Baseball Aerodynamics and Unsteady, High-Fidelity CFD

Brent Pomeroy
NASA Langley Research Center
Configuration Aerodynamics Branch

brent.w.pomeroy@nasa.gov
Outline

• Motivation and Application to the Space Launch System
• Baseball Geometry and Grid
• Computational Methods
• Flight Characteristics of Baseball
  – Knuckleball
  – Prescribed rotation
  – Six Degree of Freedom (6-DOF)
• Conclusions
Motivation

• High-fidelity computations are actively performed at NASA Langley
  – Low-speed portion of the Space Launch System (SLS) mission profile
  – Massive separation (> 90 deg)
  – Program requirements necessitate CFD

• Langley CFD efforts focused on the early portions of the mission
  – Rocket static on the launch pad
  – In proximity of the tower
  – Above the tower, before ascent

• Challenging computational state
SLS Low-Speed Flight Regime

• Prelaunch
  – Begins when vehicle exits the Vehicle Assembly Building
  – Can last for numerous weeks
SLS Low-Speed Flight Regime

• **Prelaunch**
  – Begins when vehicle exits the Vehicle Assembly Building
  – Can last for numerous weeks

• **Liftoff and Transition Near Tower**
  – Vehicle stationed on launch pad
  – Freestream alpha from 0 to 90 deg
  – Roll angle from 0 to 360 deg

Representative SLS-type launch vehicle at liftoff conditions
SLS Low-Speed Flight Regime

- **Prelaunch**
  - Begins when vehicle exits the Vehicle Assembly Building
  - Can last for numerous weeks

- **Liftoff and Transition Near Tower**
  - Vehicle stationed on launch pad
  - Freestream alpha from 0 to 90 deg
  - Roll angle from 0 to 360 deg

- **Liftoff and Transition in Isolation**
  - Begins after rocket clears the tower
  - Ends at Mach 0.3
  - Centered on the isolated vehicle
  - Angle of attack 0 to 80 deg
  - Roll angle 0 to 360 deg
SLS Computational Complexities

- Configuration Complexity
  - RANS SLS Grid Resolution Study
- Flow Complexity
  - Capsule Splashdown
  - Homogeneous Isotropic Turbulence
- Large Database
  - High-Speed S&C Aircraft Performance
- High-Speed Aircraft Performance
- Weather Modeling

DES SLS Database
Artemis Support

Databases

Reduced Order Modeling

Launch Environment Effects

Launch Pad and Tower

Crew Access Arm

Launch Abort System Hatch

Axial Force

Launch Environment Effects

Reduced Order Modeling

Databases
Kestrel CFD Solver

- Computational code from Department of Defense CREATE-AV
- Satisfies requirements for database-level low-speed SLS CFD analysis
  - Advanced IDDES model contributes to a high-fidelity solver
  - Inner unstructured grid and adaptive offbody Cartesian grid yields reduced cost
  - Offbody Cartesian solver is extremely fast and efficient
  - Integrates well with HeldenMesh unstructured mesh generator
Kestrel Technology Advancement

• **Kestrel contains many models**
  – Aerodynamic, propulsion, stability and control, multi species, fluid-structure interaction, and more
  – Key to DOD contract bidding process

• **Team leverages Kestrel methods in regular work**
  – IDDES (Improved Delayed Detached Eddy Simulation)
  – Adaptive mesh refinement
  – Computational efficiency

• **Desired methods development to advance computational capabilities**
  – Free transition
  – Surface roughness
  – Prescribed motion
  – Responding-body motion
Selection of Baseball

• Not ITAR protected (good for interns)

• Why a baseball?
  – Topologically simple yet yields complex aerodynamics
  – Testing of new automated geometry preparation tool
  – Availability of flight data and surface roughness measurements

• Provides vehicle to investigate applicability of new technology to other programs

Source: NASA
History of Baseball Geometry

- Varying geometry over original era
  - Differing weight, moment of inertia, materials, and other considerations
  - Efforts to reduce variability in mid 1800s
  - National League defined rules in 1876
  - Live ball era entered in 1920s

