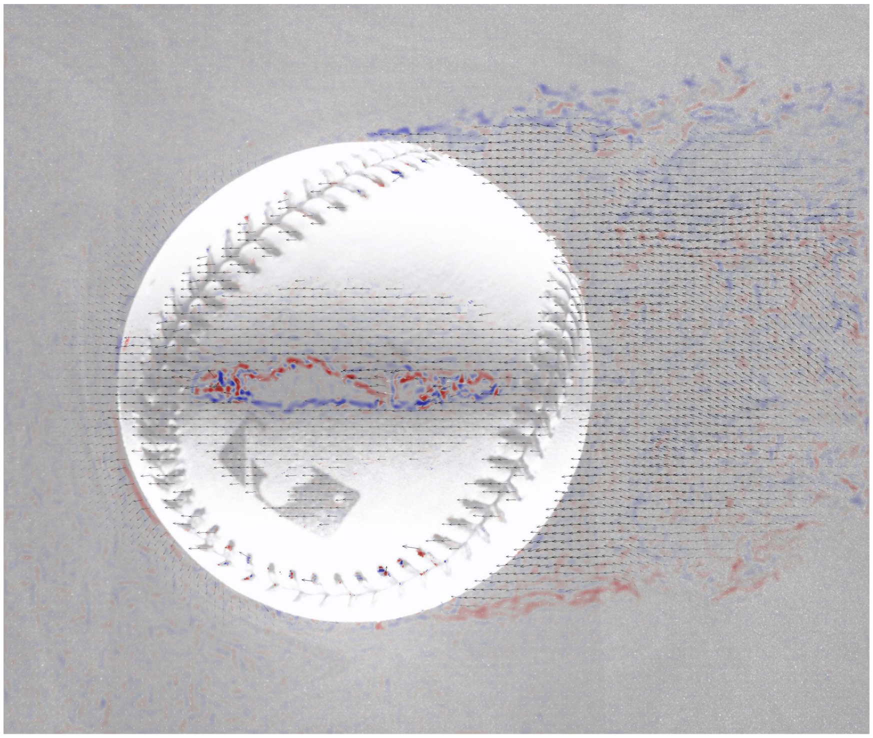

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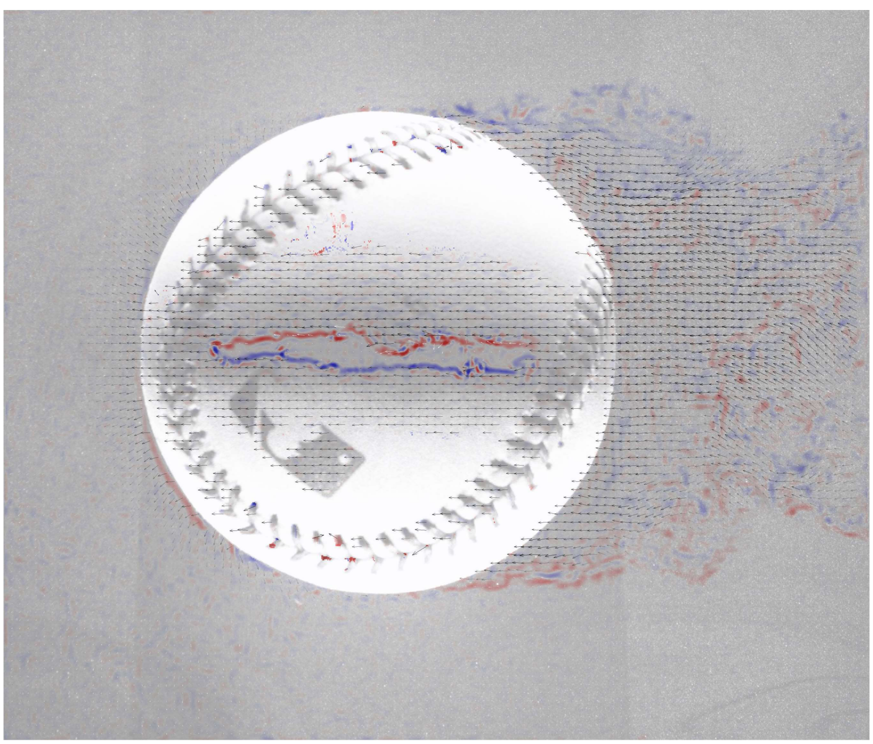

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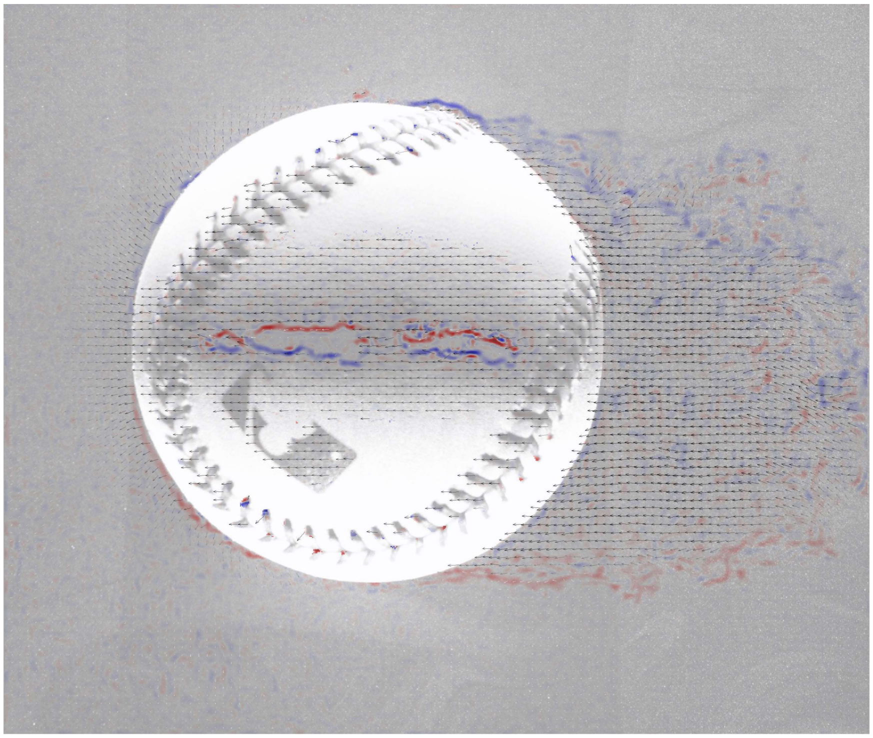

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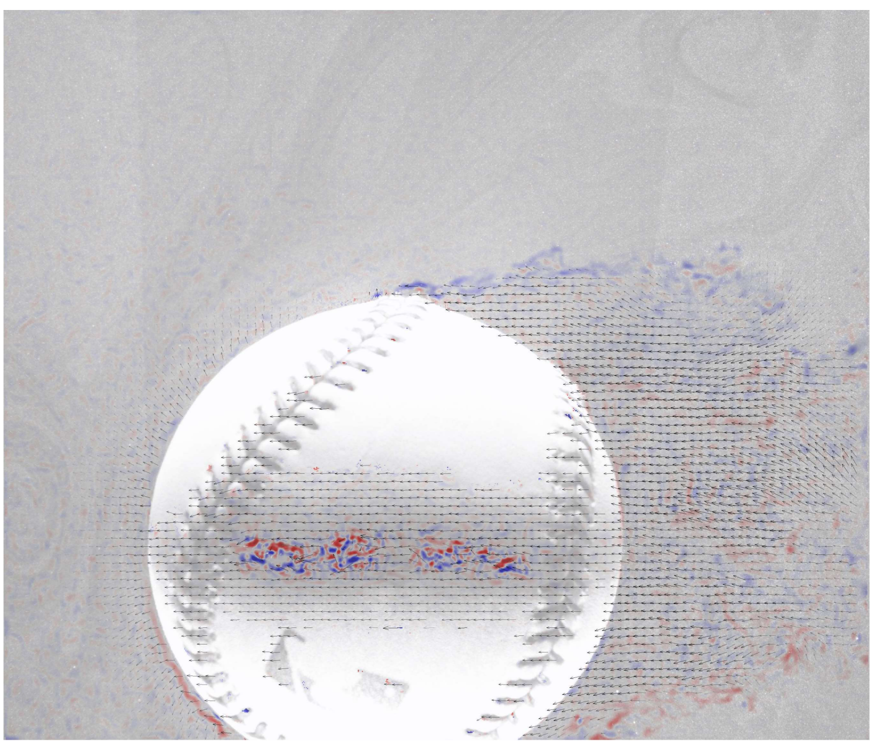

