In Co-Simulation with Abaqus

Fatigue Strength Analysis of Commercial Vehicle Engine Mounts
Contents

• Introduction

• Fatigue simulation method

• Determining fatigue strength / durability parameters

• Determining the local stress
  – Material properties for FEM simulation
  – Simulation of deformations

• Examples
  – Three-component simulation and testing

• Summary
Introduction

• **Task of engine mounts:**
  – Absorption of loads caused by operation of the engine and by excitation from the road surface
  – Vibration isolation and damping

• **Large Displacements** have to be withstood

• The necessary elasticity can be obtained by using elastomeric mounts with often very **complex geometries**.

• Therefore **fatigue strength** of engine mounts **is very important** and should be considered in an early design phase before the first prototypes are built.
Introduction

Initial situation
► Estimation of vibration fatigue based on single FEM simulations.
► Tasks:
  ▶ What is the critical load cases?
  ▶ Considering nonlinearities: material model, big displacements, contact and folds.

Objective
► Simulation Method which allows
  ▶ the assessment of vibration strength of engine mounts
  ▶ based on n-dimensional-component loads
  ▶ in an early development phase
  ▶ for meaningful results before the first prototypes have been built.
Testbench 3 Channel-Loading
Testbench 3 Channel-Loading
Fatigue simulation method

Determining fatigue strength

S/N curve experiments with different loads

Component load – local damage value

Fatigue strength: Wöhler curves, Haigh diagrams

Determining the local stress

Load pattern of the mount

Discretization of the load pattern

Material model

FEM simulations

Local stress curve for every node of the FEM-model

Fatigue Simulation

Rainflow count
Damage accumulation
Critical plane method

Failure theory

Stress
Strain, Energy

Damage results
Fatigue simulation method

Determining fatigue strength:
- Wöhler experiments with different loads
- Component load – local damage value
- Fatigue strength: Wöhler curves, Haigh diagrams

Determining the local stress:
- Load pattern of the mount
- Discretization of the load pattern
- Material model
- FEM simulations
- Local stress curve for every node of the FEM model

Failure theory:
- Stress
- Strain
- Energy

Fatigue Simulation:
- Rainflow count
- Damage accumulation
- Critical plane method
- Damage results
Determining fatigue strength

- Material from literature* was used
  - No specimen fatigue data for this engine mount material available
- Loads from literature*
  - Several constant load amplitudes with different R-ratios tested
  - 33 tests with constant amplitude
  - At least 2 specimens per load level
- Haigh Diagram for 1E5 LC was used for the NR material

- Hourglass test samples
  - Signal: Force-controlled-signal
  - Load cycles until failure are counted


Determining fatigue strength

Force-stress relationship

Force /Cycle curves from tests

S/N curves

Failure theory

Stress
Strain, Energy

Force-stress relationship generated by FEM-Simulations

Example: F-σ Diagram for different materials
Determining fatigue strength

Haigh-Diagram

Amplitude Stress [MPa]

Mean stress [MPa]

NR FLAMM DISS

Measurement


Date: 2014  Author: FEMFAT SUPPORT  © ECS / Disclosure or duplication without consent is prohibited
Fatigue simulation method

Determining fatigue strength

- Wöhler experiments with different loads
- Component load – local damage value
- Fatigue strength: Wöhler curves, Haigh diagrams

Determining the local stress

- Load pattern of the mount
- Discretization of the load pattern
- Material model
- FEM simulations
- Local stress curve for every node of the FEM-model

Fatigue Simulation

- Rainflow count
- Damage accumulation
- Critical plane method
- Stress
- Strain, Energy
- Damage results
Fatigue simulation method

**Determining fatigue strength**
- Wöhler experiments with different loads
- Component load – local damage value
- Fatigue strength: Wöhler curves, Haigh diagrams

**Determining the local stress**
- Load pattern of the mount
- Discretization of the load pattern
- FEM simulations
- Local stress curve for every node of the FEM-Model

**Failure theory**
- Stress
- Strain, Energy

**Fatigue Simulation**
- Rainflow count
- Damage accumulation
- Critical plane method

**Damage results**
Determining the load
Material properties for FEM simulation

- **Workflow:**
  - **Measurement:**
    - Determine the Force-Displacement Relationship with a specimen on the test bench
  - **FEA:**
    - Calibration of the material model with the measured data

- Material properties are hyper elastic, the viscoelasticity was neglected (low Shore-Hardness of engine mount material)
Determining the local stress

Wöhler experiments with different loads
Component load – local damage value
Fatigue strength: Wöhler curves, Haigh diagrams

Determining the local stress

Load pattern of the mount
Discretization of the load pattern
Material model
FEM simulations