- Standardization in 1934 largely reflects current ball

- Unknown inventor of stitch pattern
Baseball Topology

- Made by hand by Rawlings in Costa Rica
- Geometry consists of a variety of features
  - Stitches, puffs, troughs, holes, and panels
  - 108 stitches
  - Puffs previously unnamed
  - Spanwise and chordwise thickness distributions
Baseball Topology

- Made by hand by Rawlings in Costa Rica
- Geometry consists of a variety of features
  - Stitches, puffs, troughs, holes, and panels
  - 108 stitches
  - Puffs previously unnamed
  - Spanwise and chordwise thickness distributions
- CFD geometry includes simplifications
  - Stitches do not extend across trough
  - No stitch holes

Source (all): NASA
Major League Baseball (MLB) Geometry Digitization

- **Point-scanned rubbed, unused regulation MLB ball**
  - 2.56 million point measurements
  - Measured at Washington State University (WSU) Sports Science Lab
  - Interrogated data for thickness distributions

- **WSU data augmented with LaRC measurements**
Physical Geometry

- Geometry defined by league rules
- Digitized height and depth
  - Stitch height = 0.031 in
  - Puff height = 0.018 in
  - Trough depth = 0.011 in
- Idealized ball
  - Weight = 5.125 ounces
  - Moment of inertia = 4.01 ounce-in²
  - Centered center of mass
  - Identical stitch geometry
  - Identical puff thickness distributions
Nondimensional Thickness Distributions

Stitch

Spanwise

Chordwise

Puff

Spanwise

Chordwise

Trough

Spanwise

Chordwise
Geometry Preparation

• **HeldenTool**
  – Developed by Helden Aerospace
  – Interactive and graphical suite of programs

• **HeldenPatch**
  – Automatically generated 869 patches and associated NURBS surfaces
  – Required hand work for ~20 patches
  – Reduced engineering time by multiple orders of magnitude
HeldenMesh

• **Unstructured grid generator from Helden Aerospace**
  – Input-file driven command-line utility
  – Advancing layer/advancing front method
  – Triangular surface elements
  – Single element surface cells (triangles)
  – Mixed element volume cells (prisms and tetrahedra)
  – Utilizes similar technology to Vgrid (ViGYAN)

• **User has significant control of density**
  – Cell size can be specified by patch name or family name
  – Volume sourcing can also be specified

• **Target number of layers and surface $y^+$ control viscous grid growth**
Surface Grid

• Triangular surface grid
  – About 843k cells
  – Similar cell size on stitches and puffs
  – Coarser cells on panels
  – Geometry necessitates finely-resolved trough

• Target surface $y^+ < 0.7$
Volume Grid

• **Dual mesh inner/outer grid formulation**
  – Inner unstructured grid and adaptive offbody Cartesian grid
  – Inner grid trimmed at constant offset distance
  – Cartesian solver is extremely efficient

• **Inner grid details**
  – Prisms in viscous layer, tetrahedra in volume
  – Trimmed at 0.20 inches (0.07 diameter)

• **Outer grid details**
  – Inner-most Cartesian cell automatically determined to be similar characteristic length
  – Domain extended 75 reference diameters in all directions

• **Domain extends 100 diameters**
Offbody Grid Adaptation

- Refinement domain 3 diameters from ball
- Grid refinement applied during solution
  - Refined on vorticity every 50 iterations
  - Baseline grids ~220 million points
Offbody Grid Adaptation

One iteration before refinement and one iteration after refinement
Supercomputing Environment

• Executed on NASA Advanced Supercomputing (NAS) facility
  – Supported by NASA Ames
  – Comprised of four different supercomputers
  – More than 11,000 nodes and 241,000 compute cores
  – Contains both Intel and AMD chips
  – TOSS3 (Linux 3) operating system

• Resource usage
  – Intel Skylake nodes on Skylake (Electra) and Cascade Lake (Aitken)
  – Run with ~2,000 processors
  – Walltime from 18 hours to a few days

Source: NASA
Solution Setup

• **KCFD (inner solver) and SAMAir (outer solver)**

• **Computational Approach**
  – SARC-QCR (QCR 2000)
  – HLLE++ inviscid flux and LDD+ viscous flux
  – Second-order spatial and temporal accuracy
  – Temporal damping applied to inner and outer grids