Fig. A.31: 2-seam 31

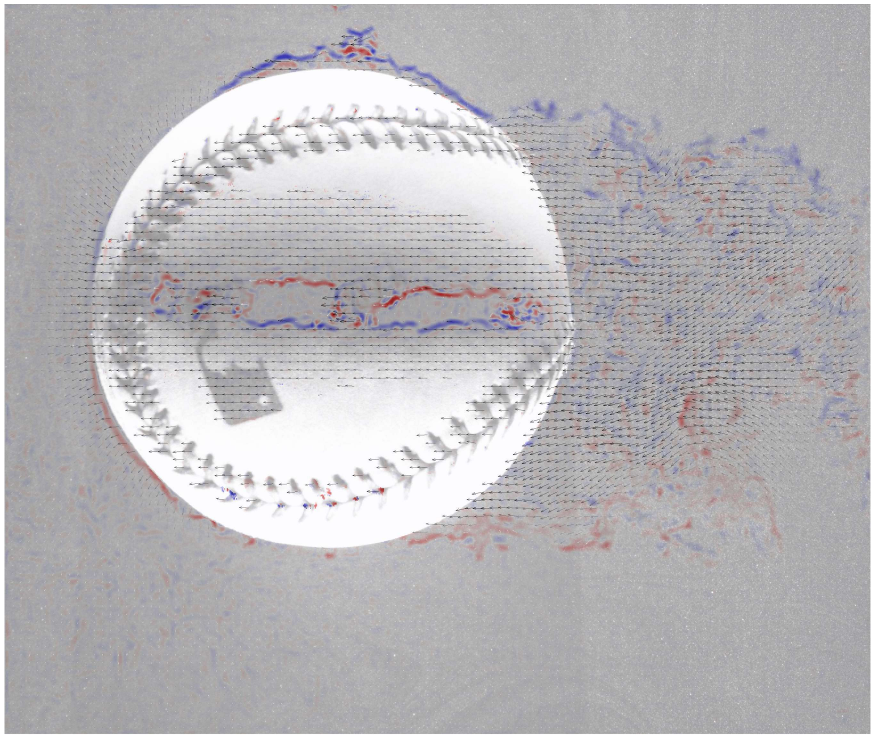

Fig. A.32: 2-seam 32

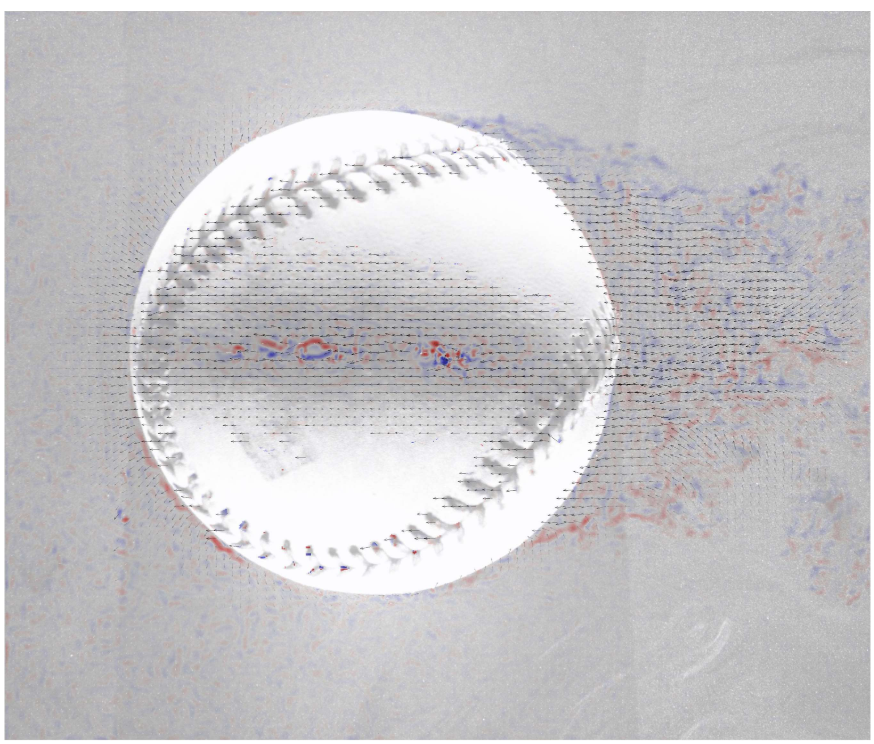

Fig. A.33: 2-seam 33

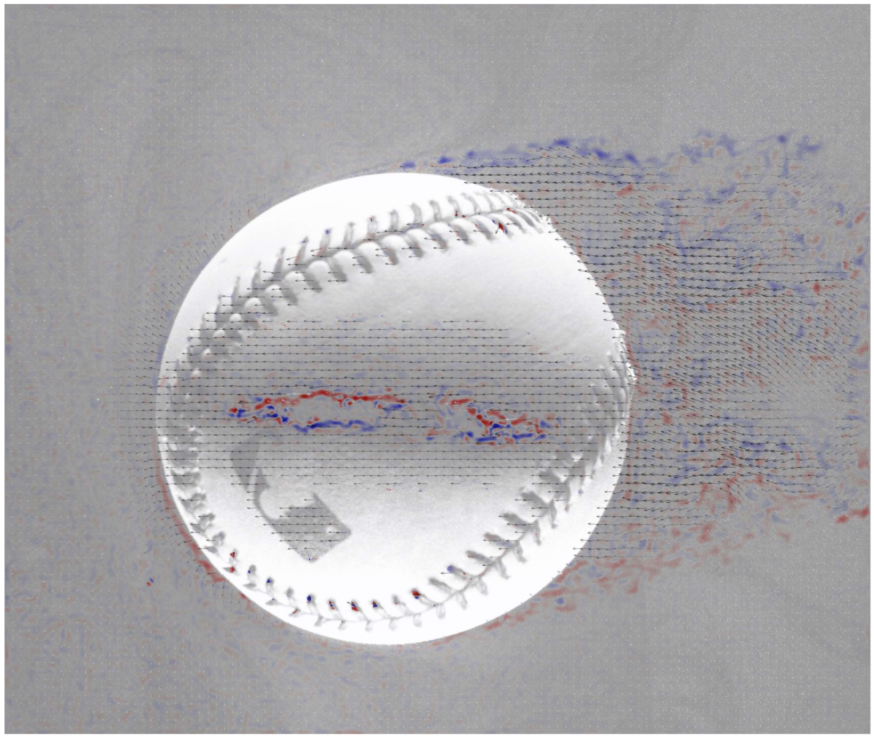

Fig. A.34: 2-seam 34

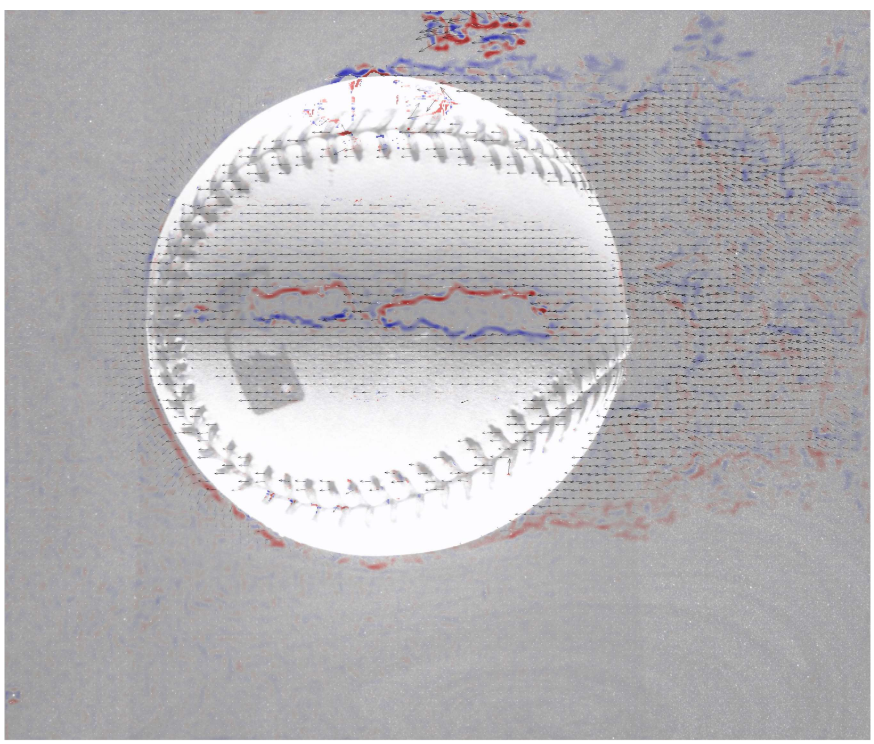

Fig. A.35: 2-seam 35

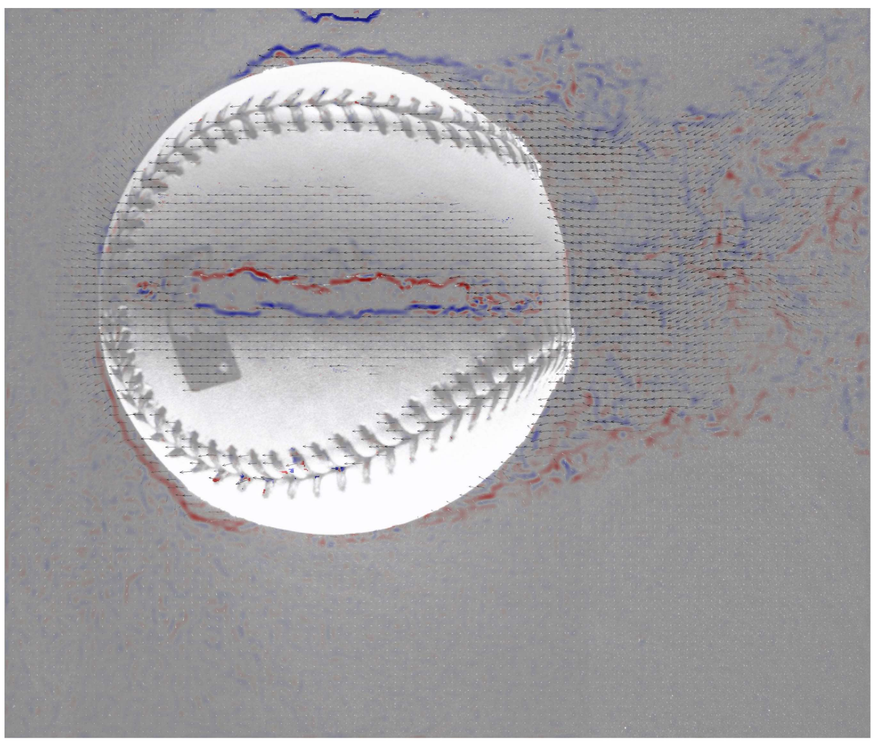

Fig. A.36: 2-seam 36

APPENDIX B

All 4-Seam PIV data sets used to define the boundary layer separation map.

