Vibration Calibration Technique and basics of Vibration Measurement

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Torben Rask Licht, B&K Denmark

- Product Manager Vibration Calibration Systems
- MSc EE, solid state physics, 1968
- Career 43 years at B&K
  - 9 Years R&D, Vibration Transducers/Calibration
  - 3 Years R&D & Marketing Acoustic Emission
  - 7 Years Vibr. Transducer R&D Group Manager
  - 6 Years International Product Manager Vibration Transducers & Calibration Systems
  - 3 Years Technology Monitoring and Innovation
  - 3 Years Project Manager Customized Projects
  - 4 Years Project Manager Innovation
  - 5 Years Product Manager Calibration Systems
  - 2 Years Vibr. Transducer R&D Group Manager
Standardisation work

- Chair of TC108/SC3, "Mechanical vibration and shock - Use and calibration of vibration and shock measuring instruments")
- IEEE-SA member.
- Chair of IEEE 1451.4 "Smart Transducer Interface for Sensors and Actuators”.
- Member of the Danish S-206 “Mechanical vibration and shock”
- As representative for the Danish Primary Laboratory of Acoustics (DPLA) participating in EURAMET and CCAUV
Audience profile assumptions

- Involved in vibration measurement
- Seeking more information about vibration measurement and calibration
- Planning to buy new equipment
- Needs calibration of equipment
- Want to establish calibration facilities
- Want to be educated to be able to participate in the above
Agenda

- Introduction to Vibration
- Vibration Transducers
- Vibration instrumentation and analysis software
- Transducer Calibration
- Calibration and standardisation
- Primary calibration methods and systems
- Secondary calibration methods and systems
- Questions
Introduction to Vibration

- What is vibration
- Why measure vibration
- Signal types
- Vibration Signal Descriptors
Introduction to Vibration

- What is vibration
- Why measure vibration
- Signal Types
- Vibration Signal Descriptors
**Definition**

from Shock and Vibration Handbook

**Vibration** is an **oscillation** wherein the quantity is a parameter defining the **motion** of a mechanical system.

**Oscillation** is the variation, usually with time, of the magnitude of a quantity with respect to a specified reference when the magnitude is alternately greater and smaller than the reference.
Vibration In Everyday Life
Useful Vibration
Mechanical Parameters and Components

Displacement

\[ F = k \times d \]

Velocity

\[ F = c \times v \]

Acceleration

\[ F = m \times a \]
**Simplest Form of Vibrating System**

Displacement: \[ d = D \sin \omega_n t \]

**Displacement**

**Time**

**Frequency**

**Period,** \( T_n \) in [sec]

**Frequency,** \( f_n = \frac{1}{T_n} \) in [Hz = \( 1/\text{sec} \)]

\[
\omega_n = 2 \pi f_n = \sqrt{\frac{k}{m}}
\]
Mass and Spring

Increasing mass reduces frequency

$$\omega_n = 2\pi f_n = \sqrt{\frac{k}{m+m_1}}$$
Mass, Spring and Damper

Increased Damping Reduces the Response Time
Forced Vibration

\[ F \]
\[ m \]
\[ k \]
\[ c \]
\[ d_m \]
\[ d_F \]

\[ d_m = d_f \]

\[ +90^\circ \]
\[ 0^\circ \]
\[ -90^\circ \]
Response Models

- Single Degree of Freedom (SDOF)
- Multi Degree of Freedom (MDOF)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$</td>
<td></td>
</tr>
</tbody>
</table>

$F$
Introduction to Vibration

- What is vibration
- **Why measure vibration**
- Signal Types
- Vibration Signal Descriptors
Why Make Frequency Analysis

- To make *diagnosis* of Rotating Machinery
Forces and Vibration

Forces caused by
- Imbalance
- Shock
- Friction
- Acoustic

Structural Parameters:
- Mass
- Stiffness
- Damping

Vibration Parameters:
- Acceleration
- Velocity
- Displacement

Input Forces $\times$ System Response = Vibration
Why Do We Measure Vibration?

- To verify that vibrations do not exceed the material limits
- To verify that Vibrations do not harm the human body
- To make diagnosis of Rotating Machinery
- To plan maintenance on machines
- To construct or verify computer models of structures and thereby to be able to dampen or isolate vibration sources
Why Do We Measure Vibration?

Vibration Testing

- To verify that vibrations do not exceed the material limits

Standard Driven Standards as MIL 810
Why Vibration Testing

After design → Test for reliability

Qualification test → Realistic vibration simulation in lab

Quality assurance → May require temperature and humidity tests

During qualification test ↔ Visual inspection or frequency response

After qualification → Functional test
Practical example
Why Do We Measure Vibration?

