APPLICATION OF AN INTEGRATED HIGH-PERFORMANCE COMPUTING RELIABILITY PREDICTION FRAMEWORK TO HMMWV SUSPENSION SYSTEM

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Presentation Scope:

- To present an overview of an integrated HPC stochastic physics-based framework that has been developed for vehicle reliability prediction.

- Illustrative application to the HMMWV system

DISCLAIMER: The HMMWV dynamic model and the suspension system configuration used in this research are slightly different than the actual HMMWV hardware.

Focus on:

- The front-left suspension system (FLSS)
- Qualitative aspects and methodology, not on quantitative results
VEHICLE RELIABILITY PREDICTION MULTISTEP PROCESS

**FUTURE**
- Baseline System
  - Stochastic Environment
    - Modeling Uncertainty
      - Test Data
        - Stochastic System
          - Stochastic Stress/Damage Model
            - Reliability
              - Update Response
    - Lack of Data

**PAST**
- Baseline System
  - Deterministic/Single Environment
    - Random Geometry Deviations = Design Variables
    - Manufacturing deviations
  - (Semi) Stochastic System
    - Deterministic/Single Stress/Damage
      - Reliability
        - Update Response

**Note:** HPC Future Need = 100…1,000 X Present HPC Need!
Stochastic Road Surfaces

High Spatial Transverse Correlation

Low Spatial Transverse Correlation

Simulated vs. Measured Road Profiles
Vehicle Behavior to Stochastic Road Surfaces

Using HMMWV Model
Effects of Road Topography on FLSS UCA Ball Joint Forces

- **Straight Road Segment**
- **Rolling Hills Segment**

Graphs showing force on UCA ball joint at 30MPH for different road segments.
Front-Left Suspension System (FLSS) Models

FLSS ADAMS RBD Model and SPARTACUS FE Model
(36 Joint Component Forces/Moments Considered for FLSS)

ADAMS Model

SPARTACUS Model

36 joint forces considered

SPARTACUS Stochastic Input

Parallel FE Partition

Parallel FEAP

Parallel FEAP

Parallel Multigrid Solver

Prometheus AMG PC

FarMetis

FE Model

Parallel FE Mesh Graph Partitioning METIS/ParMETIS

Parallel Unstructured FE Mesh Algebraic Multigrid PDE Solver PETSC/PROMETHEUS

Stochastic Preconditioning via Dynamic Simulation

GP Technologies in collaboration with UC Berkeley/LBL
Stochastic FEA Using HPC. Scalability Study – Linear, Static

Scalability for FEA Problems with 100,000 to 20,000,000 Dofs

<table>
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<th>500 k</th>
<th>1 M</th>
<th>5 M</th>
<th>10 M</th>
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Parallel Multigrid

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</table>
Stochastic Response Surface Modeling for Stress Computation

10 D Stochastic Surface Using High-Order Stochastic Field Models

Computed Data

50% Probability

5% Probability

95% Probability
Sensitivity Studies: Effects of Road Topography on FLLS Joint Forces and Stresses

Moderate Roughness Road at 30 mph: Straight, Long Turns, Rolling Hills

LCA Ball Joint Force

Critical Location Von-Mises Stress Variations

- Straight
- Long Turns
- Rolling Hills
Interactive Fatigue Damage Mechanisms for Vehicle on Rough Terrain

Vehicle Steering Knuckle Arm

Vibratory Component (HCF) (Road Roughness)

Working Load Component (LCF) (Maneuvering Operations)

HCF-LCF Interaction Using DCA Damage Model (NASA GRC)

Linear Damage Rule

Minimum Damage Curve Approach

LCF cycle fraction, $a_t/N_{t1}$

HCF cycle fraction, $a_t/N_{c1}$

$N_{t1}/N_{t1}$

$N_{c1}/N_{c1}$

$\sigma_{max} = 275 \text{ MPa}$

$\sigma_{max} = 255 \text{ MPa}$

$\sigma_{max} = 235 \text{ MPa}$

$\sigma_{max} = 215 \text{ MPa}$

$\sigma_{max} = 205 \text{ MPa}$
Simultaneous Corrosion-Fatigue Model. Validated Against Field Data.