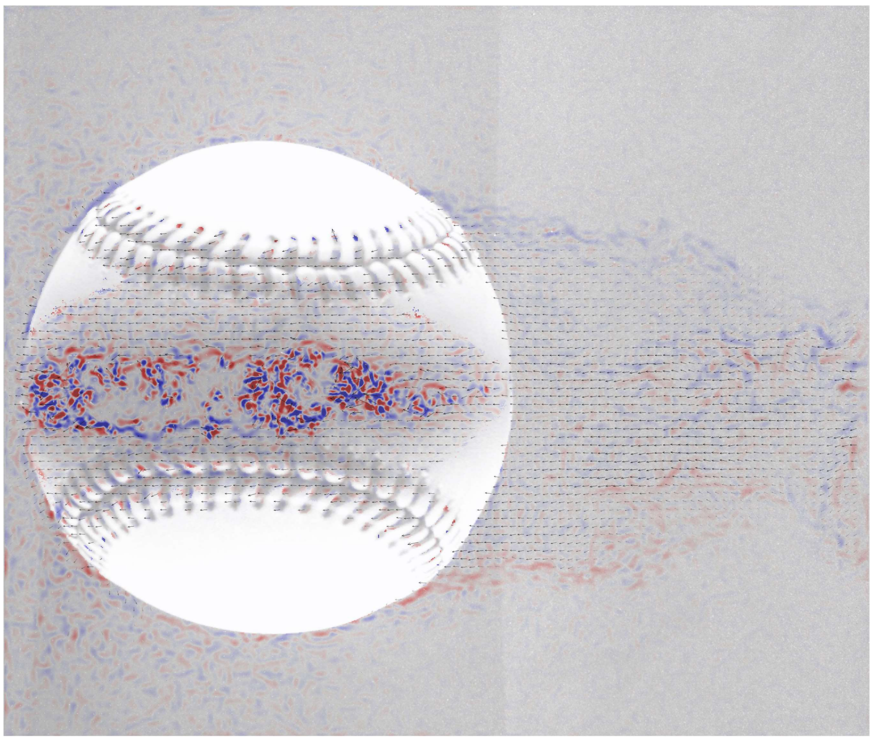

Fig. B.1: 4-seam 1

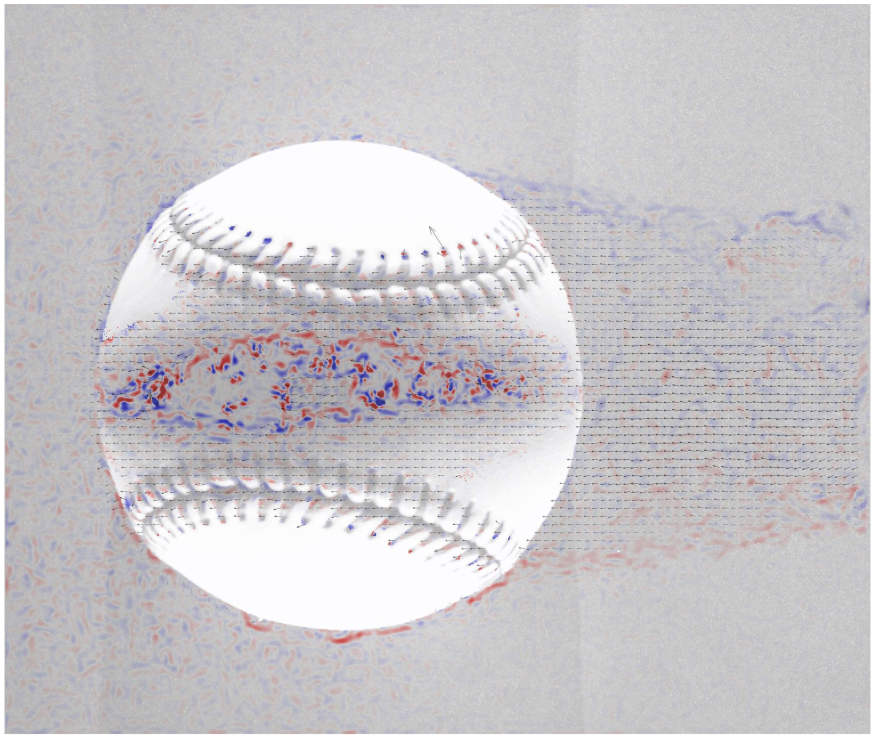

Fig. B.2: 4-seam 2

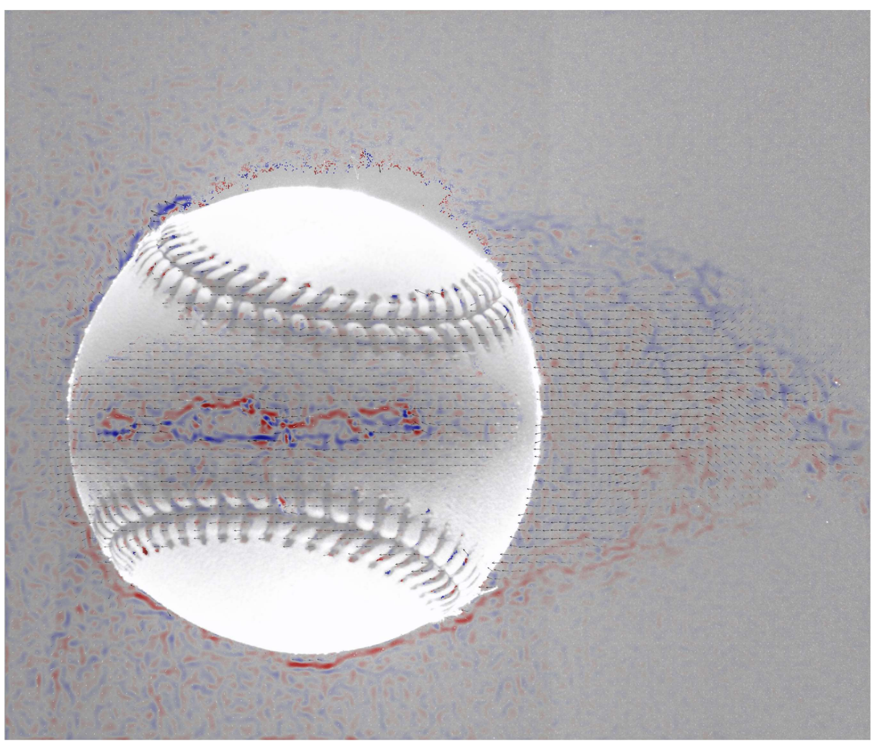

Fig. B.3: 4-seam 3

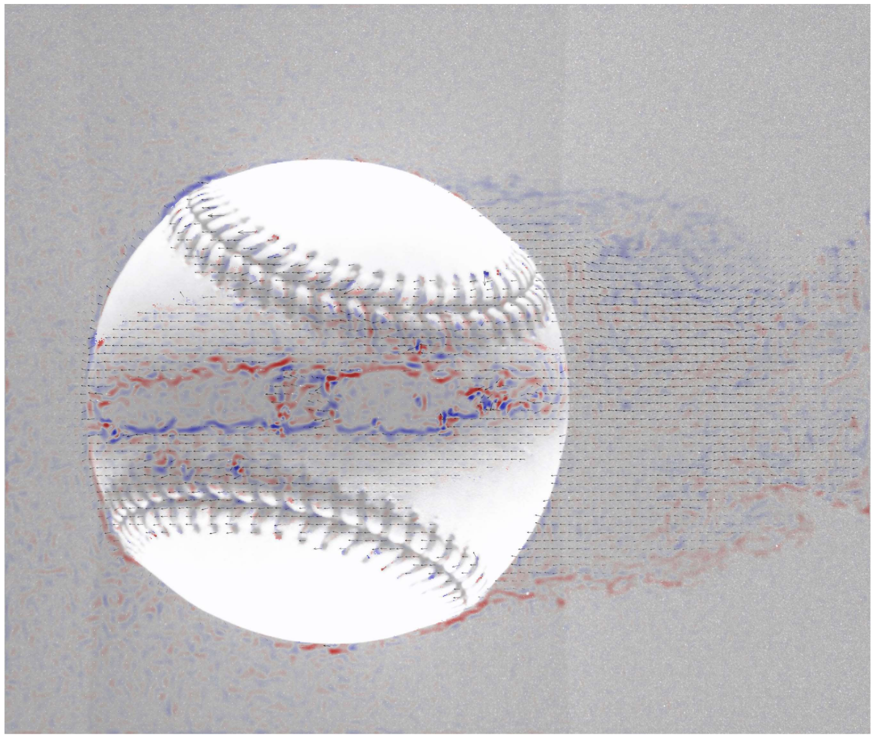

Fig. B.4: 4-seam 4

