Virtual Load Development & Fatigue Analysis

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Leading Edge Engineering

- Provide Simulations Services and Software, with focus on Dynamics, Fatigue and Load Development
- Strong background in the off-highway industry
- Focused on helping our customer implement simulation processes and tools to drive product development
- MSC VAR
- Founded 2001
Virtual Loads/Fatigue Process

• **What it is**
  – Set of tools to develop system level models to understand system dynamics and predict fatigue life
  – Use in the concept development phase to generate load data for untested systems or to iterate through design alternatives

• **What it is NOT**
  – Doesn’t replace physical testing – it augments it
  – Physical testing is critical to validate assumptions simulation inputs
Motivation behind Virtual Loads/Fatigue Process

• **Majority of our customer base is using FE tools to validate and drive product design processes**
  – Off-Highway customers are typically working with structural components and weldments, concerned about fatigue issues
  – Typically using some type of “screening loads” (G load, max or limit load, etc.), then apply each load individually to Stress-Life fatigue analysis
  – Difficulty correlating fatigue failures with screening load failure locations and life predictions

• **Limitations of Measured Duty Cycle Fatigue Loads**
  – Acquisition of measured loads are expensive and time consuming tasks
  – Measured loads are vehicle/component dependent and scaling to other vehicles can be difficult
  – Difficult to acquire data for new events and vehicles to be relevant during development process
Components of a Virtual Loads/Fatigue Process

- **Software**
  - MBD Tool - Adams
  - FE Solver - Nastran
  - Fatigue Analysis – MSC Fatigue

- **System Models - Duty Cycle Events**
  - Simply mimic test track, or complete set of events

- **Fatigue Analysis Method**
  - Quasi-Static or Dynamic Analysis
  - Stress & Strain life Algorithms
  - Weld Fatigue Analysis

- **Damping (how to measure and define)**

- **Correlation to Test**
Virtual Load Development – System Models

- Multi-Body Dynamics System Models to virtually simulate dynamic events and predict loads
- Incorporate Flexible Components and control Systems
- Loading is used to calculate stress histories, then predict fatigue life
## Duty Cycle Example

<table>
<thead>
<tr>
<th>Vehicle Model</th>
<th>MA-1</th>
<th>MA-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cycle Time (min)</td>
<td>25.0</td>
<td>22.0</td>
</tr>
<tr>
<td><strong>Loading</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digging</td>
<td>1.30</td>
<td>1.20</td>
</tr>
<tr>
<td>Soft Material</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Rock</td>
<td>0.85</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Transition to Haul</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washboard</td>
<td>0.85</td>
<td>0.75</td>
</tr>
<tr>
<td>Ditches (Straight)</td>
<td>1.10</td>
<td>0.50</td>
</tr>
<tr>
<td>Ditches (Diagonal)</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Hauling</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trans Shift</td>
<td>9.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Washboard</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Braking</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Haul Slope</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td><strong>Dump</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dump</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Brake Stop</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Transition to Return</strong></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1.00</td>
<td>0.75</td>
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</table>
Fatigue Analysis Processes

• **4 Basic Methods**
  
  – *Quasi (Pseudo)-Static*
    • Unit loads are individually scaled by corresponding load, then summed at each point in time to calculate stress histories
  
  – *Transient*
    • Stress histories are calculated by FEA at each point in time
  
  – *Modal Participation Factor*
    • Modal stresses are multiplied by modal participation factor, then summed at each point in time
  
  – *PSD Approach*
    • Input PSD uses a transfer function to calculate output stress PSD
Simple Problem description

What is the stress history and what is the fatigue life?

