Ultrasonic Monitoring and Evaluation of Very High Cycle Fatigue of Carbon Fiber Reinforced Plastics

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Motivation

- Carbon fiber reinforced plastics (CFRP): lightweight materials
- Increasingly gain significance for industrial applications such as e.g. aerospace structures and automotive body parts
- Request for nondestructive testing (NDT) techniques for quality assurance of CFRP components during production and in operation
  - covering materials characterization and defect and damage detection as well as
  - monitoring and evaluation of ageing phenomena (fatigue) and failure prediction
- CFRP components in service: subjected to oscillating loads
  - amount up to $10^{11}$ cycles in a typical lifespan of more than 20 years
  - special interest on fatigue of CFRP in the very high cycle regime, i.e. more than $10^9$ loading cycles.
Very High Cycle Fatigue (VHCF) Testing

Fatigue behavior of CFRP: investigated up to about $N=10^7$ loading cycles so far because of missing testing devices

Servo-hydraulic oscillation device (5 Hz): $\approx 6.5$ years

Mechanical resonance pulsator (100 Hz): $\approx 4$ month

Ultrasonic testing device (20 kHz) (effective test frequency $\approx 2$ kHz): $\approx 6$ days

Collaborative project with the Institute of Materials Science and Engineering at the University of Kaiserslautern, Germany (WKK):

- Development of a three point bending ultrasonic fatigue testing system
- Combination with online monitoring of the fatigue processes
Ultrasonic Fatigue Setup (University Kaiserslautern)

- Machine frame
- Loading device
- Laser vibrometer
- Plane table
- Compressed air valve
- Measuring and controlling device
- Visual display and operating unit
- Control device laser vibrometer
- Data acquisition
- Ultrasonic generator
Online Monitoring of Ultrasonic Fatigue Processes

3-point cyclic bending loading device, online monitoring of the fatigue processes

Cyclic loading device working at a frequency of $f = 20$ kHz

CFRP - sample

Offline ndt techniques
- Ultrasound
- X-ray computer tomography
- Optical Microscopy
- Active thermography

Characterization and material properties measurements of the initial state of the samples, during loading pauses and after loading and/or failure
Ultrasonic Fatigue Setup (University Kaiserslautern)

Process control via infrared camera

Loading device

Surface strain

Pulse length

Pulse pause

Temperature

Pulse length = 100 ms (f = 20 kHz)
Pulse pause = 1000 ms

Temperature control

Sample

Temperature

Shoulders

40 °C

20 °C

Thermography image
Investigated CFRP Material

Tepex® dynalite 207-C22/50 % (CF-PPS, Bond Laminates)

- Orthotropic fiber fabric layout (200 g/m³)
- Polyphenylensulfide (PPS)-matrix, thermoplastic, density: $\rho_{PPS} = 1.35$ g/cm³
- Glass transition and melting temperature: $T_g = 90^\circ$C, $T_M = 285^\circ$C
- Commercially available, reproducible quality
Sample Vibration and Radiation Time Signals During Loading

**CF-PPS,** \( N = 8.3 \cdot 10^5 \) (\( = 0.3\% \) \( N_f \))

Laser vibrometer

Microphone

\( N = \) number of loading cycles
\( N_f = \) number of cycles to failure

1. Pulse start
2. Constant amplitude
3. Active damping
4. Dying amplitude
Distorted Time Signal Because of the Laser Spot Position

\[ N = 5.3 \times 10^7 \, (= 0.001\% \, N_f) \]

Laser vibrometer

-50 0 50 100 150 200
Amplitude [µm]

Time [ms]

N: number of loading cycles

N_f: number of cycles to failure

Laser spot

Different reflection coefficients of fiber and matrix material at the sample surface
Fast Fourier Transform of Laser Vibrometer Time Signals

**CF-PPS**  \( N \): number of loading cycles, \( N_f \): number of cycles to failure

\[
N = 8.3 \cdot 10^5 \quad (= 0.3\% \, N_f)
\]

\[
N = 2.33 \cdot 10^8 \quad (= 70\% \, N_f)
\]

