Realistic Simulation of Golf Ball Impact

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Why Golf Ball Impact?

- Cool video from U.S. Golf Association (USGA)
  [http://www.youtube.com/watch?v=00I2uX DxbaE](http://www.youtube.com/watch?v=00I2uX DxbaE)
- Golf ball hitting a steel plate @ 150mph
Why Golf Ball Impact for an Engineer?

- A challenging problem: Large deformation at very high speed

- A relevant problem: manufacturers strive to maximize performance
Outline

• Realistic impact simulation
  – Material testing and characterization

• Discussion of material model selection
Golf Ball Impact Overview

• USGA Calibration Ball: two-layer construction
  – Cover: Surlyn
  – Core: Polybutadiene

• Core dominates impact behavior
  – Strain rate spans a wide range, as high as 5000 sec\(^{-1}\)
Golf Ball Core Material Characterization

• Need reliable data from a wide range of strain rates
High-Rate Testing of Golf Ball Core

Data Collection

High rate testing of soft polymer materials can be tricky. Auxiliary procedures may be required:
- FE simulation as verification
- Reverse engineering
- Other types of testing

Test set-up:
- Striker speed
- Bar material
- Specimen size

Data handling:
- Data shifting
- Noise removal
- Dispersion correction
Core Material Data

- Use data from literature for comparison
  - Quintavalla and Johnson*
  - Strain rate 0.00003~5332 sec\(^{-1}\)

*Rubber Chemistry and Technology 77, 972 (2004)
Core Material Calibration

• Material model needs to account for:
  – Rate-dependence
  – Large strain
  – Untested strain rates: adaptivity

• Parallel Network Model (PNM)
  – Material behavior characterized by a number of networks
  – Allow highly nonlinear visco-elastic/plastic behaviors
  – Part of the Veryst PolyUMod© Library of polymer UMATs and VUMATs
PNM for Golf Ball Core

• Network 1
  – Eight-chain hyperelastic model with small strain softening

\[
\sigma = \frac{\mu_{\text{eff}}}{J \lambda^*} \frac{\mathcal{L}^{-1}(\lambda^*/\lambda_L)}{\mathcal{L}^{-1}(1/\lambda_L)} \text{dev}[b^*] + \kappa(J - 1)I
\]

\[
\mu_{\text{eff}} = \mu_f + (\mu_i - \mu_f) \left(1 - \exp \left[\frac{-\varepsilon_{\text{eff}}}{\dot{\varepsilon}}\right]\right) \frac{\dot{\varepsilon}}{\varepsilon_{\text{eff}}}
\]
PNM for Golf Ball Core

• Network 2
  – Eight-chain hyperelastic model with power-law viscous flow

\[
\sigma = \frac{\mu}{J\lambda^*} \frac{L^{-1}(\lambda^*/\lambda_L)}{L^{-1}(1/\lambda_L)} \text{dev}[\mathbf{b}^*] + \kappa(J - 1)I
\]

\[
\dot{\gamma}^p = \left( \frac{\tau}{f_p f_{\varepsilon_p} f_{\theta} \dot{\tau}} \right)^m
\]
PNM for Golf Ball Core

• Network 3
  – Eight-chain hyperelastic model with Bergström-Boyce viscous flow

\[ \sigma = \frac{\mu}{J \lambda^*} \frac{\mathcal{L}^{-1} (\lambda^*/\lambda_L)}{\mathcal{L}^{-1} (1/\lambda_L)} \text{dev}[b^*] + \kappa (J - 1) \mathbf{I} \]

\[ \dot{\gamma}^p = [\lambda_L - 1 + \xi]^C \cdot \left( \frac{\tau}{f_P f_{\varepsilon \dot{\lambda}} f_{\theta \dot{\lambda}}} \right)^m \]
Core Material Calibration

- PNM model can adapt to the wide strain-rate range
Golf Ball FE Model

• Golf ball modeling
  – Multi-layer construction with dimples
  – Parametric model generation via scripting
Impact Simulation
Strain Rate During Impact

• Peak strain rate is below $6000 \text{ sec}^{-1}$
• Strain rate spans a wide range
Material Model Selection

- Calibrate a linear viscoelastic (LVE) model

LVE has difficulty adapting to a wide strain rate range!
Comparison: PNM vs. LVE

- Rebounding behavior
  - LVE under-predicts hysteresis, hence less loss of kinetic energy
Comparison: PNM vs. LVE

• More rebounding behavior
  – Rebounded height at 2ms

PNM

LVE

3.5 inch

2.5 inch
Remarks on Material Model Selection

• LVE works well for:
  – Small-strain deformation
  – Relatively narrow strain-rate range

• It is possible to calibrate LVE to match a particular output for a particular impact case, but to predict realistic behavior under different impact scenarios requires an advanced material model such as PNM

Neither is true for golf ball impact!
Advanced Simulation: Spin Generation

- Oblique impact generates spin
- Requires accurate modeling of ball-club interaction
- Ongoing effort
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