Lebensdaueranalysen im Zeit- bzw. Frequenzbereich

Axel Werkhausen (ECS), Gerhard Spindelberger (ECS)
ECS - Historical Overview

- 1864: J. & F. Werndl & Coomp. STEYR
- 1899: J. PUCH Erste Steierm. Fahrrad-Fabriks AG
  Graz
- 1899: Österr. DAIMLER Motorenges. Wr. Neustadt
- 1914: PUCHWERKE AG
- 1914: J. & F. Werndl & Coomp. STEYR
- 1926: STEYR-WERKE AG
- 1928: AUSTRO-DAIMLER-PUCHWERKE AG
- 1929: TORONTO CANADA
- 1934: STEYR-DAIMLER-PUCH AG
- 1957: MAGNA
- 1989: Truck Division of SDP acquired by MAN
- 1995: Engineering Center Steyr
- 1998: Engineering Center Steyr
- 2001: MAGNA STEYR
- 2005: MAGNA POWERTRAIN
ECS - Location / Area

1. Proving Ground
2. Office Building
3. Production, Engine- & Drivetrain Testing
4. Fatigue Lab
5. Chassis Dyno
Testing Services
Fatigue Testing & Measurement Engineering

- Servo-hydraulic Fatigue Test
  - Road simulators up to 24 channels
  - Axel test benches up to 12 channels
  - Component test benches
  - Test bench development & consulting

- Measurement data logging and processing
  - Fatigue relevant data
  - Engine relating data
Simulation Services

- Cost Management by using “Design for Manufacture & Assembly” (DFMA) Methodology and Tool
- Multi-Body-Simulation (MBS) for load and comfort
- Finite Element Analysis on fatigue, vibration and acoustics
- Simulation and optimization of the vehicle thermal & energy management
- Driving simulation determines driving performance parameters (consumption, losses, emissions, ...)
- Fluid flow calculation (CFD)
- Product & Engineering Data Management (PDM / EDM)
- PLM / SAP services (EIB)
- CAD based Dip-Coating simulation
ECS Software Products

- Dip Paint Simulation
- PLM data exchange and integration platform
- Sub-model analysis and data mapping
- Operational strength analysis based on FEM results
- Automatic calibration of engine control units
- Optimization of energy management for vehicles
- Non-linear joints for multi-body simulations
- Journal bearing model for multi-body simulations
- Automatic meshing
- NC programming system for turning, drilling and milling
- Pre- and post-processing of acoustic analysis on a modal basis

www.ecs-software.com
How to use FEMFAT MAX in Time Domain?

WHEN ???

- Direction of Principle Stresses are permanently altering
- Direction and location of forces and boundary conditions are constant
- Existing Load Histories
- More than one channel, which are generally not in phase

IMPORT

- One stress result for each channel (e.g. for unit load)
- One load history for each channel

EXAMPLEs

- Chassis parts like: Knuckles, subframes, H-Arms,...
- Body in White
- Crankshaft with modal approach
FEMFAT in the Frequency Domain

WHEN ???
- Load definition is a PSD
- Random characteristic signals
- Multiple axis can be combined

IMPORT
- Stresses from modal frequency response analysis
- PSD for load spectra per axis
- Probability model (Dirlik, Rayleigh,…)

EXAMPLE
- Engine firing excitations (high frequencies)
- Buildings (wind excitations)
- Electronics (frequencies)
- Comparison with shaker tests in laboratories
Local Stress Concept
Crack Initiation

Influences in FEMFAT
- Stress Tensors
- Stress Gradient
- Mean Stress Influence
- MultiAXial Load
- Temperature Influence
- PLASTic Deformations
- etc.

Specimen Material Data

Stress Amplitude

Load cycles

Finally: Component S/N curve including all influences
FOR EACH NODE & for each RFM entry

Stress Amplitude

Load cycles

UCS  Mean Stress  UTS
Local Stress Concept
Crack Initiation

Amplitude stress $\sigma_A$

$$\text{Endurance safety factor / damage (fatigue limit)}$$

$$\sigma_{\text{Endurance}}$$

$$\sigma_A$$

$$SF_A = \frac{\sigma_{\text{Endurance}}}{\sigma_A}$$

$$N \ (\log)$$

$$\sigma_A$$

Damage $d_1 = \frac{n_1}{N_1}$

... for a certain survival probability in %

Analyzed S/N Curve at a FE-Node by FEMFAT
Data Processing in Fatigue Analysis

- FE- Data
  - Nodes & Elements
  - Physical Properties
  - Group Data
- Stress Result Data
  - Amplitude Stress
  - Mean Stress
  - Constant Stress
- Fatigue Influences

- Load Spectra
  - Rainflow
  - Stepped
  - Synthetic

Specimen Material Data

Finite Element Method for Fatigue

- RESULTS
  - Damage Values,
  - Life
  - Endurance Safety Factors,
  - Analysis Report
Motivation for Fatigue Analysis in Frequency Domain

Signals with random characteristics!

