Early detection of fatigue cracks in truck trailer structures by acoustic emission testing

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Abstract

In fatigue tests, acoustic emission can be measured when cracks occur. In this work the equivalent stresses on a test specimen, modelled after a section of a truck trailer, are calculated using FEA. This information is used to determine the position with the highest probability of a crack occurring. After performing a series of fatigue tests to generate a Wöhler diagram and recording acoustic emissions, an adaptive filter for processing the signal data is presented. In a further experiment, a sample is tested in a fatigue test until acoustic emissions can be detected with the help of the presented signal processing. Further, the resulting crack is examined by preparation of a microsection. Subsequent analysis of the samples strongly indicate that the AE detection algorithms were indeed able to detect microfractures well in advance of the occurrence of failures. In this paper, the accuracy of the detections is discussed by comparing their results with those from the metallographic and microscopic examinations of the tested samples. The use of external variables to validate the detections is also presented, as well as the experimental set-ups and post-processing strategies.

1. Introduction

Condition monitoring by acoustic emission (AE) testing is used in a wide range of applications, e.g. in the fields of composite materials (1), aerospace (2) or civil engineering (3). Particularly in transportation, the demand for lightweight structures increases the risk of fractures (4). If such fractures, usually fatigue failures, are detected early, catastrophic failures can be avoided. However, the detection of microfractures by means of acoustic emissions is hindered by their very small amplitudes.

In this work, piezoceramic sensors were used to continuously record structure-borne sound during dynamic fatigue tests of S700MC steel samples. These consisted of sections of truck trailer frames where the highest probability of fatigue failure was estimated by a combination of empirical usage data and finite element analysis (FEA). In a set of fatigue tests, automatic detection algorithms continuously monitored acoustic emissions. As soon as the AE signals indicated the emergence of fatigue cracks, the test was interrupted.
2. Empirical usage data, finite element analysis (FEA) and fatigue tests

2.1 Typical damage cases

With help of the analysis of customer complaints, the main problems with the construction of a trailer frame can be identified and corrective measures in form of repair orders and design changes be defined. In many cases, the approach consists in introducing a stiffening in the form of an additional sheet metal or in renewing the welds. If all critical positions are reinforced by appropriate constructions, this leads to an increase in the total weight and thus contradicts the idea of lightweight construction. While many issues in the region near to the trailer axes could be eliminated by the defined changes, the cross connections remain a problem. By using a steel of higher quality grade, problems like the material failures in the crossbeams were eliminated. Nevertheless, the welds of these constructions tend to fail during cyclic loading. An example for these structures and failures can be found in (5).

2.2 Finite element analysis

Finite element analysis is a powerful tool to calculate the mechanical stress in complex geometries. In this case, the used test samples are examined in order to find the point where the probability for an initiating crack is the highest. As the used material is a ductile steel of the type S700MC, the von Mises stress is calculated to give an estimation of the most probably point of failure. The equivalent tensile stress is calculated by

\[
\sigma_v = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x \sigma_y - \sigma_x \sigma_z - \sigma_y \sigma_z + 3 (\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2)},
\]

where \(\sigma\) are the normal stress components and \(\tau\) are the shear stress components (6). Figure 1 shows the resulting von Mises stress on the used test specimen, computed using finite element analysis.

**Figure 1.** Simulation of the von Mises stress on a longitudinal chassis sample.
The highest equivalent tensile stress occurs at the point highlighted in figure 1. The stress is greater in this area and pronounced in a larger area than in the other comparable edges. This is due to the rejuvenation of the retaining plate. In a fatigue test a crack will most likely emerge at this point.

2.3 Fatigue behaviour of longitudinal chassis sample

The determination of the fatigue behaviour of a longitudinal chassis sample has been carried out in a resonant testing machine under pulsating, displacement controlled tensile stresses ($R = \sigma_l/\sigma_o = 0.1$) with a frequency of 10 Hz. The maximum stress $\sigma_o$ has been varied in a range between 20 – 67 MPa to determine the dependence of the maximum stress $\sigma_o$ on the number of cycles to failure $N_B$ in form of a rough Wöhler diagram. A crack propagation under displacement controlled testing conditions causes an increase of the displacement due to the decreasing stiffness of the sample with increasing crack length. The cycles to failure $N_B$ have been defined for the event of a machine displacement increase of 1.5 mm.

The diagram in figure 2 (left) shows the results of the carried out fatigue tests, whereby a maximum stress of 20 MPa has resulted in a fatigue-tested specimen without rupture.

![Figure 2: Dependency of $\sigma_o$ on the number of cycles to failure $N_B$ (left), typical appearance of a fatigue crack at longitudinal chassis sample with $\sigma_o = 50$ MPa and $N_B = 124307$ (right).]

3. Data Processing

3.1 Adaptive Filtering of AE Signals

Due to the broad pulsating spectrum of the recorded acoustic signals, it is necessary to apply a filter to the data. When using ordinary FIR bandpass filters it is necessary to set the passband and stopband edges properly. If the signal spectrum gets broadens or even narrows, the filter does not fit to the signal anymore. AE signals differ from the machine or friction noise. The machine noise is present all over the fatigue test with oscillating amplitude and a varying but limited frequency range, whereas AE signals occur in broadband bursts. With this knowledge a spectral subtraction filter is used to filter the signal. For this filter first a short time spectrum $S_{yy}(\Omega_i)$ of the measured sequence is estimated. The signal is modelled by $S_{yy}(\Omega_i) = S_{nn}(\Omega_i) + S_{ss}(\Omega_i)$, where $\Omega_i$ is the
normalized angular frequency, $S_{yy}(\Omega_i)$ is the short time power spectrum of the measured signal. $S_{nn}(\Omega_i)$ denotes the spectrum of the additive noise and $S_{ss}(\Omega_i)$ is the short time power spectrum of the desired signal. At first an initial estimation of $S_{nn}(\Omega_i)$ is set to the first measured spectrum of $S_{yy}(\Omega_i)$. After that the noise estimation is updated in every step by