Increase of nonlinearity with increasing number of loading cycles

Higher harmonics distortion factor

\[
K[\%] = 100 \cdot \sqrt[2]{\frac{A_2^2 + A_3^2 + ...}{A_1^2 + A_2^2 + A_3^2 + ...}}
\]
Higher Harmonics Distortion Factor of Time Signals

CF-PPS

- Increase of the distortion factor with increasing number of loading cycles $N$ (generation of cracks and clapping or kissing bonds?)
- Strong increase followed by a step like decrease of the distortion factor (opening of delaminations?)
- Higher nonlinearity in the microphone than in the laser vibrometer time signal (nonlinearities of the loading device?)
Short Time Fourier Transform of Laser Vibrometer Signals

**CF-PPS**  
N: number of loading cycles, \( N_f \): number of cycles to failure

\[
N = 8.3 \cdot 10^5 \quad (= 0.3\% \quad N_f) \\
N = 2.33 \cdot 10^8 \quad (= 70\% \quad N_f)
\]

- Division of a time signal into increments of constant time length
- Evaluation of each increment by FFT: Time-frequency-spectrum
- Increasing time increment: increasing frequency/decreasing time resolution

\[\text{Amplitude [\mu m]}\]
\[\text{Time [ms]}\]
\[\text{Frequency [KHz]}\]
\[\text{Energy [dB]}\]
Hilbert Huang Transformation (HHT)

- Empirical mode decomposition (EMD) of a time signal (sifting process) into its intrinsic mode functions (IMF)
- Intrinsic mode function (definition)
  - The number of local extrema and the number of zero crossings are equal or differ only by 1.
  - The average of the upper and the lower envelope of the signal is zero.
- Hilbert transformation / Hilbert spectrum of each IMF
  - Instantaneous frequency of each IMF and corresponding amplitude,
  - Time frequency spectrum,
  - Marginal spectrum (time integration of the time frequency spectrum, corresponds to the FFT of the complete time signal).
Hilbert Huang Transform of Laser Vibrometer Time Signals

**CF-PPS**  
N: number of loading cycles, \( N_f \): number of cycles to failure

\[
N = 8.3 \cdot 10^5 \left(= 0.3\% \, N_f \right)
\]

\[
N = 2.33 \cdot 10^8 \left(= 70\% \, N_f \right)
\]

Small nonlinearity: variations in the fundamental instantaneous frequency
Increasing nonlinearity: increasing amplitude of the variations and higher harmonics generation with increasing variations in instantaneous frequencies
Optical Micrograph: CFRP Sample

CF-PPS

N: number of loading cycles
$N_f$: number of cycles to failure

$N = 3.3 \times 10^8$ (= 100 % $N_f$)

Imprint of a shoulder

Optical micrograph
Ultrasonic Immersion Technique: Set-up

Transducer: GE H5MP15; $f = 5$ MHz; sampling rate: 50 MS/s
Ultrasonic Images: Immersion Technique

CF-PPS

N, N_f: number of loading cycles and cycles to failure

4 mm  N = 0  15.5 mm

B-Scan

N = 3.3 \times 10^8 (= 100 \% N_f)

4 mm  15.5 mm  25 \% Offset

B-Scan

Fiber - matrix structure, delaminations; f = 5 MHz; sampling rate: 50 MS/s
Summary

- Ultrasonic fatigue system for CFRP, operation frequency of 20 kHz, developed at Kaiserslautern, Germany
- Online monitoring during fatiguing
  - Infrared camera: Temperature control to prevent overheating
  - Laser vibrometer: Sample vibration during loading
  - Microphone: Sound radiation during loading
- Evaluation of the sample vibration and radiation time signals and their change with the number of loading cycles
  - FFT: frequency spectrum, distortion factor
  - STFT: time frequency spectrum
  - HHT: time frequency spectrum, instantaneous frequency
- Offline characterization of the specimens: initial state, during loading pauses, and after fatigue
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