Excitation examples:
- High frequency vibration of firing excitation
- Shaker tests (electronic devices, automotive components)
- Turbulence (aerospace)
- Wind/wave excitation (buildings)
- …

Road excitation

Acceleration excitation

Side force excitation
Frequency Domain – Fourier Transformation

Power Spectral Density (PSD) = Square of Fourier Transformed Signal = Mean Value of “Power of the signal”
Linear Time-Invariant (LTI) Systems

\[ f(t) \xrightarrow{\text{Linear Time-Invariant System}} u(t) = \int_{-\infty}^{+\infty} h(t-\tau)f(\tau)d\tau \]

\[ u(t) = h(t) \ast f(t) \]

**h(t)...Impulse-Response**

(System-Property)

![Image of LTI system diagram]

**Fourier-transformation:**

Convolution in time-domain \(\Rightarrow\) Multiplication in frequency-domain

\[ U(\omega) = H(\omega)F(\omega) \]

**Advantage:**

Simple multiplication in frequency-domain
The Equation of Motion for Linear Elastic Mechanical Systems

Dynamic Stiffness Matrix \( Z \):

\[
\left( -\omega^2 M + i\omega V + K \right) \cdot U(\omega) = F(\omega)
\]

\[
Z(\omega) U(\omega) = F(\omega)
\]

Transfer Matrix \( H \):

\[
U(\omega) = Z^{-1}(\omega) F = H(\omega) F(\omega)
\]

Input = Excitation

Output = Structural Response
Dynamic Transfer Behavior of System
Time Domain
Analysis Technique in Time Domain

Structural Analysis:

Load - Time - History

Modal Transient Response Analysis

Stress - tensor - Time - History
Modal Frequency Response

Property of Mechanical System

Modal Stresses

\[ \sum \]

Modal Transfer Functions

\[ \times \]

Stress Scaling

Unit Load Case 1

Modal Transfer Functions

Unit Load Case 1

Unit Stresses 1

Modal Transfer Functions

Unit Load Case 2

Unit Stresses 2

Modal Transfer Functions

Unit Load Case N

Unit Stresses N
Hybrid Models
FE + MBS + FEMFAT ChannelMax

Component Modes
\( \phi_1, \phi_2, ..., \phi_n \)

MBS and (E)HD
(Co - Simulation)

Modal Stresses
\( \sigma_1, \sigma_2, ..., \sigma_n \)

FE

Modal Coordinates
Channel 1
\( q_{1(t)}, \sigma_1 \)
Channel 2
\( q_{2(t)}, \sigma_2 \)
Channel n
\( q_{n(t)}, \sigma_n \)

FEMFAT

Fatigue

Additional Load Cases (Bolts,...)

Lifetime prediction of dynamic loaded parts considering dynamic effects due to natural vibrations
Analysis Technique in Time Domain

Structural Analysis:

Load - Time - History

Modal Transient Response Analysis

Stress - tensor - Time - History

Fatigue Analysis:

Cutting Plane Method
Cutting Plane Criteria

Current Cutting Plane depending on $\varphi$ and $\gamma$

\[ \sigma_{ae} = \sqrt{\sigma_{an}^2 + \left(\frac{\sigma_{alt,TC}}{\tau_{alt}}\right)^2} \cdot \tau_a^2 \]

\[ \sigma_{me} = \text{sign}(\sigma_{mn}) \cdot \sqrt{\sigma_{mn}^2 + \left(\frac{\sigma_{Yield}}{\tau_{Yield}}\right)^2} \cdot \tau_m^2 \]
Critical Cutting Plane Criteria

- HAIGH diagram and loading points are calculated for all cutting planes.

Criteria (σm=const) for critical loading point:

\[
\frac{\sigma_{a \text{ endu}}}{\sigma_{a \text{ e crit}}} \rightarrow \text{Min}
\]
Analysis Technique in Time Domain

Structural Analysis:

Load - Time - History

Modal Transient Response Analysis

Stress- tensor - Time - History

Fatigue Analysis:

Rain Flow Matrix

Cutting Plane Method
Rainflow Counting of Closed Hysteresis Loops

Rainflow

time
Rainflow Counting: Principle I

Pictures from Radaj: Ermüdungsfestigkeitsnachweis
Rainflow Counting: Principle I

Classes

Time t

Rainflow counting

Closed Hysteresis

Points

Classes

Strain
RainflowMatrix for Time-Domain

Rainflow Matrix / Load History

Damage according normal stress lateral to the weld seam direction

Damage in Node Number: 102: 12.46337e-003
Content according to closed Load Cycles: 95.80%
Content according to open Load Cycles residual: 4.20%

Time Load History

Moments

Force
Analysis Technique in Time Domain

Structural Analysis:

Load - Time - History

Load

Time

Modal Transient Response Analysis

Stress - tensor - Time - History

Stress

Time

Fatigue Analysis:

S-N-Line

S

N

DAMAGE

Rain Flow Matrix

Cutting Plane Method

© ECS / Disclosure or duplication without consent is prohibited
MINER Rule in FEMFAT

Load spectrum entry $A_1, M_1, n_1$

Damage $d_1 = \frac{n_1}{N_1}$

Crack is initiated at $d_{total} = 1$

Analyzed S/N Curve at a FE-Node by FEMFAT...