- To verify that vibrations do not exceed the material limits
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Mechanical Models of the Human Body

Whole body

Shoulder girdle (4 - 5 Hz)

Lung volume

Chest wall (50 - 60 Hz)

Lower arm

Abdominal Mass (4 - 8 Hz)

Seated person

Spinal column (axial mode) (10 - 12 Hz)

Legs

(Variable from ca. 2 Hz with knees flexing to over 20 Hz with rigid posture)

Standing person

Hand-arm

Eyeball, intraocular structures (ca. 25 Hz)

Head (axial mode) (20 - 30 Hz)

Hand grip (50 - 200 Hz)
Why Do We Measure Vibration?

- To verify that Vibrations do not harm the human body
Why Do We Measure Vibration?

- To verify that Vibrations do not *harm the human body*

### Compliance

- EU Directive 2002/44/EC
- ISO 8041:2005
- ISO 2631-1:1997
- ISO 5349-1 and 2:2001
Why Do We Measure Vibration?

- To verify that Vibrations do not *harm the human body*
- *By* making human Vibration measurements
Why Do We Measure Vibration?

- To verify that vibrations do not exceed the material limits
- To verify that vibrations do not harm the human body
- To make diagnosis of Rotating Machinery
- To plan maintenance on machines
- To construct or verify computer models of structures and thereby to be able to dampen or isolate vibration sources
To make *diagnosis* of Rotating Machinery

And thereby plan when repair is needed
Why Do We Measure Vibration?

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- To plan maintenance on machines
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Forces and Vibration

Forces caused by:
- Imbalance
- Shock
- Friction
- Acoustic

Structural Parameters:
- Mass
- Stiffness
- Damping

Vibration Parameters:
- Acceleration
- Velocity
- Displacement

Input Forces \times \text{System Response} = \text{Vibration}
The Automotive Industry

With vibration measurement and models you can:

- Reduce development time
- Improve NVH Vehicle Quality – less noise and vibration with improved sound quality

By applying solutions for:

- Diagnostics and Troubleshooting
- Benchmark and Compliance Testing
- Advanced NVH Investigations
- Crash Testing
Introduction to Modal Testing 1

Static Testing and Analysis
- A science studied for over a century

Structural Dynamic Testing
- Term differentiating it from Static Testing and Analysis
- In contemporary language it is Modal Analysis and Modal Testing
Introduction to Modal Testing 2

Present day demands
- Increasing speed in transportation
- Higher fuel economy
- More lightweight constructions

The demands achieved by **reducing the mass of structures**

Consequences
- Structures become inherently weak
- Resonances move down into the frequency region of excitation forces
- Structures fail because of **dynamic loads**
Beyond Modal Testing

Finite Element Modelling, FEM → Prediction of test model → Modal Testing

Damping data → Comparison and Validation of Modal Model

Valuation → Curve fitting → Validation

Update

Comparison and Validation of Modal Model → Final Model

Simulation: “What if” → Trouble Shooting
The Aerospace & Defence Industry

• With vibration measurement and models you can:
  – *Reduce* time to market
  – *Improve* the quality of their products
  – *Comply* with legislation

• By applying solutions for:
  – The world’s largest assortment of dynamic transducers
  – Complete measurement/recording solution
  – Real time analysis for monitoring and validation
  – Diagnostics and troubleshooting
  – Benchmark and compliance testing
Introduction to Vibration

- What is vibration
- Why measure vibration
- **Signal Types**
- Vibration Signal Descriptors
Types of Signals

Stationary signals

Deterministic

Random

Continuous

Non-stationary signals

Transient
Deterministic Signals and Harmonics
Random Signals
Impact-Impulse-Shock Signals
Signal Types and Spectrum Units

**Correct use of Units**

<table>
<thead>
<tr>
<th>Time</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Deterministic, Periodic Signal" /></td>
<td><img src="image" alt="Power" /></td>
</tr>
<tr>
<td><img src="image" alt="Random Signal" /></td>
<td><img src="image" alt="Power Spectral Density" /></td>
</tr>
<tr>
<td><img src="image" alt="Transient" /></td>
<td><img src="image" alt="Energy Spectral Density" /></td>
</tr>
</tbody>
</table>
Introduction to Vibration

- What is vibration
- Why measure vibration
- Signal Types
- Vibration Signal Descriptors
Linear vs. Oscillatory Motion

Detroit 35 Miles

Speed limit 65 MPH

TEST 0-60 MPH in 8.6 second

Displacement

Velocity

Acceleration
Conversion from Displacement to Acceleration

Displacement, \(d\)  
\[d = D \sin \omega t\]

Velocity, \(v\)  
\[v = D \omega \cos \omega t\]
\[v = D \omega = D2\pi f\]

Acceleration, \(a\)  
\[a = D \omega^2 \sin \omega t\]
\[a = D \omega^2 = D4\pi^2 f^2\]
Vibration Parameters

\[ f = 0.1591 \text{ Hz} \]

