

Let's innovate the  
workflow together.

# Good Vibrations

Einführung in die vibrationsbasierende  
Dauerhaltbarkeitsprüfung

# Good Vibrations

<b>1. Introduction .....</b>	<b>9</b>
1.1. Definition .....	10
1.2. History.....	11
1.3. Development Process .....	12
1.4. Frequency.....	13
1.5. Vibration .....	14
1.6. Linear Systems .....	18
<b>2. Fatigue Break Down .....</b>	<b>21</b>
2.1. Woehler .....	21
2.1.1. History.....	21
2.1.2. The Wöhler Curve.....	23
2.2. Fatigue Damage .....	26
2.3. Accelerated Test.....	29
<b>3. The Vibration Test System .....</b>	<b>36</b>
<b>4. Accelerometers.....</b>	<b>38</b>
4.1. Type of Sensors.....	38
4.1.1. Contactless Sensors.....	38
4.1.2. Contact Sensors.....	40
4.1.3. Piezoelectric Accelerometer .....	40
4.1.3.1. Piezoelectric Quartz or Ceramic:.....	41
4.1.3.2. Frequency Response:.....	42
4.1.3.3. Discharge Time Constant .....	43
4.1.3.4. Temperature: .....	44
4.1.3.5. Linearity: .....	45
4.1.3.6. Base Strain Sensitivity:.....	45
4.1.3.7. Transverse Sensitivity:.....	45
4.1.3.8. Discharge Time Constant .....	46
4.1.3.9. Electrical Connection:.....	46
4.1.3.10. Mounting Base: .....	47
4.1.3.11. Protection Class (Housing): .....	47
4.1.4. Types of Piezoelectric Accelerometers .....	47
4.1.4.1. Compression type:.....	48
4.1.4.2. Shear type:.....	48
4.1.4.3. Flexural or Bending type: .....	49
4.1.4.4. Overview and Comparison:.....	50
4.1.5. Force-Balance Servo Accelerometer .....	50
4.1.6. Capacitive Accelerometer.....	51
4.1.7. MEMS .....	53
4.1.7.1. Servo MEMS Accelerometers.....	55
4.1.7.2. Resistive Accelerometer.....	56
4.1.7.3. MEMS Example.....	59
<b>5. Instrumentation and Measurement Amplifier.....</b>	<b>60</b>
5.1. Charge Amplifier .....	60
5.1.1. Single Channel Charge Amplifier.....	60
5.1.2. Low Pass Filter and High Pass Filter .....	61

# Good Vibrations

5.1.3.	Calibration Factor and Output Amplifier .....	61
5.1.4.	Multi-Channel Solutions .....	61
5.2.	Detailed Discussion .....	61
5.3.	IEPE, CCLD or ICP® Accelerometers .....	64
5.4.	Charge-to-IEPE Converter.....	67
5.5.	Noise .....	68
5.6.	TEDS .....	69
<b>6.</b>	<b>Analog to Digital Conversion .....</b>	<b>71</b>
6.1.	Analog Signals and Digital Signals – Sampling Frequency.....	71
6.2.	Analog to Digital Conversion .....	73
<b>7.</b>	<b>Time Domain and Frequency Domain .....</b>	<b>75</b>
7.1.	Why the Frequency Domain .....	75
7.2.	Fourier and the Bode Plot .....	76
7.3.	Reconstruction of the Time Signal.....	78
7.4.	Frequency Resolution .....	80
7.5.	Properties of the Fourier Transform .....	81
7.5.1.	Linearity .....	82
7.5.2.	Convolution .....	82
7.6.	DFT and FFT .....	83
7.7.	Aliasing.....	84
7.8.	Time Window .....	87
7.9.	Conclusion of the FFT Process.....	90
<b>8.</b>	<b>Vibration Control .....</b>	<b>92</b>
8.1.	The Vibration Controller .....	92
8.1.1.	The Seventies .....	92
8.1.2.	The Eighties .....	94
8.1.3.	The PC Generation.....	94
8.2.	Control Strategy and Transfer Function.....	96
8.2.1.	Self-Check and Start-up .....	98
8.2.2.	Run Schedule .....	100
8.2.3.	Programming the Controller .....	101
8.2.4.	Dynamic Range.....	103
8.2.5.	Conclusion.....	106
8.3.	Random .....	106
8.3.1.	Amplitude Distribution.....	107
8.3.2.	Sigma Clipping.....	109
8.3.3.	Power Spectral Density and DOF.....	111
8.3.4.	Oversampling and Overlap Processing.....	116
8.3.5.	Calculation of “g <sub>RMS</sub> ” .....	118
8.3.6.	Calculation of the maximum Displacement.....	122
8.3.7.	Control or Reference Channel.....	123
8.3.8.	Kurtosis.....	124
8.4.	Sine .....	127
8.4.1.	Sine Reference Profile.....	127
8.4.2.	Sweep Rate and Compression Rate.....	131
8.4.3.	Control Signal – Tracking Filter.....	133
8.4.4.	COLA Output.....	135