... for a certain survival probability in%
Linear Damage Accumulation by Palmgren Miner

\[ D = \sum d_i = d_1 + d_2 + d_3 + \ldots + d_n \]

\[ d_i = \frac{n_i}{N_i} \]

Analysed S/N Curves at a FE-Node by FEMFAT
The Frequency Domain
Analysis Technique in Frequency Domain

Structural Analysis:

Load in Frequency Domain

- Load -PSD
- Frequency

Modal Frequency Response Analysis

Stress-tensor in Frequency Domain

- Stress-PSD
- Frequency

Fatigue Analysis:

S-N-Line

- Probability Density Function

DAMAGE

PDF: Dirlik, Rayleigh

Cutting Plane Method
Multiaxial Load Cases / Frequency Domain

Structural – Analysis: Frequency Response

- Unit Load Case 1
- Unit Load Case 2

FE – Solver

Frequency Response – 3 Mode System

\[ \Delta \omega \approx 2\delta \]

DAMAGE – Analysis:

- Auto -PSD 1,1
- Auto -PSD 2,2
- Cross -PSD 1,2

\[ \sum \]

Stress - PSD

Multiaxial Fatigue - Analysis

Damage

- frequency range < modal base
- spectral resolution \(\Leftrightarrow\) damping
Method of Modal Reduction (to Reduce Size of Equation System)

Modal Stresses - FILE.OP2
- 78 Hz
- 156 Hz
- 187 Hz

Modal Transfer Functions - FILE.PCH

Unit Load Case 1

Unit Load Case 2

Unit Load Case 3
Stress PSD Matrix – Cutting Plane Method

\[
G S^2_{\text{equi}} (\omega) = \sum_{i,j \in I} a_i a_j \cdot G_{\sigma_i \sigma_j}
\]

6 x 6 Stress PSD
Equivalent Stress Methods

Supported Methods:
- von Mises Stress
  \[ \sigma_{eq} = \sqrt{\sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 - \sigma_{11}\sigma_{22} - \sigma_{22}\sigma_{33} - \sigma_{11}\sigma_{33} + 3\left(\tau_{12}^2 + \tau_{23}^2 + \tau_{13}^2\right)} \]
- Normal Stress in Critical Plane
- Equivalent Stress in Critical Plane
- Modified Equivalent Stress in Critical Plane
- Automatic (brittle ↔ ductile materials)

According to FKM-Guideline, values for shear fatigue strength factor \( k \) are:
- Steel: \( k = 1.73 \)
- Nodular cast iron: \( k = 1.54 \)
- Cast aluminum alloys: \( k = 1.33 \)
- Gray cast iron: \( k = 1.18 \)

FEMFAT SPECTRAL uses statistically correct equivalent stress PSDs!
Probability Model and Damage Analysis

Aim: Estimation of stochastic Amplitude-Stress-Distribution from PSD

**Inertia of Moment**

\[ m_i = \int_0^{\infty} \omega^i G_{\sigma\omega}(\omega) d\omega \]

- \( m_0 \) ... Area
- \( m_1 \) ... Center of Area
- \( m_2 \) ... Geometric Moment of Inertia

**PDF**

Rayleigh -> narrow band signals

Dirlik -> broad band signals

\[ D_{\text{total}} = \int_0^{\infty} p(\sigma_a) D(\sigma_a) d\sigma_a \]
Example: Battery-Carrier

Node Label: 92493
Damage M/Mod: 1.89e-009
Stress Ampl.: 18.4
Mean Stress: -2.24
Supported Influence Factors

- Probability model (Dirlik, Rayleigh)
- Stress Gradient (endurance limit, slope/Cycle limit)
- Surface Roughness
- Constant Stress (bolt pre-tension)
- Modified Haigh Diagram (ultimate tensile strength)
- Size Influence
- Statistical Influence
- Isothermal Temperature
- Rotating Principal Stresses Influence
Summary

Advantages:
- Fast method (structural analysis, fatigue analysis)
- Load-case superposition (very flexible)
- Simple combination of different load situations
- Simple simulation chain (no multi-body simulation, reverse FFT not required)

Disadvantages:
- Linear elastic behavior assumed/required (superposition)
- Less accuracy compared to time domain (no rainflow-counting; statistics)

Conclusions:
- FEMFAT SPECTRAL is a reliable and effective tool for damage analysis of multi-axially stochastically loaded systems.
The future is ours to make.