Acceleration
\[ a = \frac{dv}{dt} \]

Velocity
\[ v \]

Displacement
\[ D = \frac{v}{\omega} \]
\[ D = \int v \, dt \]

\[ \omega = 1 \]

\[ \omega = \omega \]

Relative Amplitude

Frequency

0.1 1 10 100 1 k 10 kHz
Which Parameter to Choose

**Measurement A**
- Choose Displacement

**Measurement B**
- Choose Velocity

**Measurement C**
- Choose Acceleration
# Units of Vibration Signals

<table>
<thead>
<tr>
<th>Units</th>
<th>Symbol</th>
<th>Unit</th>
<th>Conversion (ms⁻²)</th>
<th>Approximate Conversion (in/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>a</td>
<td>1ms⁻² (m/s²)</td>
<td>= 0.102g</td>
<td>= 39.4 in/s²</td>
</tr>
<tr>
<td>Velocity</td>
<td>v</td>
<td>1ms⁻¹ (m/s)</td>
<td>= 3.6 km/h</td>
<td>= 39.4 in/s</td>
</tr>
<tr>
<td>Displacement</td>
<td>d</td>
<td>1m</td>
<td>= 1000 mm</td>
<td>= 39.4 in</td>
</tr>
</tbody>
</table>

1g ≡ 9.80665 ms⁻²
“Real World” Vibration Levels

- 1 000 000 ms\(^{-2}\)
- 1000 ms\(^{-2}\)
- 100 ms\(^{-2}\)
- 1 ms\(^{-2}\)
- 0.001 ms\(^{-2}\)
- 0.000 001 ms\(^{-2}\)

- 240 dB
- 180 dB
- 120 dB
- 60 dB
- 0 dB

Various vibration levels are shown, ranging from the intensity of an explosion to the quietness of a residential area.
Vibration Transducers

Types of Vibration Transducers
The Piezoelectric Accelerometer
Choosing an Accelerometer
Using an Accelerometer
Calibration
The Measurement Chain

Transducer → Preamplifier → Filter(s) → Detector/ Averager → Output
GIGO

Garbage In = Garbage Out
Early Methods of Vibration “Measurements”
Mechanical Lever

Application:
Obsolete, but still found in a few old power stations
Eddy Current Proximity Probes

Applications:
- Relative motion
- Shaft eccentricity
- Oil film thickness
- Etc.
Velocity Pickup

e = Blv

Limited frequency range: 10 < f < 1000 Hz
Piezoelectric Accelerometer

Principles of operation

\[ V \text{ [mV]} \propto F \]
\[ Q \text{ [pC]} \propto F \]
Types of Accelerometers

- Planar Shear
- Centre-mounted Compression
- Annular Shear
- Delta Shear®
- ThetaShear®
- OrthoShear®

**Components:**
- P: Piezoelectric Elements
- E: Built-in Electronics
- S: Spring
- R: Clamping Ring
- B: Base
- M: Seismic Mass

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Operational Range of Vibration Transducers

Relative Amplitude

- Piezoelectric Accelerometer
- Velocity transducer
- Eddy current Proximity probe

Frequency

- 0.2
- 2
- 20
- 200
- 2k
- 20kHz

Amplitude ratios:
- $10^8:1$
- $10^6:1$
- $10^0:1$
- $10^1:1$
Choosing an Accelerometer

- General Purpose, medium weight and sensitivity
- Small, light and high frequency

<table>
<thead>
<tr>
<th>Acceleration (ms⁻²)</th>
<th>Weight</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000-100,000</td>
<td>10-50 gram</td>
<td>5-12k</td>
</tr>
<tr>
<td>0.003-0.01</td>
<td></td>
<td>~0.1 - ~1</td>
</tr>
<tr>
<td>0.0001-0.001</td>
<td></td>
<td>15-30k</td>
</tr>
<tr>
<td>0.1 - 0.3 pC/ms⁻²</td>
<td>0.5 - 3 g</td>
<td></td>
</tr>
<tr>
<td>1 - 10 pC/ms⁻²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Brüel & Kjær Delta Shear® Design

- Piezoelectric material
- Clamping Ring
- Seismic Mass
- Base
Accelarometer Model Spring-Mass System

Spring Force: \( F = k(x_s - x_B - L) \)
Force on Base: \( m_B \ddot{x}_B = F + F_e \)
Force on Seismic Mass: \( m_s \ddot{x}_s = -F \)

Equation of motion:

\[
\ddot{x}_S - \ddot{x}_B = -\frac{F}{m_s} - \frac{F + F_e}{m_B}
\]
Force Sensitivity of Piezoelectric Element

Polarisation direction

Domains in undeformed state

Applied Force

Compression deformation of domains

Shear deformation of domains

\[ Q[pC] = S_F[pC/N] \cdot F[N] \]