Crack Initiation

Strain-Life Curve:
\[ \frac{\Delta\varepsilon}{2} = \frac{e_f (2N_f)}{E} \]

Ramberg-Osgood Curve:
\[ \frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K}\right)^{1/\ell} \]

\[ a(t) = \text{IDS} + \left[ \sum_{n,t} a(n)^{\alpha} + p(t)^{\beta} \right]^{\gamma} \]

Crack Propagation

Forman FCG Model (NASA JPL, 1996)
\[ \frac{da}{dN} = \frac{C(1-R)^m \Delta K^p (\Delta K - \Delta K_{th})^{\delta}}{[(1-R)K_e - \Delta K]^q} \]

Uncertain Parameters

\[ \Delta K_{CF} = \psi(t) \Delta K_F \]

\[ \psi(t) = \sqrt{1 + \frac{p(t)}{a(n)}} \]
Predicted FLSS Life Using LDR and DCA Damage Models

LDR

Mean = 745

DCA

Mean = 416

Sensitivity Studies: Effects of Damage Mechanism Model on Life Predictions
Sensitivity Studies: Effects of Vehicle Weight Increase on Predicted FLSS Life

Predicted FLSS LCA Life Without and With Armour Weight Increase (50% of total vehicle weight)

Mean = 1027

Mean = 96.4
Bayesian Updating (BU) vs. Bayesian-Probability Transformation Updating (BPTU). Many Test Data

All 250 Test Data Have Perfect Prediction
Bayesian Updating vs. BPT Updating

Only 5 Random Test Data With Perfect Prediction
Bayesian Updating vs. BTU Updating

10 Random Test Data With Perfect Prediction

50 Random Test Data With Perfect Prediction
Statistical Strain-Life Curve. Effect of Nonlinear Correlation Between SLC Parameters (Sigmaf, Epsf, b, c)

Low Nonlinear Correlation

High Nonlinear Correlation
Statistical Strain-Life Curve for Low and High Nonlinear Correlations

Effect of Nonlinear Correlation Between SLC Parameters (Sigmf, Epsf, b, c)

Low Nonlinear Correlation

High Nonlinear Correlation

200 simulated strain life data points

Strain Amplitude

Fatigue Life

Strain Amplitude

Fatigue Life
Lack of Data Effects (250 simulations) on Life PDF, and 99% & 95% Reliability Life

**High Roughness**

Modeling Uncertainty Effect at Node=2275, Moderate Roughness,

Reliability | Mean   | 95%
---|---|---
R=99% | 235.8 | 180.7
R=95% | 462.1 | 372.8

**Moderate Roughness**

Modeling Uncertainty Effect at Node=2275, High Roughness,

Reliability | Mean   | 95%
---|---|---
R=99% | 300.0 | 25.5
R=95% | 725.5 | 63.9
## Effect of Limited FEA Simulations (250) on FLSS Life for Given Reliability

<table>
<thead>
<tr>
<th>Road Profile Type (including topography)</th>
<th>Mean Life (days)</th>
<th>Life with Given Reliability 99% and 95% (days)</th>
<th>No Modeling Uncertainty</th>
<th>With Modeling Uncertainty</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deterministic</td>
<td>50% Confidence</td>
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<tr>
<td>High Roughness</td>
<td>620</td>
<td>99%</td>
<td>31</td>
<td>30.0</td>
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<tr>
<td></td>
<td></td>
<td>95%</td>
<td>72</td>
<td>72.5</td>
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<tr>
<td>Moderate Roughness</td>
<td>3200</td>
<td>99%</td>
<td>249</td>
<td>235.8</td>
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<tr>
<td></td>
<td></td>
<td>95%</td>
<td>459</td>
<td>462.1</td>
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</tbody>
</table>
Sensitivity Studies for FLSS Predicted Life. Effects of Road Topography for Moderate Road Surface Roughness

Governing Critical Location

Node=2275 on Moderate Roughness Roads

Other Critical Section

Node=348 on Moderate Roughness Roads

Life Distribution

Life time (days)

Life Distribution

Life time (days)
Sensitivity Studies for FLSS Predicted Life. Effects of Corrosion for Different Road Surface Roughness