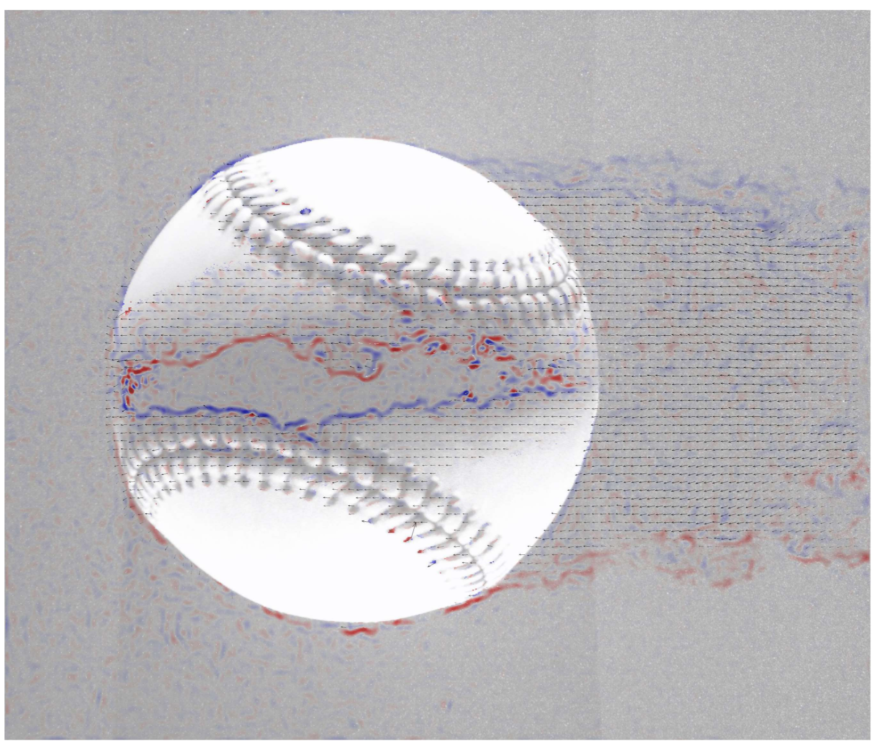

Fig. B.5: 4-seam 5

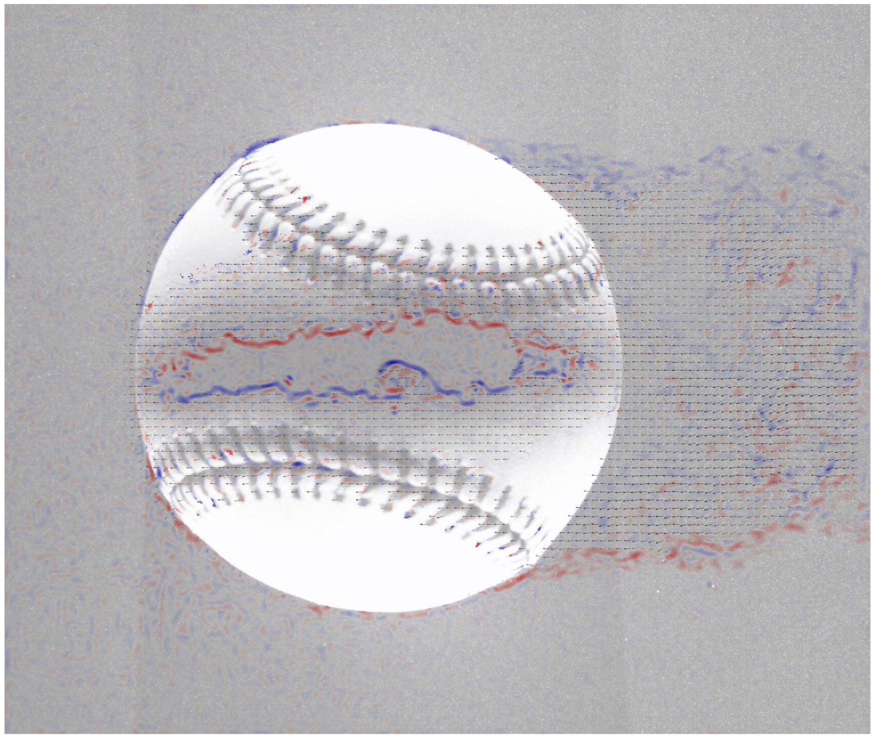

Fig. B.6: 4-seam 6

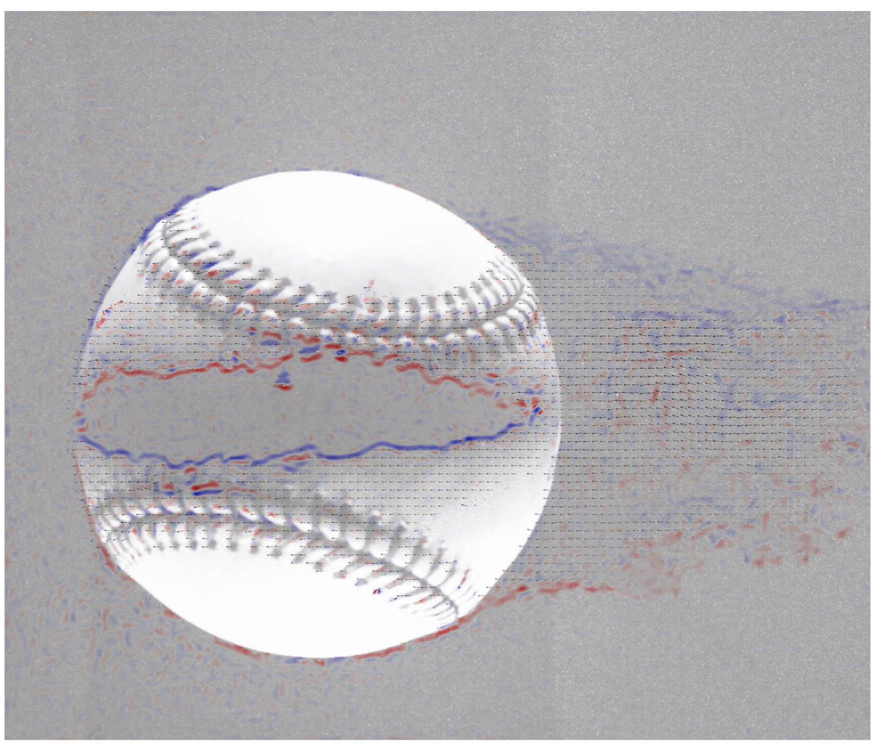

Fig. B.7: 4-seam 7

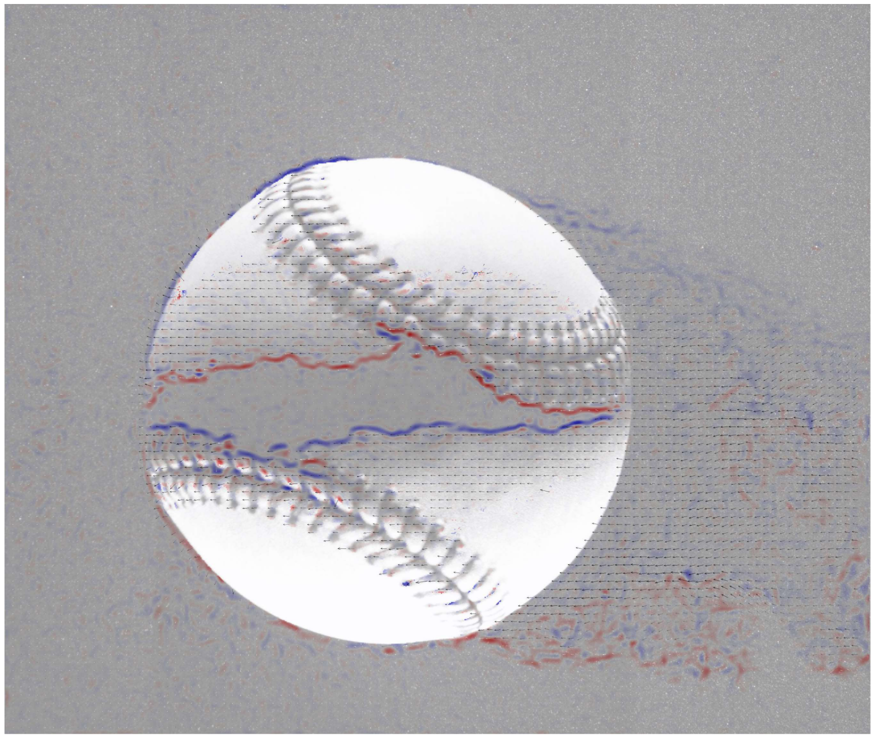

Fig. B.8: 4-seam 8