- \( Q \) = Generated Charge
- \( S_F \) = Force Sensitivity
- \( F \) = Applied Force
Useful Frequency Range

Amplification Factor $A$

Vibration of Seismic Mass

Mounted Resonance Frequency $f_m$

$10\%$ limit $\approx 0,3 f_m$

$3\,\text{dB}$ limit $\approx 0,5 f_m$

Vibration of Base

$f / f_m$

Relative Frequency
**Sensitivity and Frequency Range**

- **Sensitivity**
  - pC/ms^-2
  - 31.6
  - 1
  - 0.004

- **Frequency Range**
  - kHz
  - 13, 42, 180
Accelerometer Mounting — Fixed

- Thin double adhesive tape
- Cementing stud
- Stud Mounting

Beeswax
Max. 40 °C

Level dB
0 10 20 30

Frequency
200 500 1k 2k 5k 10k 20k 30k 50 kHz

Accelerometer Mounting — Fixed

Accelerometer Mounting — Fixed

Accelerometer Mounting — Fixed

Accelerometer Mounting — Fixed
Accelerometer Mounting — Handheld

Hand held probe

Magnet

Level dB

Frequency

200 500 1k 2k 5k 10k 20k 30k 50kHz
**Isolating the Accelerometer**

**Electrical**  
(Prevention of ground loops)

![Mica washer and insulating stud](image)

**Mechanical Filter**  
(Protection against high shocks)

![Mechanical filter diagram](image)
Choosing a Mounting Position
Loading the Test Object

- 0.1 pC/ms\(^{-2}\)
  - 0.65 g \(\rightarrow\) \(M > 7\) g

- 10 pC/ms\(^{-2}\)
  - 54 g \(\rightarrow\) \(M > 600\) g

- 1000 pC/ms\(^{-2}\)
  - 470 g \(\rightarrow\) \(M > 5\) kg

Dynamic Mass

\[< \frac{1}{10} M\]
Environmental Effects

- Base Strain
- Humidity
- Acoustic noise
- Corrosive substances
- Magnetic fields
- Nuclear radiation
Conclusion

- Due to its wide dynamic range and wide frequency range the piezoelectric accelerometer is the most widely used vibration transducer.
- From the mechanical point of view, the piezoelectric accelerometer is a seismic transducer employing a spring-mass system.
- Velocity pick-ups can be well suited and cheap for vibration measurements in the mid-frequency range.
- Proximity probes are used for relative, low frequency, motion, especially for monitoring shafts in bearings.
Vibration instrumentation and analysis software

- The newest from B&K is the PULSE LAN-XI modules with PULSE Software running on a PC.
LAN-XI Multi-Purpose Module

Multi-purpose module:
- DeltaTron & Microphone conditioning
- 51.2 kHz freq-range

Microphones (200Vp)
Accelerometers
Proximity probes
DC-Accelerometers (diff. input).
AC & DC
Charge via DeltaTron converter

Dyn-X  REq-X  TEDS  CIC
Cost and Time Savings using Distributed System

Reduced complexity Transducer Hub System
- Cabling costs reduced 50-70%
- Instrumentation time reduced 50-70%
Transducer Calibration

Why calibrate
- To find the sensitivity

Why recalibrate
- Legal obligation - QA requirement
- Good instrument practice
- Test for damage
Calibration Levels

Measurements must be comparable and measurement uncertainty known

- **Primary calibration**
  - Often performed as absolute calibration that means as close as possible to the fundamental physical units (MKSA in the SI system)

- **Secondary calibration (comparison to a reference)**
  - Transducers, calibrators, instruments

- **Field calibration**
  - Field calibrators like

- **Field measurements**
B&K Calibration Systems all PULSE based

Hydrophones
- Reciprocity
- Comparison
- Directional R.

Instruments
- SLM
- Dose meter
- Octave Filter
- Calibrator

Accelerometers
- Laser
- Comparison
- Shock 10k
- Shock 100k
- Low-frequency Comparison
- Transverse
- Conditioners

Microphones
- Reciprocity
- Comparison
- Phase Comp.
- Dyn. Linearity
- Low-frequency
- Fr. Resp. Coup.