# Good Vibrations

8.4.5.	<i>Notching or Limit Channels</i> .....	137
8.4.6.	<i>Fatigue Cycles</i> .....	138
8.4.7.	<i>Resonance Search and Dwell</i> .....	140
8.4.8.	<i>Stepped Sine or Dwell Series</i> .....	146
8.4.9.	<i>Multi-Sine</i> .....	146
8.4.9.1.	<i>Delayed Sine Tones</i> .....	147
8.4.9.2.	<i>Multiple Intervals</i> .....	147
8.4.9.3.	<i>Multi-Sine Justification</i> .....	149
8.5.	<b>Shock</b> .....	151
8.5.1.	<i>Acceleration, Velocity and Displacement</i> .....	152
8.5.2.	<i>Compensation Technique</i> .....	153
8.5.3.	<i>Frequency Bandwidth</i> .....	156
8.5.4.	<i>Classical Shocks</i> .....	159
8.5.5.	<i>Functional Test</i> .....	160
8.5.6.	<i>Mechanical Shock Test Machines</i> .....	162
8.5.7.	<i>Drop Tests</i> .....	164
8.6	<i>Time Waveform Replication</i> .....	166
8.6.1	<i>Resampling</i> .....	166
8.6.2	<i>Filtering</i> .....	170
8.6.2.1	<i>High Pass Filter and Low Pass Filter</i> .....	170
8.6.2.2	<i>Time Window and Filtering</i> .....	171
8.6.2.3	<i>Trend Removal</i> .....	175
8.6.2.4	<i>Transient Duration</i> .....	175
8.6.3	<i>Control Strategy</i> .....	177
8.6.3.1	<i>On-Line Control</i> .....	177
8.6.3.2	<i>Off-Line Control</i> .....	179
8.7	<i>SRS – Shock Response Spectrum</i> .....	180
8.7.1	<i>Shock Damage</i> .....	180
8.7.2	<i>SRS Technique</i> .....	181
8.7.3	<i>SR Analysis</i> .....	184
8.7.4	<i>SR Synthesis</i> .....	187
8.8	<i>PVSRS – Pseudo Velocity Shock Response Spectrum</i> .....	190
8.8.1	<i>Shock Damage and Pseudo Velocity</i> .....	191
8.8.2	<i>PVSRS and the 4C-plot</i> .....	193
8.8.3	<i>Shock Response and Shock Duration</i> .....	197
<b>9.</b>	<b><i>Power Amplifier</i></b> .....	<b>200</b>
9.1.	<i>Input Stage</i> .....	200
9.2.	<i>Analog Power Amplifier</i> .....	203
9.3.	<i>Switched Mode Power Amplifier</i> .....	205
9.4.	<i>Control Functions and Connections</i> .....	209
<b>10.</b>	<b><i>Electrodynamic Shaker</i></b> .....	<b>213</b>
10.1.	<i>Classification</i> .....	213
10.2.	<i>Principle of Operation</i> .....	214
10.3.	<i>Construction</i> .....	217
10.3.1.	<i>Generalized Model</i> .....	217
10.3.2.	<i>Armature Guidance and Unbalance</i> .....	219
10.3.3.	<i>Damping</i> .....	223