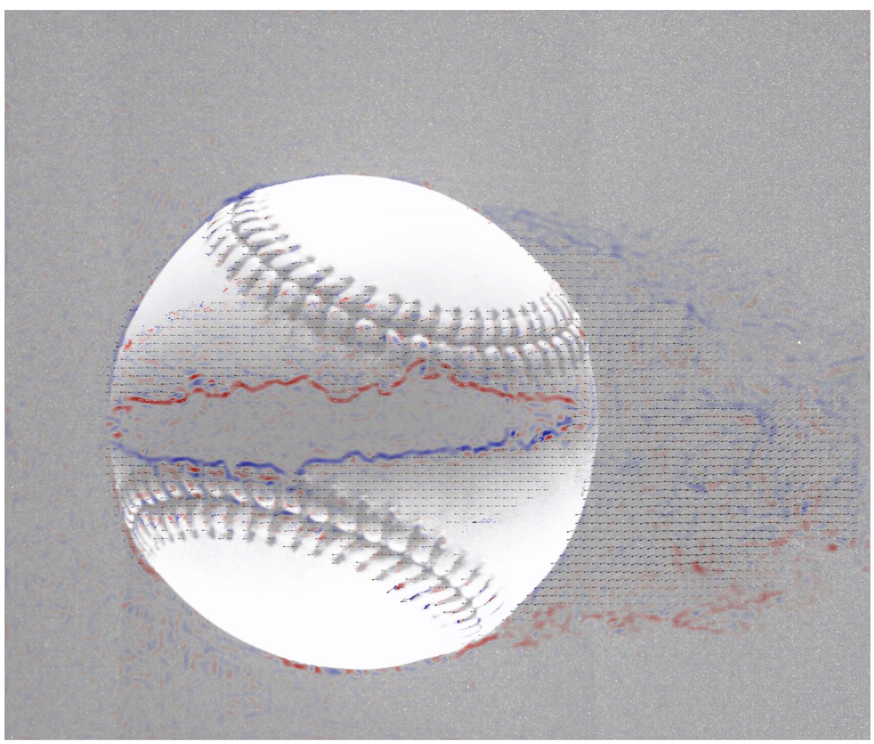

Fig. B.9: 4-seam 9

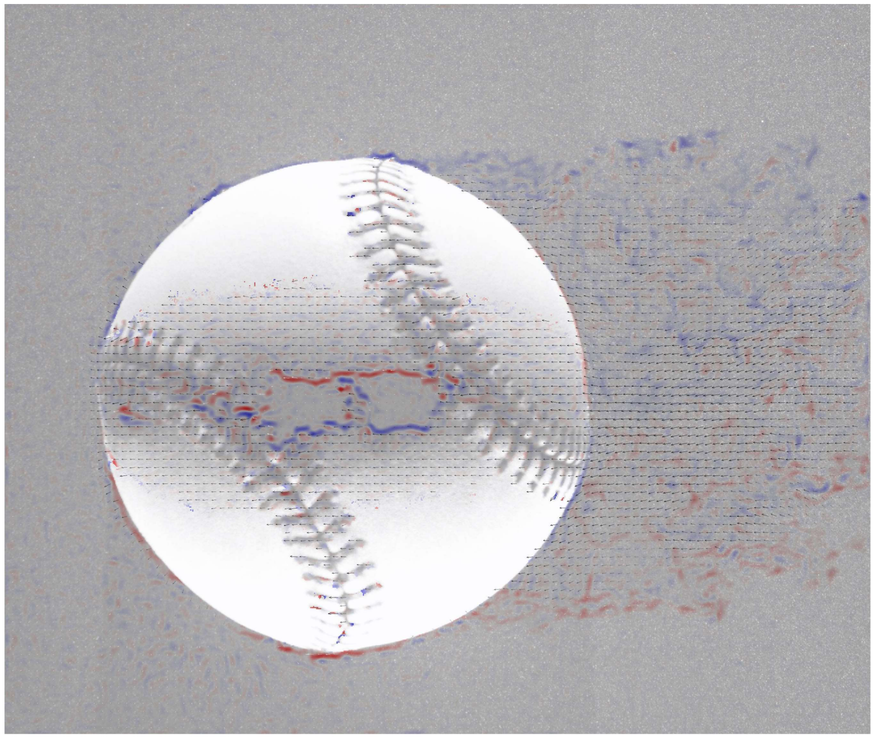

Fig. B.10: 4-seam 10

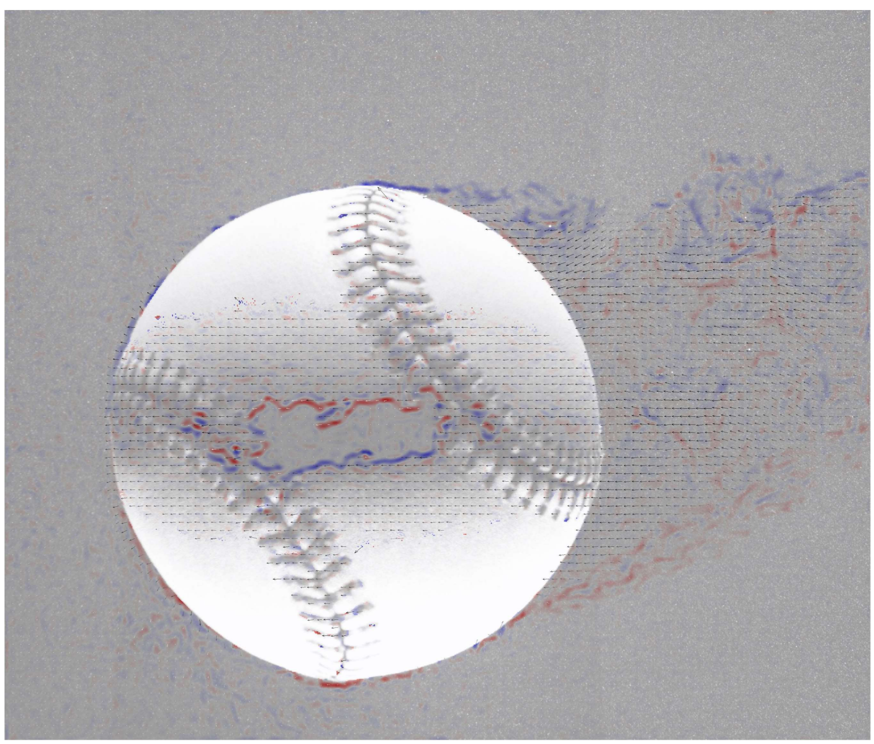

Fig. B.11: 4-seam 11

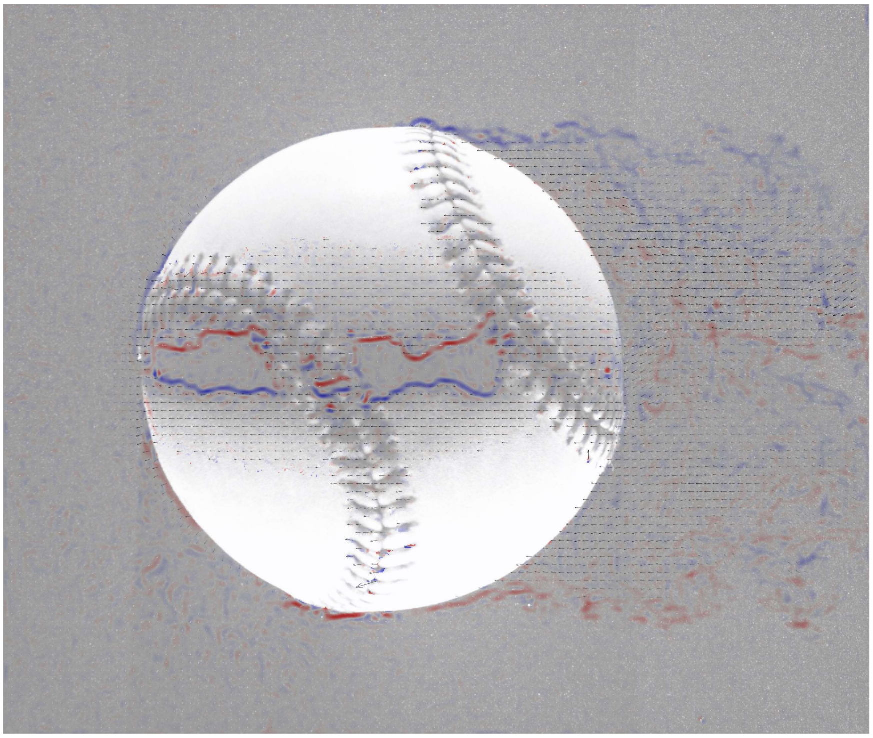

Fig. B.12: 4-seam 12