Turn-key Systems
- instructions on screen
- printing of certificates
- uncertainty budgets
- support

Primary
PULSE based

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Calibration standardisation

- Standardisation is important
- For vibration there is however far less legal requirements, but the number is increasing.
## Survey of the ISO 5347/16063 series and status

<table>
<thead>
<tr>
<th>Number</th>
<th>Title</th>
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<tbody>
<tr>
<td>5347-0:1987</td>
<td>Basic concepts</td>
<td>revised, 16063-1:1998</td>
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<tr>
<td>5347-1:1993</td>
<td>Primary vibration calibration by laser interferometry</td>
<td>revised, 16063-11:1999</td>
</tr>
<tr>
<td>5347-2:1993</td>
<td>Primary shock calibration by light cutting</td>
<td>withdrawn</td>
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<tr>
<td>5347-6:1993</td>
<td>Primary vibration calibration at low frequencies</td>
<td>withdrawn</td>
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<tr>
<td>5347-7:1993</td>
<td>Primary calibration by centrifuge</td>
<td>confirmed 2004/2009</td>
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<tr>
<td>5347-8:1993</td>
<td>Primary calibration by dual centrifuge</td>
<td>confirmed 2004/2009</td>
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<tr>
<td>5347-9:1993</td>
<td>Secondary vibration calibration by comparison to a reference transducer</td>
<td>withdrawn</td>
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<tr>
<td>5347-10:1993</td>
<td>Primary calibration by high impact shocks</td>
<td>confirmed 2004/2009</td>
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<tr>
<td>5347-20:1997</td>
<td>Primary vibration calibration by the reciprocity method</td>
<td>revised, 16063-12:2002</td>
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<tr>
<td>5347-11:1993</td>
<td>Testing of transverse vibration sensitivity</td>
<td>revision, WD 16063-31, lack of project leader 2010</td>
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<tr>
<td>5347-12:1993</td>
<td>Testing of transverse shock sensitivity</td>
<td>confirmed 2004</td>
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<tr>
<td>5347-14:1993</td>
<td>Resonance frequency testing of undamped accelerometers on a steel block</td>
<td>confirmed 2004, PWI- 2008</td>
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<tr>
<td>5347-16:1993</td>
<td>Testing of mounting torque sensitivity</td>
<td>confirmed 2004</td>
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<tr>
<td>5347-17:1993</td>
<td>Testing of fixed temperature sensitivity</td>
<td>confirmed 2004</td>
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<tr>
<td>5347-22:1997</td>
<td>Accelerometer resonance testing -General methods</td>
<td>confirmed 2004</td>
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<tr>
<td>16063-15:2006</td>
<td>Primary angular vibration calibration by laser interferometry</td>
<td>confirmed 2010</td>
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<tr>
<td>16063-41:2011</td>
<td>Calibration of laser vibrometers</td>
<td>Approved 2011</td>
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<tr>
<td>5348</td>
<td>Mechanical mounting of accelerometers</td>
<td>confirmed 2004</td>
</tr>
</tbody>
</table>

The ISO 16063 series of documentary standards has specified upgraded and new standard methods to allow metrological traceability to be extended to all six motion quantities (vibration and shock).
Accelerometer Check

- In the field
  - Sensitivity check
  - Total system check

- In the lab
  - Frequency Response
  - Sensitivity Calibration

Frequency = 159.2 Hz
\( \omega = 1000 \text{ rad/sec} \)

Acceleration = 10 ms\(^{-2} \) +/-3%

Calibration Exciter with built-in or external reference accelerometer

Brüel & Kjær
Primary calibration methods and systems
Absolute Calibration by Laser Interferometry

Primary Vibration Transducer Calibration System
Type 9636 1993

Similar system used by DPLA since 1990

First system created 1969 and used to calibrate 8305 since 1971
Fringe counting principle ISO 16063-11, method 1

$\lambda_L = 4.74 \times 10^{14}$ Hz
$\lambda_L = 632.815$ nm

Shaker
Detector
Laser
Reference mirror
Accelerometer
Detector signal
Min. Frequency
Half Counting Cycle
Max. Frequency
Basic formula

\[ R_f = \frac{d \times 2^{\text{Laser beam (Forth & Back)}} \times 2^{\text{Peak to Peak}} \times 2^{\text{Full Counting Cycle}}}{\lambda} \]

\[ a = \omega^2 \cdot d \]

\[ R_f = \frac{8 \cdot a}{\omega \cdot \lambda} = \frac{8 \cdot a_{\text{RMS}} \cdot \sqrt{2}}{(2 \cdot \pi \cdot f)^2 \cdot \lambda} \]

for \( a_{\text{RMS}} = 50 \text{ m/s}^2 \) and \( f = 159,155\text{Hz} \)

\[ R_f = 893.92 \]
DPLA calibration history

Calibration History of Transfer Standards

NIST/PTB - Calibration
re.
B&K - Calibration at 159.2Hz

WW 5164

SES/JLS, 11.04.2005
ISO Method 3, 1999

Key
1  Frequency generator (3.2)
2  Power amplifier (3.3)
3  Vibrator (3.3)
4  Moving part of vibrator
5  Dummy mass
6  Accelerometer
7  Amplifier
8  Interferometer (3.6)
9  Laser (3.5)
10 Light detectors
11 Digital waveform recorder (3.13)
12 Voltmeter (3.10)
13 Distortion meter (3.11)
14 Oscilloscope (3.12)

Figure 3 — Measuring system for the sine-approximation method (Method 3)
Primary methodologies, ISO method 3