$$S_{\hat{n}n}^{(k+1)}(\Omega_i) = \begin{cases} S_{\hat{n}n}^{(k)}Y_{\text{inc}} & \text{for } S_{\hat{y}y}^{(k)}(\Omega_i) > S_{\hat{n}n}^{(k)}(\Omega_i) \\ S_{\hat{n}n}^{(k)}Y_{\text{dec}} & \text{for } S_{\hat{y}y}^{(k)}(\Omega_i) \leq S_{\hat{n}n}^{(k)}(\Omega_i) \end{cases},$$

(2)

where $k$ represents the $k^{th}$ measurement. In the next step the weighting factors $w_i$ are calculated by

$$w_i = \max \left( w_{\text{min}}, 1 - \frac{S_{\hat{n}n}(\Omega_i)}{S_{\hat{y}y}(\Omega_i)} \right).$$

(3)

In the next step the spectrum of the desired signal is estimated by

$$S_{\hat{s}s}(\Omega_i) = w_i \cdot S_{\hat{y}y}(\Omega_i).$$

(4)

In the last step the time signal is synthesized by using the inverse short time fourier transform. This filtering process usually is applied to speech signals (7), where the constants $\gamma_{\text{inc}}$ and $\gamma_{\text{dec}}$ are chosen close to unity. For eliminating the machine and friction noise $S_{nn}(\Omega_i)$, a signal sample, where the desired signal $S_{ss}(\Omega_i) = 0$, is used to find the coefficients which minimize the residual

$$R = \sum_\Omega |S_{\hat{y}y}(\Omega_i) - S_{\hat{n}n}(\Omega_i)|.$$

(5)

It was found, that $\gamma_{\text{inc}} = 1.1$ and $\gamma_{\text{dec}} = 0.59$ minimize the residual for this specific application. The subsequent detection procedure (5) is carried out by setting a threshold on the short time variance of the synthesized signal.

### 3.2 Validation of detections using the machine displacement information

The propagation of cracks most likely occurs in the semicircles when the stress on the specimen increases. With the detected signals and the additionally recorded displacement signal the detections are additionally verified. Only if the amplitude of the path signal increases (the sample opens), a detection is valid. Therefore, the phase $\phi_d$ of the sinusoidal path signal is estimated and evaluated. If the phase is between $-\pi/4$ and $\pi/4$ the detection is valid, otherwise it is neglected.

### 3.3 Detection of AE during fatigue tests

During fatigue tests there are three different stages (8). In the first stage (the crack initiation phase) many AE signals can be detected. In the second stage (the slow crack propagation phase) less events can be detected. Before the repeated loading leads to a catastrophic failure, the AE activity increases rapidly in stage III, the rapid crack propagation phase. Figure 3 shows this behaviour, which was observed during the fatigue test of the sample depicted in Figure 2.
Figure 3. Cumulative number of detected AE signals during the fatigue test of a probe loaded with $\sigma_0 = 66.7$ MPa. The process is divided in three stages. Stage I: Crack initiation; Stage II Slow crack propagation; Stage III Rapid crack propagation.

4. Results

With the knowledge of the fatigue behaviour, crack detection has been carried out by acoustic emission at higher maximum loads to provoke a crack initiation at a moderate number of loading cycles. Cyclic loading was interrupted in case of a secured crack detection by AE.

Figure 4: Acoustic emission event detected in the crack initiation stage within the first 3000 loading cycles (left). Fatigue crack after 3000 loading cycles with $\sigma_0 = 66.7$ MPa (right).

In Figure 4 a sample of a processed AE signal detected in the crack initiation stage is shown. Additional detected AE signals have a worse SNR and lower amplitudes but are detected during the rising load. Due to the application of the adaptive filter, the amplitudes are normalized. The amplitudes and therefore the SNR remain very small. Further investigation of the incipient fatigue crack has been carried out by preparation of a microsection. Figure 5 shows the overview of the cross section (left). The loading
direction in the fatigue test is marked. The heat affected zone (HAZ, a) and the weld metal (b) are visible. The transition zone from the weld metal to the HAZ shows a fatigue cracking, whereby a crack of 830 µm length propagates though the HAZ at the upper side and along the weld metal (600 µm) at the lower side of the joint.

![Figure 5. Overview of the etched weld joint and the enlarged sections. Cracks can be seen in the zoomed sections (right).](image)

5. Conclusions

The FEA is a suitable tool to estimate the position of crack initiation. The applicability of the procedures to significantly more complex geometries must be verified in further experiments. The presented adaptive filter is well suited to remove time-variant noise. Where an ordinary FIR filter damps the desired signal and the noise, the adaptive filter emphasizes the short transient signals. A drawback is that the computation of the adaptive filtering is more complex than the application of FIR filters. With this kind of adaptive filtering and event detection it is possible to detect cracks even in the crack initiation phase. In a fatigue test, which was interrupted when the first events were detected, a crack with a depth of 830 µm could be measured. Cracks are detectable in a very early stage, although the AE-Signals are very short and have a very small amplitude. For the application of the signal processing in a real-time system the processing steps have to be optimized with respect to computational time. In addition, in real environments like truck trailers the signals have to be classified by further algorithms to distinguish between environment noise and AE arose by cracks.

References