• **Executed with Kestrel 12.4.1 SDK**
Freestream Conditions

- Set for Seattle Mariners at T-Mobile Park
- Representative fall start-of-game temperature of 60 deg (during a playoff run)
- Elevation 20 ft
  - Elevation at second base
  - Field variation from ~18 to ~30 ft, depending on tides
- Conditions set based on velocity and elevation

Source: NASA
Time Step

- **Example fastball (95.0 mph and 2250 RPM)**
  - Goal of $dt^* < 0.01$ or rotation < 0.5 deg/time step
  - Selected time step of 0.00001 is smaller than both $dt^*$ (0.0000346 sec) and revolution (0.0000370) goals

\[
\frac{dt^*}{dt} = \frac{V_{\infty} \ dt}{D} \left( \frac{1672 \text{ in}}{\text{sec}} \right) dt
\]

\[
0.01 = \frac{0.0000346 \text{ sec}}{2.9 \text{ in}}
\]

- **Representative fastball rates (95 mph and 2250 RPM)**
  - About 175 iterations/diameter
  - Approximately 2600 iterations/rotation

\[
2250 \left( \frac{\text{rev}}{\text{min}} \right) \left( \frac{1 \text{ min}}{60 \text{ sec}} \right) \left( \frac{360 \text{ deg}}{1 \text{ rev}} \right) \left( \frac{1 \text{ it}}{0.5 \text{ deg}} \right) = \frac{27,000 \text{ it}}{\text{sec}}
\]

\[
dt = \frac{1 \text{ sec}}{27,000 \text{ it}} = 0.0000370 \text{ sec}
\]
Standard Baseball Coordinate System
Computational Coordinate System
Baseline Solution

- Static, fully turbulent, and perfectly smooth at 95.0 mph (very fast four-seam knuckleball)
Static, Fully Turbulent – F&M

• Static, fully turbulent, and perfectly smooth at 95.0 mph (very fast four-seam knuckleball)

• Periodic changes in $C_D$
  – About 1100 iterations (0.011 sec, 6.25 $D_{ball}$)
  – For reference: ball travels ~230 diameters from mound to batter
Static, Fully Turbulent – Flow Separation

- **Stitches have significant effect**
  - Promote attachment or separation
  - Behavior depends on stitch location
  - Attachment promoted by vortex generator (VG)-like behavior

**Total pressure coefficient**
Measure of momentum loss
Static, Fully Turbulent – Flow Separation

- **Stitches have significant effect**
  - Promote attachment or separation
  - Behavior depends on stitch location
  - Attachment promoted by vortex generator (VG)-like behavior

- **Separation pattern driven by complex stitch/puff interactions**

- **Attachment/separation pattern may be leveraged for increased pitch control**

Isosurface of $C_{p,t}$
Slice of $\omega$
Static, Fully Turbulent – Surface Fluctuations

- **Unsteady variation observed**
  - Evidenced by both $C_p$ and $C_f$
  - Largest differences near top of horseshoe
  - Accentuated by streamline pattern
  - Separation varies by seam width (~0.28 in)

- **Variations in pattern must be considered when performing experimental comparisons**

- **Animations shown every 0.01 sec**
Kestrel Free-Transition Model

• One-equation Menter intermittency transport equation
  – Galilean invariant, Spalart-Allmaras (SA) or Menter
  – Freestream turbulence values can have a significant impact
  – No wall functions (requires $y^+ < 10$)

• Multiple transition modes available
  – Bypass, crossflow, separation-induced, and compressible second modes
  – Forced transition is also possible
  – Permits relaminarization

• Turbulence intermittency indicates flow regime

\[ \gamma = \frac{\mu_t}{\mu_{t, model}} \begin{cases} < 0.02 & \text{laminar} \\ > 0.03 & \text{turbulent} \end{cases} \]
Static, Free-Transition Results

• First base view (ball rotated 30 deg)
  – Transition scheme does not affect separated flow upstream of stitches (expected)
  – Attached, turbulent flow observed near top and bottom of ball
Static, Free-Transition Results