- 10 years of development in technology have changed the available instrumentation considerably
  - Integrated compact laser-interferometers are available with quadrature outputs
  - Standard FFT analyzers with high speed and high resolution are available for analysis (=sine approximation) and building on the ever increasing power of the processors in the computers
  - Integrated compact laser-interferometers are available with direct digital outputs of vibration quantities. These are well suited as precision reference transducers.
Goals for new systems according to Method 3

- Simpler
- Easier to use
- Wider frequency range
- Phase measurement
- Automated to save manpower
- Higher accuracy
- Lower price
(B&K) Setup with quadrature output (2. Generation 2004)

PC with front-ends for Conditioning, data acquisition/generation Calculation/analysis

Laser

Interferometer

Detectors

Mirror

Power amplifier

Shaker

Accelerometer
B&K Setup with quadrature output (2. Generation 2004)
Determination of the Mod angle

- The output values can graphically be explained as shown

\[ u_1(t_i), u_2(t_i) \]

\[ \varphi_{\text{Mod}}(t_i) \]
ISO 16063-11: Primary vibration calibration by laser interferometry

\[ \varphi_{\text{Mod}}(t_i) = \arctan \frac{u_2(t_i)}{u_1(t_i)} + p\pi \]

where the integer \( p \) has to be chosen properly to avoid discontinuities. In the standard these results are then used to create \( N+1 \) equations

\[ \varphi_{\text{Mod}}(t_i) = A \cos \omega t_i - B \sin \omega t_i + C \]

to be solved using the least squares method to find \( A, B \) and \( C \).

\[ i = 0,1,2\ldots N \quad A = \phi_M \cos \varphi_s \quad B = \phi_M \sin \varphi_s \]

\( C \) is a constant
\( \omega \) is the angular frequency of vibration \( \omega=2\pi f \)
\( \varphi_s \) is the initial phase of the displacement
\( N+1 \) is the number of samples taken synchronously over the measurement period.
\( f \) is the vibration frequency known by the system.
It has been proved that using DFT (or the faster FFT) with appropriate sampling and taking out the values for the proper frequency is identical to the described sine approximation method using least square fitting.

\[ x(t) = \frac{\lambda}{4\pi} \arctg\left( \frac{SignalB(t)}{SignalA(t)} \right) \]
Laser cal. system Type 3629 using PULSE FFT Analyzer

- Laser with quadrature output
- PULSE FRONTEND A/D
- Stream data to disk
- PULSE Time Recorder
- Harddisk
- Generate simulated raw data
- Process data
- x(t)
- PULSE Time Analyse Data FFT
- FRF
- Apply corrections
- Harddisk
- Calibration Data
- Show results (Application)
Laser calibration system using PULSE FFT Analyzer

- Streaming the data directly to the hard disk makes it unimportant how large the files are but naturally large amounts of data take longer time to process.
- This approach permits e.g. measurements at very low frequencies, down to 0.1 Hz giving files of several hundred Megabytes each.
Laser calibration system using PULSE FFT Analyzer

Calibration of servo accelerometer 0.1 Hz to 160 Hz on long stroke shaker
Determination of the Mod angle at high frequencies

- The Mod angle becomes very small at higher frequencies
Determination of the Mod angle at high frequencies

- At high frequencies only a fraction of the circle is given making the determination of the center and thereby the angle difficult.
- The dual frequency output in the PULSE analyzer is used to add a suitable low frequency vibration.
- This ensures a full circle so that the center and thereby the angle can be determined precisely.
Laser calibration system using PULSE FFT Analyzer

Wide range (2 Hz to 50 kHz) calibration of reference in shaker
Evaluation and simulation

- The system structure permits injection of raw data
- A program has been made to create raw data with
  - Noise on transducer signal
  - Noise on detector signals
  - Ellipticity (gain difference between detector outputs)
  - Dual frequency input
  - Transducer sensitivity input
  - Vibration magnitude and frequency input
- This permits evaluation of the system sensitivity to the different parameters
- It also permits e.g. yearly performance verification for accreditation purposes
- The system includes automated calibration of the PULSE front-end using high precision voltmeter giving the highest accuracy and traceability. Data are stored and used for correction.
Result of simulation, as shown in the application.

Ellipticity 0.8
Simulations

Amplitude Deviation Result of simulation with Ellipticity 0.8 and 1

Result of lasersimulations

Amplitude Deviation %

Frequency [Hz]
Simulations

Amplitude Deviation difference in percentage results of simulation with Ellipticity 0.8 and 1

Difference in Results of lasersimulations, Ellipticity 1 and 0.8

Amplitude Deviation Difference %

Frequency [Hz]
Phase deviation results with ellipticity 0.8 and 1.