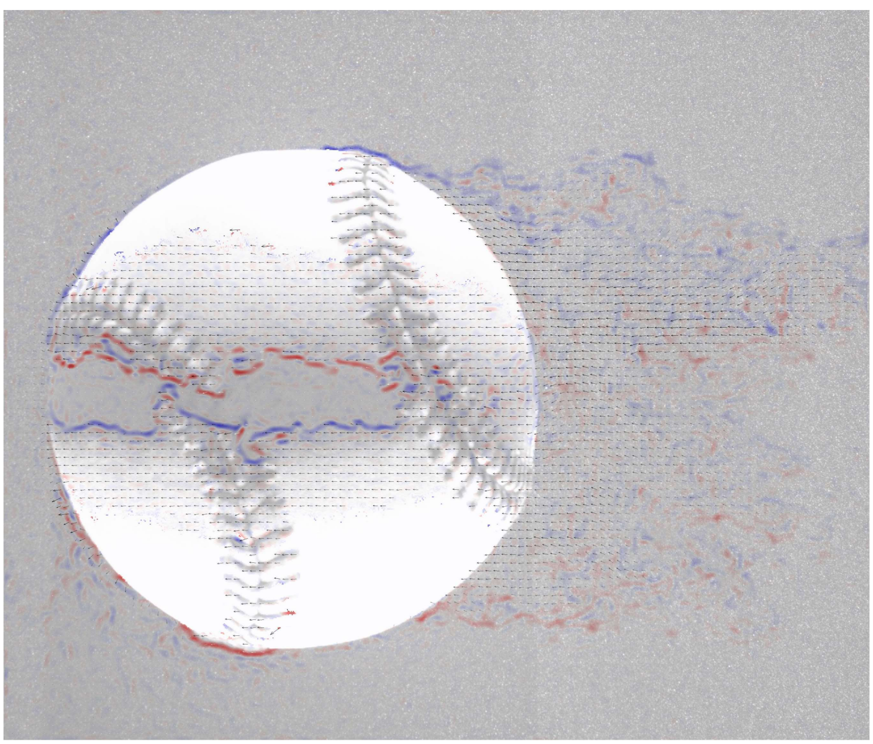

Fig. B.13: 4-seam 13

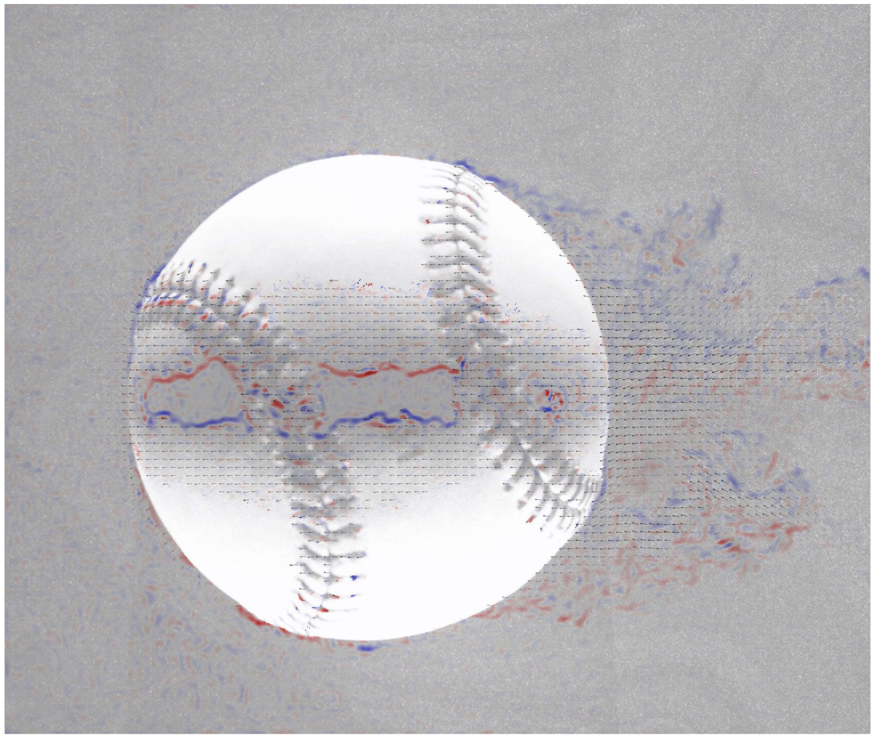

Fig. B.14: 4-seam 14

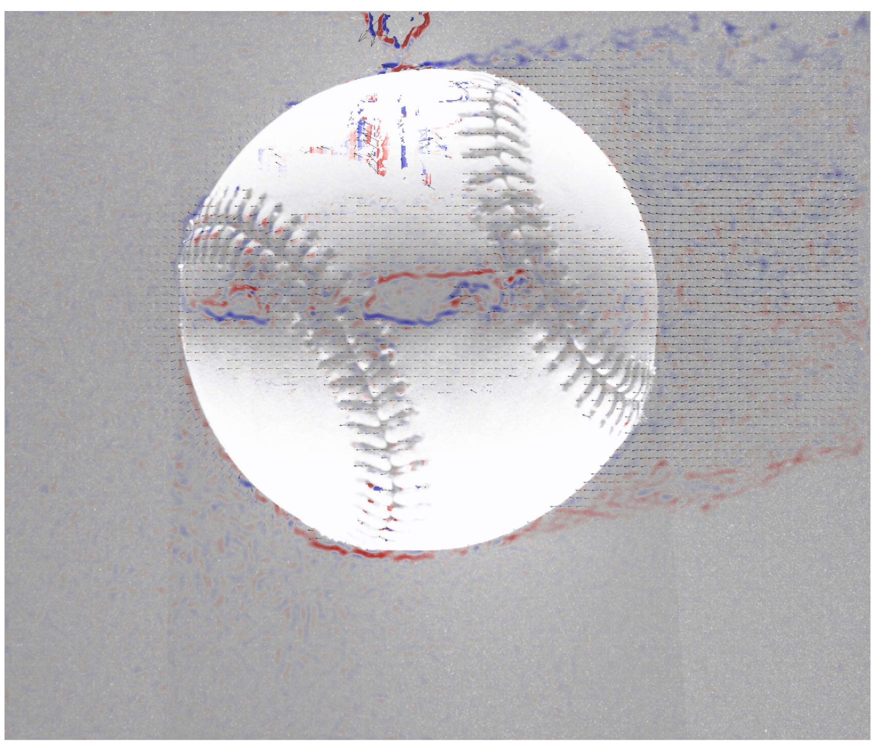

Fig. B.15: 4-seam 15

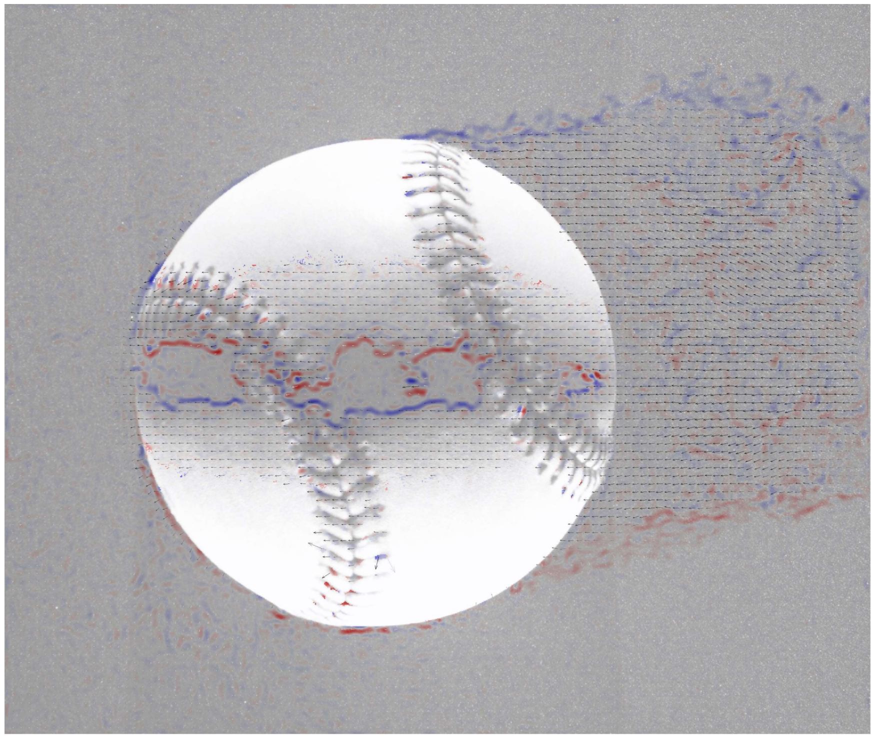

Fig. B.16: 4-seam 16