Local stress curve for every node of the FEM-model

Fatigue strength

Fatigue strength: Wöhler curves, Haigh diagrams

Fatigue Simulation

Rainflow count
Damage accumulation
Critical plane method

Failure theory

Stress, Strain, Energy

Damage results
Determining the load stress
Simulation of deformations - basis

Basis:

► three-axis load-time signal (red curve in the right plot)
► It is not possible to simulate such complex load history transient (analysis time, amount of data)
Determining the load
Simulation of deformations - discretization

► Basis:
  ► three-axis load-time signal (red curve in the right plot)
  ► It is not possible to simulate such complex load history transient

► The operating space of the signal will be discretized
  ► This is done by enclosing it by a cuboid with a pattern of simulation results (symbolized by blue stars).
  ► The simulation results are generated by FEM-simulations in vertical direction (blue lines) from top (blue surface) to bottom.

► Subsequently: Interpolation for every time-point of the load-time signal

New FEMFAT Tool ELASTOLOADS
Fatigue simulation - Method and concept

Determining fatigue strength
- Wöhler experiments with different loads
- Component load – local damage value
- Fatigue strength: Wöhler curves, Haigh diagrams

Determining the local stress
- Load pattern of the mount
- Discretization of the load pattern
- Material model
- FEM simulations
- Local stress curve for every node of the FEM model

Failure theory
- Stress
- Strain
- Energy

Fatigue Simulation
- Rainflow count
- Damage accumulation
- Critical plane method
- Damage results

Determining fatigue strength

Fatigue Simulation
Fatigue simulation
Method and concept

- Modified channel based multiaxial fatigue analysis
  - Method of critical cutting plane
    - Rainflow-counting of 3D normal stress in critical cutting plane (acc. damage hypotheses)
    - Channel based method
      - For each FE-result one corresponding channel
      - For each channel specified interpolation factors are applied, all others are 0
  - Linear damage accumulation

► Influence of mean stress is taken into account based on R-ratios

Date: 2014  Author: FEMFAT SUPPORT  © ECS / Disclosure or duplication without consent is prohibited
Example: 3 channel load
Simulation and testing

- Checking the simulation method with two different mounts and one virtually modified version

- Test
  - Excitation: by hydraulic cylinders
  - Signal measured on the real vehicle

- Simulation
  - Abaqus/Explicit solver was used because of contacts (and folds, …)
  - Consideration of the test bench including the connecting stiffnesses
  - Failure theory: Normal tension stress in critical cutting plane
Example: 3 channel load Simulation and testing

- Load: 3 channel Road-Load-Data
- 3 x 3 and 5 x 9 (higher resolution) discretization in x-y plane
- 9 and 45 FEM simulations
- 9 Increments in z-direction
- The fatigue simulation is thus based on 81 and 405 FEM results (channels) respectively

- The multiaxial fatigue simulation was done with FEMFAT channelMax
- New Tool ELASTOLOADS for the special needs of the presented method was used
- Failure theory: Normal stresses in the critical cutting plane
**Example: 3 channel load**
**Simulation and testing**

---

**Benchmark data**

- Load: 3 channel Road-Load-Data (RLD)
- Test signal mixed from measured RLD
- Signal includes 5 different manoeuvres
- Signal ~38000 time points
- 700 Repeats = 100% Real time
- Test bench >70h for 700 Repeats
- 2 different engine mounts tested

---

**TESTING**

---

**SIMULATION**

- Load: 3 channel test bench excitation
- Test bench signal directly used
- Damage analysed for 1 repeat => total repeats until crack
- Complete simulation chain takes less than < 40 h (depending on the mount and resolution)
- 3 different engine mounts simulated
- Estimation of the life increase of the third not tested mount
Example: 3 channel load
Simulation and testing

**Abaqus COARSE RESOLUTION:**
9 Analyses  
Duration: ~4h with 12CPUS

**FEMFAT COARSE RESOLUTION:**
75 of 81 channels,  
~38000 timepoints/channel  
3D cutting plane = 218/node  
No channel- and node filtering  
Duration: ~11h with 12CPUS

Total analysis time = ~15h

**Abaqus FINE RESOLUTION:**
32 Analyses  
Duration: ~14h with 12CPUS

**FEMFAT FINE RESOLUTION:**
215 of 405 channels  
~38000 timepoints/channel  
3D cutting plane = 218/node  
No channel- and node filtering  
Duration: ~25h with 16CPUS

Total analysis time = ~39h

TEST TIME UNTIL CRACK:
TOTAL TIME = ~100h

TEST TIME UNTIL STOP:
TOTAL TIME = ~115h
Example: 3 channel load Simulation and testing

- The point of failure compared to test is well predicted
- The predicted repeats differ with a factor of 1.35 (coarse) respectively 1.27 (fine) from the test
- Increasing the resolution leads to a better correlation
- The crack starts in the outer radius