Result of lasermulations

Phase \( \text{° re 0°} \)

Frequency [Hz]
CONCLUSION

It has been proved that a calibration system based on modern analyzers is well suited to perform primary absolute calibrations following ISO 16063-11, method 3.
Quadrature system in rack
Acceptance test
Quadrature system testing
Quadrature system testing
Quadrature system testing
LNE installation
LNE installation
# Uncertainty budget

## Table 2.

Budget of uncertainties for a reference piezoelectric accelerometer on a 4809 shaker from 10 Hz to 10 kHz –

<table>
<thead>
<tr>
<th>i</th>
<th>Quantity</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 10 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 20 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 40 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 500 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 1.25 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 2 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 4 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 6 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 7 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 10 kHz</td>
</tr>
<tr>
<td>1</td>
<td>$u(\Delta V)$ (Ac/DC-resolution)</td>
<td>0.028</td>
</tr>
<tr>
<td>2</td>
<td>$u(\Delta B)$ (e.g. hum and noise)</td>
<td>0.016</td>
</tr>
<tr>
<td>3</td>
<td>$u(\Delta C)$ (e.g. hum and noise)</td>
<td>0.020</td>
</tr>
<tr>
<td>4</td>
<td>$u(\Delta D)_t$ (e.g. hum and noise)</td>
<td>0.024</td>
</tr>
<tr>
<td>5</td>
<td>$u(\Delta E)$ (phase sensitivity)</td>
<td>0.035</td>
</tr>
<tr>
<td>6</td>
<td>$u(\Delta F)$ (phase sensitivity)</td>
<td>0.035</td>
</tr>
<tr>
<td>7</td>
<td>$u(\Delta G)$ (phase sensitivity)</td>
<td>0.058</td>
</tr>
<tr>
<td>8</td>
<td>$u(\Delta H)$ (phase sensitivity)</td>
<td>0.076</td>
</tr>
<tr>
<td>9</td>
<td>$u(\Delta I)$ (phase sensitivity)</td>
<td>0.076</td>
</tr>
<tr>
<td>10</td>
<td>$u(\Delta J)$ (phase sensitivity)</td>
<td>0.072</td>
</tr>
<tr>
<td>11</td>
<td>$u(\Delta K)$ (phase sensitivity)</td>
<td>0.072</td>
</tr>
<tr>
<td>12</td>
<td>$u(\Delta L)$ (phase sensitivity)</td>
<td>0.080</td>
</tr>
<tr>
<td>$u_e(S_0)$</td>
<td>Uncertainty for accelerometer sensitivity $S_0$, standard un. (k = 1)</td>
<td>0.194</td>
</tr>
</tbody>
</table>

Uncertainty for accelerometer sensitivity $S_0$ 95% conf. level (k = 2): 0.194, 0.179, 0.194, 0.211, 0.211, 0.211, 0.277, 0.374, 0.374, 0.371.
# Uncertainties

<table>
<thead>
<tr>
<th>Frequency Range (Hz)</th>
<th>Configuration</th>
<th>Magnitude Expanded Uncertainty (%)</th>
<th>Phase Expanded Uncertainty (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.2</td>
<td>LF exciter</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>0.2-0.4</td>
<td>LF exciter</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>0.4 – 2</td>
<td>LF exciter</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>2 - 10</td>
<td>LF/HF exciter</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>10 – 2000</td>
<td>HF exciter</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>2000 - 5000</td>
<td>HF exciter</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>5000 - 7000</td>
<td>HF exciter</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>7000 - 10000</td>
<td>HF exciter</td>
<td>0.6</td>
<td>1.5</td>
</tr>
<tr>
<td>10 to 15 kHz</td>
<td>HF exciter</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>15 to 20 kHz</td>
<td>HF exciter</td>
<td>2.5</td>
<td>3</td>
</tr>
</tbody>
</table>
Conclusion

- Laser interferometric measurements have matured to very accurate and efficient tools
- The mechanical setups in which these are used will often give rise to errors if the goal was to measure and describe the transducer as it will be used afterwards
- More work is needed to give better models and better descriptions of how the reference transducers shall be used
Secondary calibration methods and systems
Vibration calibration by comparison to a reference transducer

ISO 16063-21, 2003
Comparison set-up

1 Exciter
2 Amplifiers
3 Power amplifier
4 Frequency generator and indicator
5 Reference transducer
6 Transducer to be calibrated
7 Voltmeter
8 Distortion meter for occasional checks
9 Oscilloscope for visual inspection (optional)
10 Phase meter (optional)
Calibration using Back-to-back method
ISO 16063-21, 2003