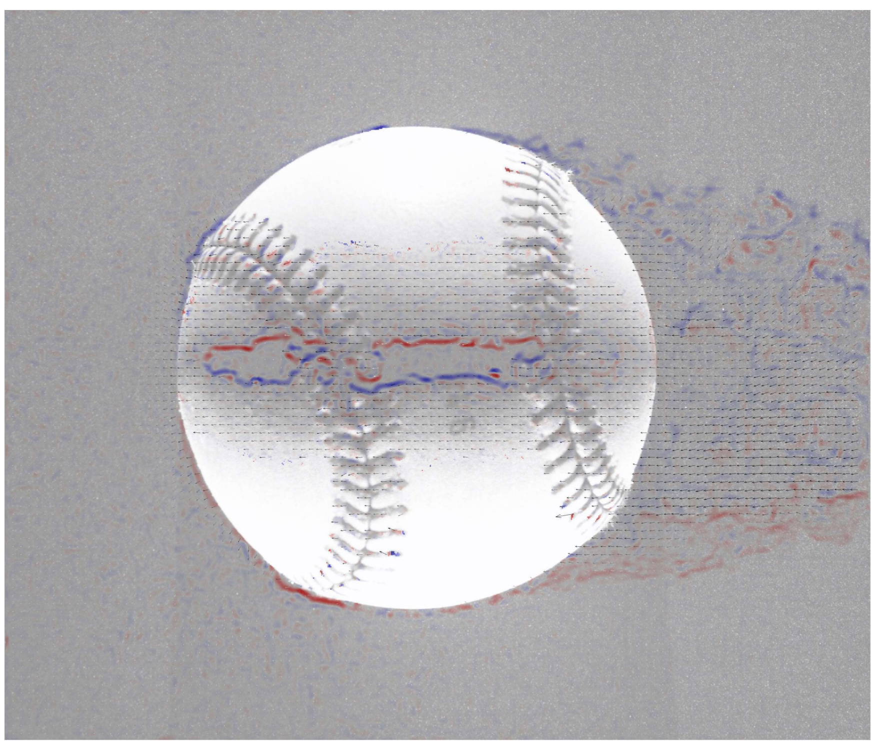

Fig. B.17: 4-seam 17

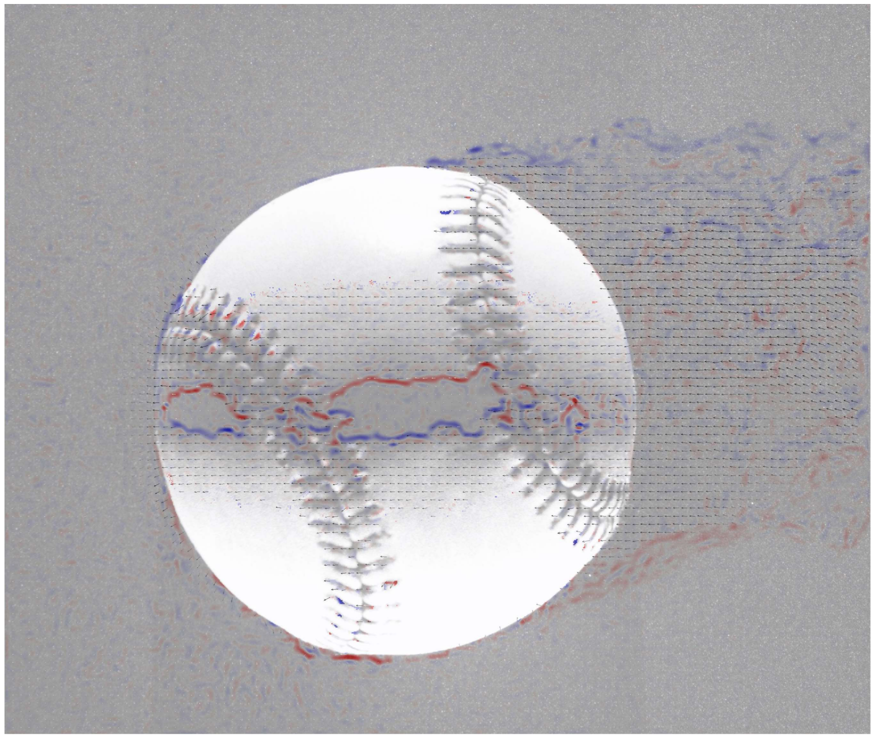

Fig. B.18: 4-seam 18

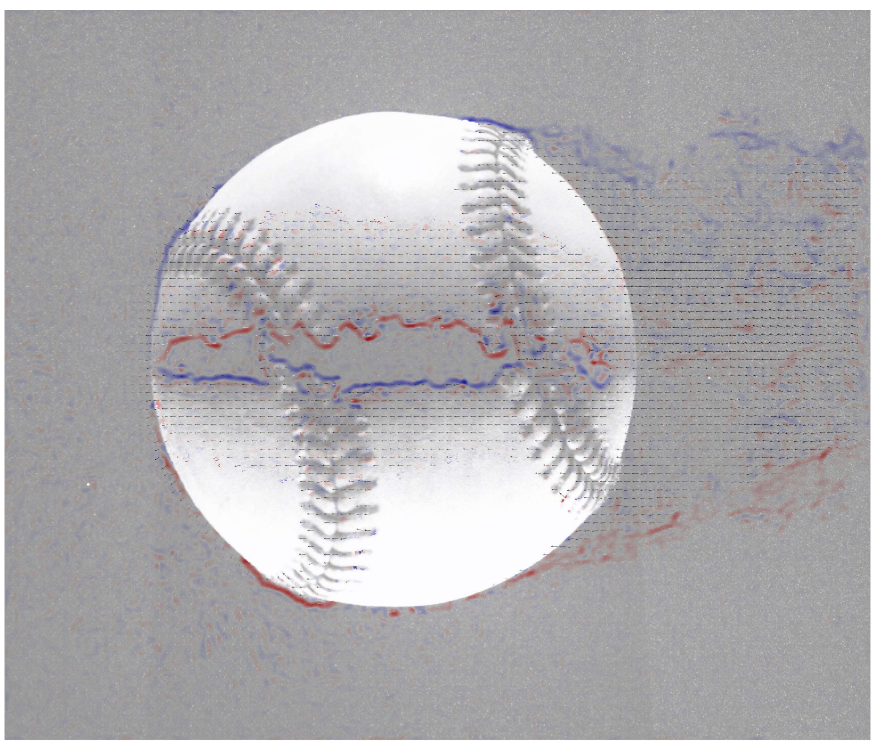

Fig. B.19: 4-seam 19

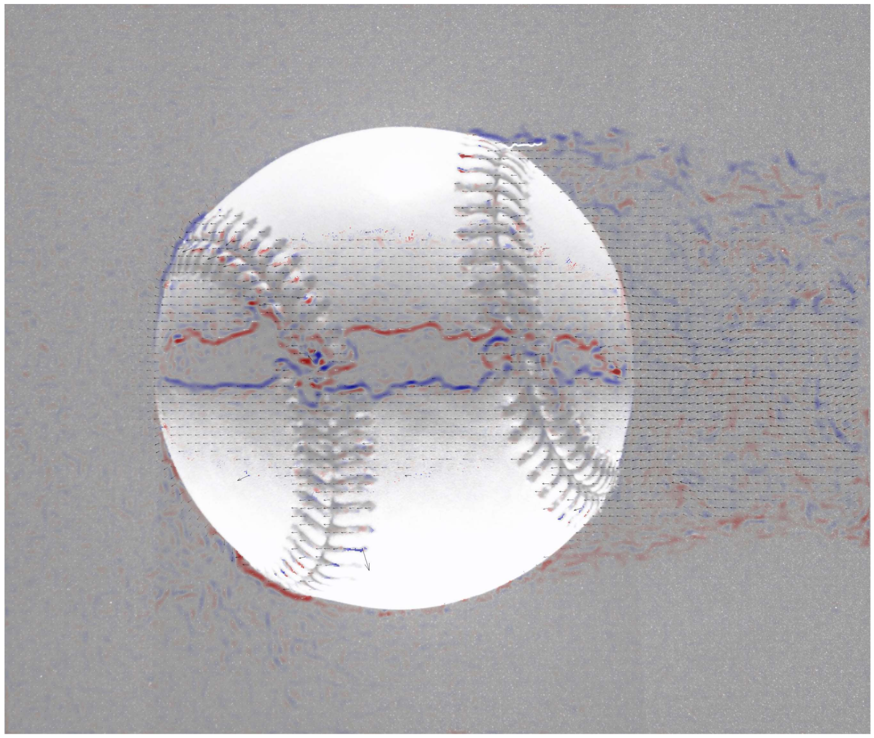

Fig. B.20: 4-seam 20