**Damage at test**

Crack after ~960 repeats

**Fatigue simulation result**

Coarse resolution ~712 repeats
Fine resolution ~757 repeats
Example: 3 channel load
Simulation and testing

**Mount R6**
41000 Nodes
35000 Elements

**Abaqus** COARSE RESOLUTION:
- 9 Analyses
- Duration: ~1.5h with 12CPUS

**FEMFAT** COARSE RESOLUTION:
- 75 channels, ~38000 TP/chan.
- 3D cutting plane = 218/node
- No channel- and node filtering
- Duration: ~6h mit 10CPUS

Total analysis time = ~8h

**Abaqus** FINE RESOLUTION:
- 32 Analyses
- Duration: ~5.5h with 12CPUS

**FEMFAT** FINE RESOLUTION:
- 215 channels, ~38000 TP/chan.
- 3D cutting plane = 218/node
- No channel- and node filtering
- Duration: ~15h mit 10CPUS

Total analysis time = ~21h

**TEST TIME UNTIL CRACK:**
- TOTAL TIME = ~170h

**TEST TIME UNTIL STOP:**
- TOTAL TIME = ~ 300h
Example: 3 channel load
Simulation and testing

▶ The failure point of the test is well predicted
▶ The predicted repeats differ with a factor of 1.35 (coarse) respectively 1.27 (fine) from the test
▶ Increasing the resolution leads to a better correlation
▶ The crack starts in the radius

<table>
<thead>
<tr>
<th>Damage at test</th>
<th>Fatigue simulation result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack after ~1630 repeats</td>
<td>Coarse resolution ~1212 repeats</td>
</tr>
<tr>
<td></td>
<td>Fine resolution ~1287 repeats</td>
</tr>
</tbody>
</table>
Example: 3 channel load
Simulation and testing

**Abaqus COARSE RESOLUTION:**
- 9 Analyses
- **Duration:** ~2h with 12CPUS

**FEMFAT COARSE RESOLUTION:**
- 75 channels, ~38000 TP/chan.
- 3D cutting plane = 218/node
- No channel- and node filtering
- **Duration:** ~6h with 12CPUS

**Total analysis time = ~8h**

---

**Abaqus FINE RESOLUTION:**
- 32 Analyses
- **Duration:** ~6h with 12CPUS

**FEMFAT FINE RESOLUTION:**
- 215 channels, ~38000 TP/chan.
- 3D cutting plane = 218/node
- No channel- and node filtering
- **Duration:** ~26h with 12CPUS

**Total analysis time = ~32h**

**Testing:**
- No Data available, because only design variant
Example: 3 channel load
Simulation and testing

- The failure point remains the same
- The predicted repeats increase with a factor of 1.47 compared to the mount R6 variant

<table>
<thead>
<tr>
<th>Version</th>
<th>R3</th>
<th>R6</th>
<th>R6 mod</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coarse</strong></td>
<td>715</td>
<td>1212</td>
<td>1799</td>
</tr>
<tr>
<td>Improvement</td>
<td>1</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Fine</strong></td>
<td>757</td>
<td>1287</td>
<td>1887</td>
</tr>
<tr>
<td>Improvement</td>
<td>1</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Test bench</strong></td>
<td>960</td>
<td>1630</td>
<td>2390*</td>
</tr>
<tr>
<td>Improvement</td>
<td>1</td>
<td>1.7</td>
<td>2.5*</td>
</tr>
</tbody>
</table>

*Estimated based on simulation results
Summary

A method was presented which allows the assessment of dynamic strength of engine mounts in an early development phase, before the first prototypes have been built.

The simulations show a good prediction quality even with less support points.

The prediction quality increases with higher resolution (fine resolution).

Due to fast simulation and good prediction quality it is possible to decrease prototype numbers and tests.

Additionally the simulation time can be reduced. Due to integrated filtering with FEMFAT:
- Channel filter => reduction of time points and channels
- Cutting plane filter => reduction of the analysed cutting planes
- Node filter => reduction of the analysed nodes

The method is independent of the time signal length and channels (real RLD instead of mixed signals can be used).

The method in combination with Abaqus and FEMFAT is fully automated and approved.

Important for the prediction quality:
- Good representation of the material model in Abaqus
- Simulation of large deformation (folding is possible to be considered, too)
- Determining of the fatigue strength of the used rubber material for FEMFAT

Application

- Assessment of geometric variants during the development phase
- Assessment of load spectra on the basis of local effects
- In general to consider nonlinear behaviour (local contact, non linear geometric behaviour)
- Additional axis like temperatures, inner pressure,… could be applied (4D, 5D,… Simulation)
The future is ours to make.