Local Stress Histories

\[ \sigma_{ij}(t) \]

Fatigue

\[ P_1(t) \quad P_2(t) \]

\[ P_1(t) \quad P_2(t) \]
Pseudo Static

\[ \sigma_{ij}(t) = \sum_{k} P_k(t) \left( \sigma_{ij,k} \right) \]

**Stress time signal at element \( ij \) in some predetermined direction**

\[ \sigma_{ij,1} \times \text{Real Load } P_1(t) + \sigma_{ij,2} \times \text{Real Load } P_2(t) = \sigma_{ij}(t) \]

\( \sigma_{ij,k} = \text{Stress for unit load case } k \)

\( F_L < \frac{1}{3} F_N \)
Modal Participation Factor method

Modal stress results at element $ij$ for modes $1,2,\ldots,m$

$$
\sigma_{ij}(t) = \sum_{m} \phi_m (t) \sigma_{ij,m}
$$

Combine Participation Factors for each mode

Stress time signal at element $ij$ in some predetermined direction

$F_L > 1/3 F_N$
Modal Participation Factors

The basis of the Modal Participation Factor (MPF) method is that each loading input can be split up into the contribution factors associated with each mode shape for the structure. In NASTRAN both the modal stresses and modal participation factors can be extracted from a single sol 112 analysis. In Adams, the modal participation factors can be exported from a simulation for each flex body. The modal superposition is then calculated as follows:

\[
\sigma(t) = \sum_i \phi_i(t) \sigma_i
\]

where \( \sigma(t) \) is the output stress tensor

\( \sigma_i \) is the stress tensor for mode \( i \)

\( \phi_i(t) \) is the modal participation factor for mode \( i \)
Is it necessary to include dynamic response?

Is the highest possible frequency of loading greater than one third of the 1st natural frequency?

\[ F_L < \frac{1}{3} F_n \]

Static Response

Transfer function

Highest loading frequency

1st natural frequency

frequency
Simulation Process – Quasi Static

Create MBD Model - Adams
- Build all kinematic connections, add track and tire data

Run Simulation - Adams
- Import MNF files for Flex Body components, run simulation for CW and CCW track

Fatigue Analysis – MSC Fatigue
- Using scale and combine technique, the analysis scales it and then linearly combines the stress state for each load component at each point in time for all elements in the model

Export Load Data - Adams
- Export load data for each attachment point on frame. This uses Adams/Durability option to export loads in proper format

Modal Analysis - Nastran
- Run normal modes analysis in Nastran and create the MNF (Modal Neutral File) file for Adams – This is the flex body representation that allows deformation in Adams simulation

Fatigue Results - Patran
- Analysis creates contour plots of results, which are then plotted in FEA post processor to view life results. In this case, scale is in hrs, with a goal of 260 hrs (equal to time on test track)

Create FEM - Patran
- Midplane geometry, create Finite Element Mesh – Midplane surfaces and meshing done in Patran

Limiting Loads & CP
Simulation Process – Modal Participation Factors

Create MBD Model - **Adams**
- Build all kinematic connections, add track and tire data

Run Simulation - **Adams**
- Import MNF files for Flex Body components, run simulation for CW and CCW track

Fatigue Analysis - **Adams**
- Using modal participation technique, the analysis takes modal stress results, scales it by the proper participation factor, then sums the stress state for each mode at each point in time for all elements in the model

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What is Failure

- Crack too big
- Total separation
- Loss of functionality
- Glue joint breaking
- Delamination
- Fatigue
- Durability
- Damage Tolerance
- Loss of stiffness
Fatigue Technology
The Three Basic Methods

• **S-N (Stress-Life)**
  Relates *nominal* or *local elastic stress* to *fatigue life*

• **e-N (Strain-Life)**
  Relates *local strain* to *fatigue life*

• **Weld Fatigue BS5400/7608**
  Uses set of S-N curves to classify weld, based on “nominal stress” at a reference distance from weld toe
Summary of “variations on a simple approach”

1. Constant amplitude fully reversed cycles in to S-N diagram
   ![Diagram of constant amplitude fully reversed cycles]

2. Block loading
   ![Diagram of block loading]

3. Mean stresses
   ![Diagram of mean stresses]

4. Irregular sequences
   ![Diagram of irregular sequences]

5. Notches, etc, etc, etc.

- Palmgren Miner
- Rainflow Cycle Counting

Log S
Log N
Low Cycle vs. High Cycle (deformation based)

Note that Strain-Life is OK for all N

- LCF, say $<10000$
- HCF, say $>10000$
- $NS^m = K$
Strain Life

Cyclic Stress Strain Curve

Neuber Equation

Solution point

$K_f$

$s$

$e$

$\sigma$

$\varepsilon$
Stress-Life Method Summary

**Strengths**
- Analysis is simple, and needs few material constants – performed by hand
- Works well for long file, constant amplitude designs
- Significant amount of literature available for variations of surface finish, load configuration, environment, etc.