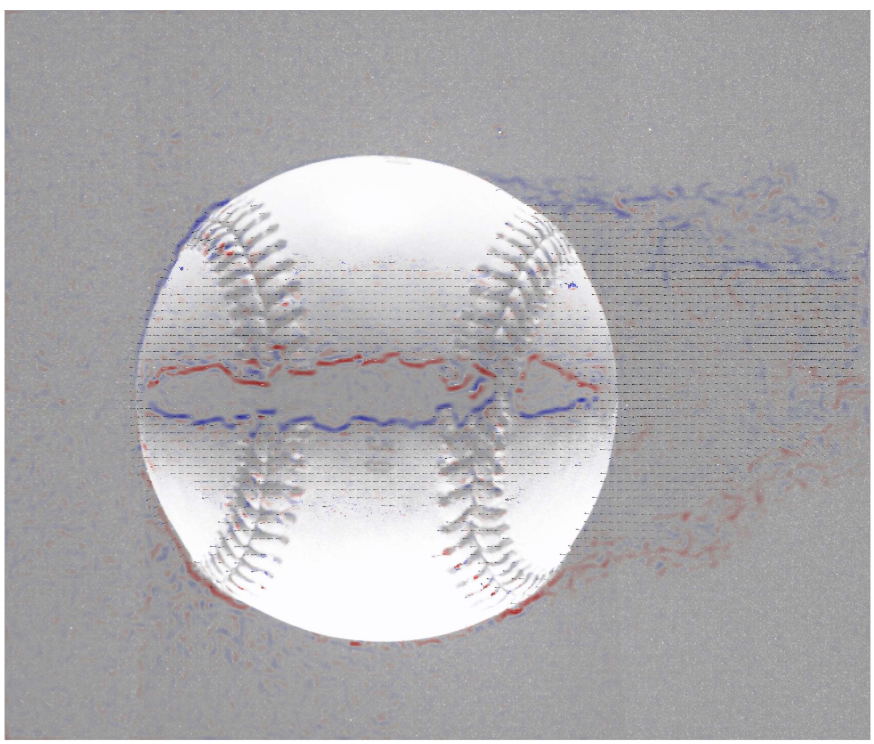

Fig. B.21: 4-seam 21

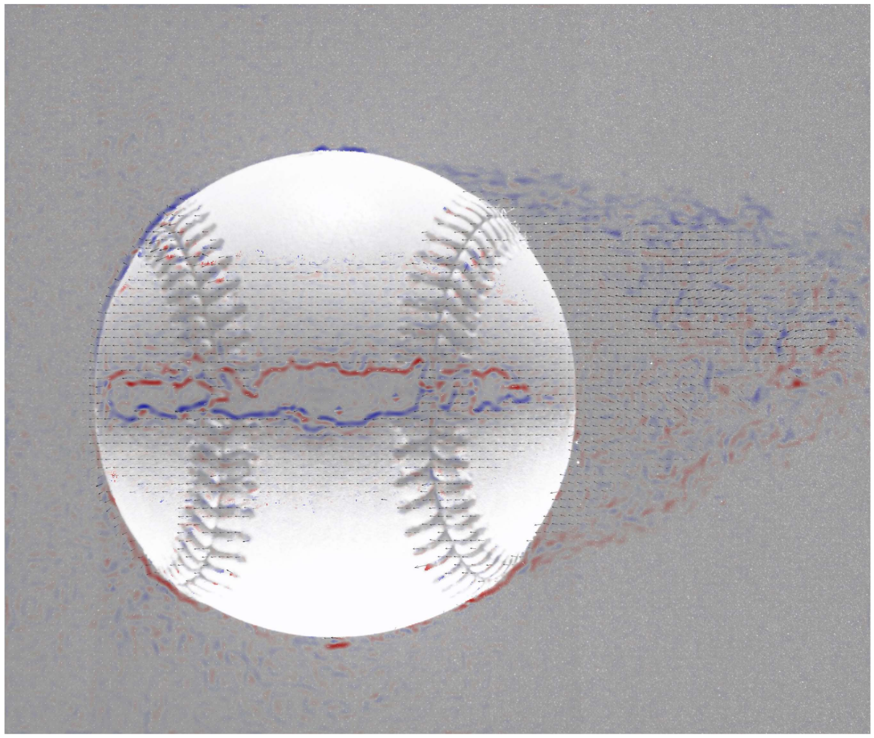

Fig. B.22: 4-seam 22

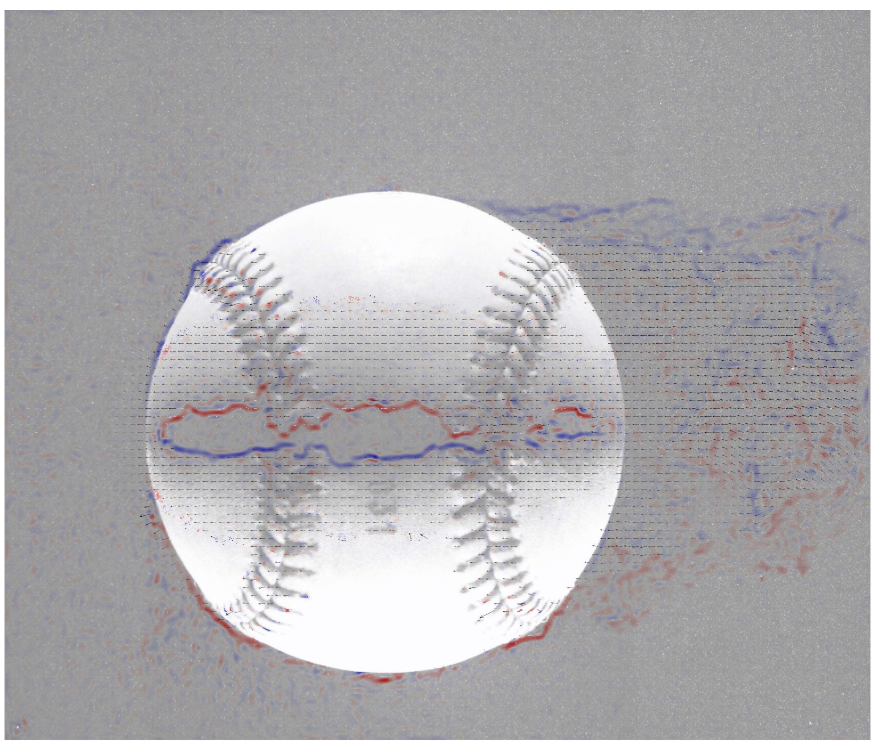

Fig. B.23: 4-seam 23

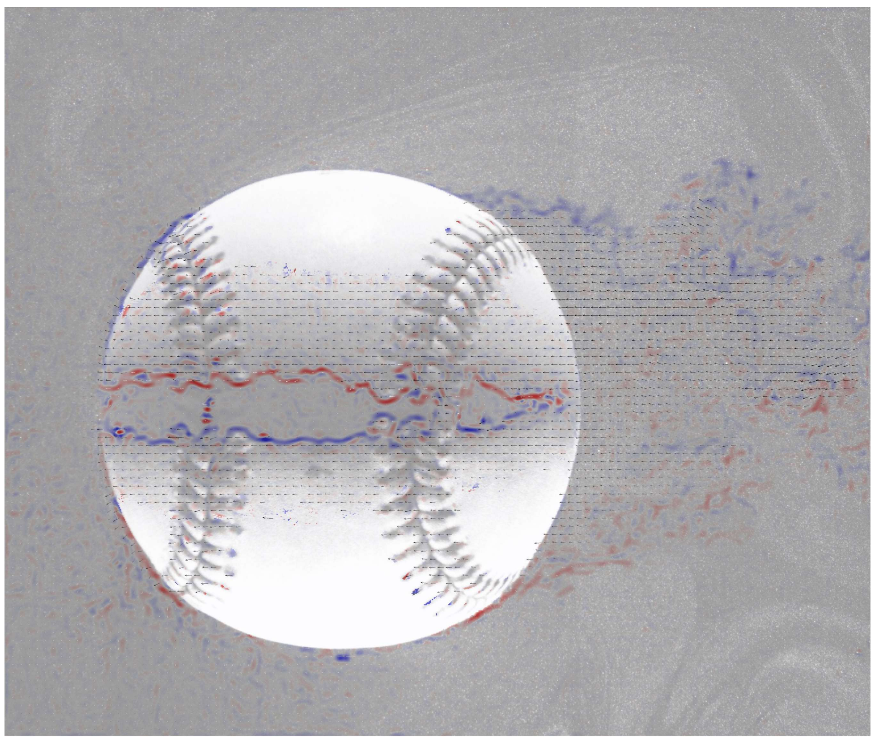

Fig. B.24: 4-seam 24