High Roughness

Moderate Roughness

Corrosion Effect at Node=2275, High Roughness Roads

Corrosion Effect at Node=2275, Moderate Roughness Roads

Life Distribution vs. Life time (days) for High and Moderate Roughness with and without Corrosion effects.
Risk-Based Maintenance Analysis Concept

Crack Size

Detection Level

Time

Inspection 1

SME

UME

$P_f$

$t_i$

Inspection 2

SME

FATIGUE

Critical Length

CORROSION-FATIGUE
Reliability-Based Maintenance Analysis
Sensitivity Studies: Given POF

Failure Risk Evolution including Maintenance
Given Probability of Failure (1.0e-5)

Failure Risk Evolution including Maintenance
Given Probability of Failure (1.0e-3)

10 October 2010
## Maintenance Schedule (Inspections and Repairs) Given POF

<table>
<thead>
<tr>
<th>Target Probability of Failure (POF)</th>
<th>Computed Probability of Failure (POF)</th>
<th>Number of Scheduled Maintenance Events</th>
<th>Mean Maintenance Interval (days)</th>
<th>Cumulative Number of Repairs per Component</th>
<th>Mean Hazard Failure Rate For Entire Period (per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 E-05</td>
<td>1.1 E-05</td>
<td>23</td>
<td>155 (372) (1.02 years)</td>
<td>18</td>
<td>7.5 E-08</td>
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<tr>
<td>1.0 E-04</td>
<td>1.1 E-04</td>
<td>17</td>
<td>205 (492) (1.35 years)</td>
<td>15</td>
<td>5.3 E-07</td>
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<tr>
<td>1.0 E-03</td>
<td>1.0 E-03</td>
<td>12</td>
<td>285 (684) (1.87 years)</td>
<td>11</td>
<td>3.5 E-06</td>
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Sensitivity Studies Given Maintenance Schedule for Design Life of 20 Years

<table>
<thead>
<tr>
<th>Sensitive Study Parameters</th>
<th>Average Maximum POF Per Interval</th>
<th>Average Hazard Failure Rate</th>
<th>Number of Repairs Per 100 Parts</th>
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<tbody>
<tr>
<td>Maint. Interval=155 days</td>
<td>1.29003e-5</td>
<td>8.32275e-8</td>
<td>853</td>
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<tr>
<td>Maint. Interval=185 days</td>
<td>5.39682e-5</td>
<td>2.91720e-7</td>
<td>745</td>
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<tr>
<td>Maint. Interval=230 days</td>
<td>2.56768e-4</td>
<td>1.11638e-6</td>
<td>617</td>
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<tr>
<td>Visual Inspection *</td>
<td>3.4119e-4</td>
<td>1.84428e-6</td>
<td>382</td>
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<tr>
<td>Eddy Inspection *</td>
<td>5.39682e-5</td>
<td>2.91720e-7</td>
<td>745</td>
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<tr>
<td>Worst Skill Operator *</td>
<td>2.37889e-3</td>
<td>1.28589e-5</td>
<td>280</td>
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<tr>
<td>Best Skill Operator *</td>
<td>3.38781e-3</td>
<td>1.83125e-7</td>
<td>384</td>
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<tr>
<td>Rejection crack size = 0.0 in*</td>
<td>5.39682e-5</td>
<td>2.91720e-7</td>
<td>745</td>
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<tr>
<td>Rejection crack size = 0.15 in*</td>
<td>1.79505e-4</td>
<td>9.70295e-7</td>
<td>170</td>
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</table>

NOTE: * Constant maintenance intervals of 185 days were considered.
An integrated HPC stochastic simulation framework has been implemented and demonstrated. This framework incorporates the following constitutive parts:

i) simulation of the stochastic operational environment,
ii) stochastic vehicle multi-body dynamics analysis,
iii) stress prediction in subsystems and components,
iv) stochastic progressive damage analysis, and
v) component life prediction including uncertainty from maintenance
vi) reliability prediction at the component and the system levels.

Remarks:
- The road surface roughness and the road topography variations impact severely on the HMMWV suspension predicted life. The non-Gaussian variations of road profiles have a significant impact on predicted fatigue life.
- The statistical nonlinear correlation patterns between the stochastic life model parameters, and the limited number of FEA simulations impacts significantly on FLSS reliability.
- Traditional Bayesian updating could often fail, especially when the number of test data is small. Including additional information on predicted data bias is key.