**Weaknesses**
- Method is completely empirical, and lacks physical insight
- Care must be taken when extrapolating relationships beyond range of data used to develop them
- True stress-strain response is ignored
  - This limits method to long life applications
  - Causes problems with non-zero mean load histories
- Does not distinguish between crack initiation and propagation, makes it difficult to apply towards the concept of damage
Strain-Life Method Summary

• **Strengths**
  – Plastic strain is accurately modeled, which allows method to be used in high strain/low cycle analysis
  – Method accounts for residual mean stress and sequence effects in load histories

• **Weaknesses**
  – More complicated to perform (need software program)
  – Method predicts crack initiation, cannot be used for propagation
  – Some aspects are empirical in nature ($K_f$ or $K_t$ in the Neuber analysis)
Method developed in the 1970s with an extensive study carried out in the performance of welded joints in structural steels. This study resulted in the development of BS5400, and later BS7608. S-N Curves for welded steel joints are defined using nominal stress ranges vs. life in cycles corresponding to different weld classifications (B, C, D, F, etc).

Assumptions in BS7608:
- Stress concentrations and defects in welds make them difficult to analyze with physics-based formulas.
- BS7608 assumes stress ranges will be calculated as if welds did not exist, i.e., the nominal stress is calculated using engineering stress analysis.
- Stress concentrations due to the weld geometry are included in the S-N curves.
BS7608 Classification Diagrams
BS7608 Classification Curves

-2s S-N curves

Endurance $N$, cycles

Stress range $S$, N/mm$^2$
General Modeling Rules

- For thin structures, this may require a fine mesh
- Results are sensitive to element quality as well

Usually 2 elements between midplane and weld toe
BS7608

Advantages

• Applies to all steels
• Probability of failure can be defined
• No mean stress correction required
• The standard includes the required S-N curves

Disadvantages

• Based on nominal stresses near the weld toe, but distance from the weld toe is subjective
• Decision on which weld curve to use is open to interpretation and based not only on geometry but also loading
• Sensitive to element size and shape
Modal Damping Table in FE Model

- This damping table calculated by correlating test and simulation models.
Generalized Damping from FEA

- Accurate damping models are paramount for accurate life predictions
- FE models can have complex material and structural damping effects and have be correlated to test
- Used Generalized Damping in Adams to import damping matrix from MSC Nastran into the MNF.
- Modal, Structural and Rayleigh damping can be added
Simulation vs. Test Correlation – Stress and Acceleration plots

When plotting stress and acceleration time signals, very rarely will they match the waveform exactly. Look for Max/Min values, appropriate frequency content, etc.

Place strain gauges in areas of nominal strain.
Simulation vs. Test Correlation – Acceleration PSD’s

- Graph PSD’s of measured accelerations vs. predicted.
- Ensure that simulation is predicting frequency content and power correctly.
- Identify unmatched areas, and review modal content, damping and other inputs to improve correlation.
- To match the engine excitation, we applied a signal generator of 60 and 120Hz at the engine mount points, and used the PSD plots to adjust the amplitude.

Spikes at 60 and 120Hz are caused by engine vibrations.
Virtual Loads/Fatigue Process Implementation

• Developing and implementing a Virtual Loads/Fatigue process requires at least 3 different software components

• Typically the knowledge required for the MBD/FEA/Fatigue domains is split between two analysts

• When developing a plan to implement this process, start slow. Implement, validate and correlate one component at a time.