- **First base view (ball rotated 30 deg)**
  - Transition scheme does not affect separated flow upstream of stitches (expected)
  - Attached, turbulent flow observed near top and bottom of ball

- **Top View**
  - Stitches can promote attachment, cause transition, or separate the flow, depending on the location of the stitches
  - Separation still observed near top-most part of the horseshoe
Flowfield Features at Three Ball Orientations

- Top view
- Rotated about y axis by 0, 15 and 30 deg

Causes transition and promotes attachment

Slight effect upon flowfield

Causes separation
Effect of Turbulence Intensity

- Freestream turbulence intensity affects transition predictions
  - Significant effect previously observed over aircraft wings
  - Minimal investigations regarding separation patterns and turbulence
Effect of Turbulence Intensity

- Freestream turbulence intensity affects transition predictions
  - Significant effect previously observed over aircraft wings
  - Minimal investigations regarding separation patterns and turbulence

- Sweep of cases from 1/10th baseline to 10 times baseline values
Ball Roughness

- Various sources of surface damage
  - Contact with ground
  - Contact with equipment

- Lena Blackburne Rubbing Mud
  - Acquired from shores of Delaware River
  - Changes color and roughness of ball

- Enhanced grip ball being tested

Rubbed

Unrubbed

Source (all): NASA
Surface Roughness Measurements

- MLB roughness determined through profilometer measurements (WSU)\(^1\)
  - Six balls in data set, four profiles per ball
  - Converted to sand grain roughness (\(k_s\)) for Kestrel
  - Previously-developed relationships define roughness\(^2\)

<table>
<thead>
<tr>
<th></th>
<th>Arithmetic Mean</th>
<th>Root Mean Square</th>
<th>Maximum Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Measured (thou)</td>
<td>0.288</td>
<td>0.394</td>
<td>5.249</td>
</tr>
<tr>
<td>Equivalent Sand Grain Roughness (thou)</td>
<td>1.69</td>
<td>1.22</td>
<td>5.14</td>
</tr>
</tbody>
</table>


Kestrel Roughness Model

- Methods leverage previously-developed models

- Discrete element approach with modeling and calibration
  - Modifies $\mu_t$ near wall to increase shear and skin friction (non-zero)
  - Coupled with reduction of turbulence damping
  - Model applied deep in laminar subregion without wall functions

- Can be applied for SA and Menter models
- Implemented for RANS, URANS, and IDDES schemes
- Roughness can be declared patch by patch

Effect of Surface Roughness

- Computed in baseline knuckleball orientation
- Utilized selected freestream turbulence value
- Less than 5 counts different for four roughness values
- No significant effect upon separation behavior
Spin Angle Coordinate System

• Axis of rotation defined by spin direction and gyro angles

• Spin direction (clock angle)
  – Pure side spin
  – Positive vector points in direction of lift

• Gyro angle
  – Pure football spin
  – Positive for right-handed pitchers
Prescribed Rotation – Pure Backspin

- Baseline tests to quantify effects of spin
  - Data can be implemented in pitch models
  - Differences quantified between pitch types

- Investigated effect of spin rate
  - 78.1 mph (Re ~144,000)
  - Eight different spin factors (0.05-0.40)
  - MLB range ~0.22 ± 0.18

\[ S = \frac{\omega r}{V_\infty} \]

- Computations performed over two ball rotations after adequate flow setup
- Maintained constant time step between simulations
Prescribed Rotation

- Significant variation in rotation rate and axis of rotation
  - Varies pitcher to pitcher, day to day, and season to season
  - Leveraged publicly-available axis of rotation data for baseline data
  - Computations on fastballs and curveball (slider included for reference)

<table>
<thead>
<tr>
<th>Pitch</th>
<th>Spin Rate</th>
<th>Clock Angle</th>
<th>Gyro Angle</th>
<th>Speed (mph)</th>
<th>Reynolds Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-Seam Fastball</td>
<td>2250-2350</td>
<td>12:30-1:30</td>
<td>0-10</td>
<td>95</td>
<td>215,000</td>
</tr>
<tr>
<td>2-Seam Fastball</td>
<td>2150-2200</td>
<td>1:00-2:00</td>
<td>10-20</td>
<td>95</td>
<td>215,000</td>
</tr>
<tr>
<td>Curveball</td>
<td>2500-2600</td>
<td>6:00-7:00</td>
<td>20-30</td>
<td>81</td>
<td>182,000</td>
</tr>
<tr>
<td>Slider</td>
<td>2400-2500</td>
<td>10:00-11:00</td>
<td>65-75</td>
<td>85</td>
<td>192,000</td>
</tr>
</tbody>
</table>