# Good Vibrations

10.3.4.	<i>Degaussing Coil</i> .....	225
10.3.5.	<i>Armature size and Inserts Pattern</i> .....	225
10.4.	Performance Chart .....	228
10.5.	Read the Specifications.....	230
10.6.	Lifetime of the Shaker Armature.....	235
10.7.	Energy Consumption and Total efficiency .....	236
10.8.	Shakers with Permanent Magnet .....	236
10.9.	Mid-Range Shakers with Air Cooling.....	237
10.10.	High-Range Shakers with Water Cooling.....	239
10.11.	Special Solutions .....	240
10.11.1.	<i>Long Stroke Shaker</i> .....	240
10.11.2.	<i>Induct-A-Ring</i> .....	241
10.11.3.	<i>Eco Shaker</i> .....	242
<b>11.</b>	<b><i>Servo Hydraulic Shaker</i></b> .....	<b>248</b>
11.1.	Principle of Operation .....	248
11.2.	Set-up of a Servo Hydraulic Cylinder .....	250
11.3.	Control Loops.....	251
11.4.	Oil Quality Inspection .....	252
11.5.	Compressor Unit .....	253
11.6.	High Frequency Servo Hydraulic Shaker .....	254
<b>12.</b>	<b><i>Slip Table</i></b> .....	<b>257</b>
12.1.	Introduction.....	257
12.2.	Classical Slip Table - Construction.....	258
12.3.	Moments of Inertia .....	259
12.4.	Hydrostatic Bearings.....	261
12.5.	Care of the Slip Table .....	265
12.6.	Slip Table with a Climatic Chamber .....	266
<b>13.</b>	<b><i>Head Expanders and Test Fixtures</i></b> .....	<b>267</b>
<b>13.1.</b>	<b><i>Head Expanders</i></b> .....	<b>267</b>
13.2.	Requirements .....	267
13.3.	Head Expander - Resonances.....	267
13.4.	Material Choice, Steel - Aluminum - Magnesium.....	269
13.5.	Breakdown Torque and Support .....	272
<b>13.6.</b>	<b><i>Fixtures</i></b> .....	<b>277</b>
13.7.	Fixing, Check and Reference Points.....	277
13.8.	Test Axes .....	278
13.9.	Standard Fixtures .....	279
13.10.	L-Type .....	280
13.11.	T-Type .....	281
13.12.	Cube .....	282
13.13.	Alternative Use of the L- and T-type Fixture .....	284
13.14.	Material Choice and Making .....	285
13.14.1.	<i>Milling</i> .....	286
13.14.2.	<i>Welding</i> .....	289
13.14.3.	<i>Bolting</i> .....	293
13.14.4.	<i>Wood, epoxy a.o.</i> .....	311
13.15.	Functional Testing .....	312

# Good Vibrations

<b>14. Multi-Shaker Systems .....</b>	<b>314</b>
14.1. Theory.....	314
14.2. Force Phase Control.....	317
14.3. Force Phase Control Set-up.....	319
14.4. Multiple Degrees of Freedom.....	320
14.5. Three Axis Translation.....	320
14.6. 6 Degrees of Freedom.....	321
14.7. Mechanical Coupling.....	322
14.8. Control Strategy.....	326
<b>15. Installation .....</b>	<b>329</b>
15.1. Vibrational Isolation.....	329
15.2. Acoustic Isolation.....	332
15.3. Cooling.....	336
15.4. Preparation and Floor Plan.....	339
15.5. Electrical Installation.....	341
15.5.1. Electrical Power and Earthing.....	341
15.5.2. Signal Transmission.....	344
15.6. Other Requirements.....	350
15.7. Surveillance.....	351
15.8. Acceptance Test.....	352
<b>16. Combined Environmental Test Systems.....</b>	<b>355</b>
16.1. Functional Interface.....	355
16.2. Electrical Interface.....	358
16.3. Mechanical Interface (Thermal Barrier).....	359
<b>17. Maintenance and Calibration .....</b>	<b>364</b>
17.1. Maintenance.....	364
17.2. Calibration.....	367
17.2.1. Calibration - Definitions.....	368
17.2.2. Standards and Standardization Committees.....	373
17.2.3. Calibration Template.....	376
17.2.4. Accelerometers.....	376
17.2.5. Measurement Amplifier.....	384
17.2.6. Vibration Control System.....	385
17.3. Measurement and Control Accuracy.....	386