Fastball
Curveball
Slider
Release Pitch Grips

Four-Seam Fastball

Curveball

Slider

Source (all): Robby Rowland
Used by permission
Rotational Axis Coordinate System

\[ \psi \]
\[ \theta \]
\[ \phi \]
Four-Seam Fastball (1:00 clock, 10 deg gyro)

- Aerodynamic forces through three rotations
- Presented as a function of the x-y plane angle
- Similar trends in $C_L$ with larger variations in $C_D$
Four-Seam Fastball (1:00 clock, 10 deg gyro)

- Drag, lift, and side force for one rotation cycle
- Similar trends observed in $C_D$
Four-Seam Fastball (1:00 clock, 10 deg gyro)

- Drag, lift, and side force for one rotation cycle
- Similar trends observed in $C_D$ and $C_L$
Four-Seam Fastball (1:00 clock, 10 deg gyro)

- Drag, lift, and side force for one rotation cycle
- Similar trends observed in $C_D$ and $C_L$ with minimal variations in $C_Y$
Two-Seam Fastball (1:00 clock, 20 deg gyro)
6DOF Responding Body Formulation

Real World

\[ V_\infty = 0 \text{ mph} \]
\[ V_0 = x \text{ mph} \]

Computational

\[ V_\infty = x \text{ mph} \]
\[ V_0 = 0 \text{ mph} \]
6DOF Responding Body Formulation

Real World

$V_\infty = 0 \text{ mph}$
$V_0 = x \text{ mph}$

Computational

$V_\infty = x \text{ mph}$
$V_0 = 0 \text{ mph}$
Physical Space Setup

• Release
  – Pitching rubber is 60’ 6” from home plate
  – Release is about 55’ from home plate
  – Vertical release about 8’ above ground level

• Axis of rotation data provided by Rapsodo

• Strike zone for a representative infielder (6’ 0”)

<table>
<thead>
<tr>
<th>Pitch</th>
<th>Velocity (mph)</th>
<th>Spin Rate (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fastball</td>
<td>95</td>
<td>2,250</td>
</tr>
<tr>
<td>Curveball</td>
<td>81</td>
<td>2,500</td>
</tr>
<tr>
<td>Slider</td>
<td>85</td>
<td>2,400</td>
</tr>
</tbody>
</table>

Strike zone for a 6’0” representative infielder
Fastball Six Degree of Freedom Movement

- Ball released from representative pitcher’s hand
- Trajectory shows expected movement
  - Black line shows position history
  - Dots shown at constant time increments
- Flight time ~0.42 seconds
- Additional work needed to accurately model pitches at various release angles
Future Work

• Backspin comparison to flight and experimental data

• Determination and comparison of separation locations

• Non-idealized ball
  – Off-center center of mass
  – Variable stitch/puff sizes

• Investigation of curveball
  – Curveball contains significant top spin
  – Slider has lots of gyro
  – Prescribed, ball joint response and 6DOF

• Sensitivity to computational setup
  – Turbulence model
  – Grid density and refinement
  – Order in spatial and temporal schemes
What It Took
Acknowledgments

• Project leveraged individuals from many organizations

• NASA Langley – Key Team
  – Richard Huang, intern
  – Sarah Langston, mentor
  – Steve Krist, mentor

• NASA Langley – Support
  – Meelan Choudhari
  – Mark Cagle
  – Kenny McNeil
  – Harlen Capen

• Clay Nunnally, MLB

• Washington State University
  – Lloyd Smith
  – Bin Lyu
  – Nick Smith

• Bart Smith, Utah State University

• John Garrett, Rapsodo

• Alan Nathan, University of Illinois
Questions?

brent.w.pomeroy@nasa.gov