Magnitude uncertainties

<table>
<thead>
<tr>
<th>Description</th>
<th>Example 1</th>
<th>Example 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>For accelerometers (0.4 Hz to 1000 Hz)</td>
<td>1 %</td>
<td>3 %</td>
</tr>
<tr>
<td>For accelerometers (1000 Hz to 2000 Hz)</td>
<td>2 %</td>
<td>5 %</td>
</tr>
<tr>
<td>For accelerometers (2 kHz to 10 kHz)</td>
<td>3 %</td>
<td>10 %</td>
</tr>
<tr>
<td>For displacement and velocity transducers (20 Hz to 1000 Hz)</td>
<td>4 %</td>
<td>6 %</td>
</tr>
</tbody>
</table>

ISO 16063-21, 2003
Phase shift
(Not mandatory)

At reference conditions (i.e. the level and frequency at which the reference transducer was calibrated)

<table>
<thead>
<tr>
<th>Example</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1°</td>
<td>3 °</td>
</tr>
</tbody>
</table>

Outside reference conditions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2,5 °</td>
<td>5 °</td>
</tr>
</tbody>
</table>
ISO 16063-21, 2003

Environmental conditions

<table>
<thead>
<tr>
<th></th>
<th>Example 1</th>
<th>Example 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room temperature</td>
<td>(23 ± 5) °C</td>
<td>(23 ± 10) °C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Max. 75 %</td>
<td>Max. 90 %</td>
</tr>
</tbody>
</table>
Comparison calibration for Force transducers

- Comparison calibration can be used for dynamic calibration of Force Transducers
- Two measurements with two different calibrated masses as load are performed
- From this the sensitivity can be calculated.
Fifth Generation Vibration and Shock Transducer Calibration System Type 3629
System Configuration (Vibration)

Vibration Transducer Calibration System Type 3629
Accelerometer Calibration System Type 3629

- Turn-key Accelerometer Calibration System
- Calibration by substitution method, direct comparison possible
- User only interface with the calibration program
- Modular on both Software and Hardware
- Accommodate user’s existing hardware
- Frequency and level range only limited by hardware
- Make Random, Sine, Sine+level, & Sine step level calibrations
- Write Calibration data to TEDS
- Handles triaxial units with one certificate
- Measures Bias and Offset voltages
Back to Back Calibration System

3560C
Pulse Sound & Vibration Analyzer

2719
Power Amplifier

10/100M LAN Interface

2647
Charge to Deltatron Converter

5308 Vibration Transducer Calibration S/W
3629-CTI 3629 system Traceable Initial Calibration

Test Transducer
WA0567 Calibration Fixture
4371 Working Standard Accelerometer
4808 Exciter / WH2651
4809 Exciter
Type 3629 System Variations

Available System Modules:

- Primary Laser Calibration (ISO 16063 - 11)
- Secondary Vibration Calibration by Comparison (ISO 16063 - 21)
- Secondary Shock Calibration by Comparison (ISO 16063 - 22)
  - Pneumatically operated piston
  - Hopkinson bar with velocity comparison
- Conditioner Calibration
Comparison calibration, Back to back

By back-to-back mounting of the accelerometers, both accelerometers are subject to the same vibration. This is assumed to be a perfectly linear motion perpendicular to the accelerometers’ common mounting surface.

The sensitivity in this direction of the DUT accelerometer can then be calculated

\[ S_{uut} = S_{ref} \times \frac{(G_{ref} \times V_{uut})}{(G_{uut} \times V_{ref})} \]
Calibration by substitution
Measurement results and formulas

\[ H \text{ is the frequency response function} \]

\[ S \text{ is the sensitivity} \]

\[
\frac{S_u(f) \ast H_B(f)}{S_x(f) \ast H_A(f)} \ast \frac{S_x(f) \ast H_A(f)}{S_r(f) \ast H_B(f)} = \frac{H_u(f)}{H_r(f)}
\]

giving the result

\[ S_u(f) = S_r(f) \ast \frac{H_u(f)}{H_r(f)} \]
## % Uncertainty under different conditions

<table>
<thead>
<tr>
<th>f-range</th>
<th>160 Hz</th>
<th>&gt; 2 to 5 Hz</th>
<th>&gt; 5 to 10 Hz</th>
<th>&gt; 10 to 20 Hz</th>
<th>&gt; 20 to 500 Hz</th>
<th>&gt; 0.5 to 1.25 kHz</th>
<th>&gt; 1.25 to 2 kHz</th>
<th>&gt; 2 to 4 kHz</th>
<th>&gt; 4 to 5 kHz</th>
<th>&gt; 5 to 7 kHz</th>
<th>&gt; 7 to 10 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPL-DUT 4809</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.34</td>
<td>0.41</td>
<td>0.41</td>
<td>0.42</td>
<td>0.56</td>
<td>0.56</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>HPL-DUT 4808</td>
<td>0.34</td>
<td>0.42</td>
<td>0.42</td>
<td>0.34</td>
<td>0.41</td>
<td>0.47</td>
<td>0.47</td>
<td>0.57</td>
<td>0.84</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>OPL-DUT 4808</td>
<td>0.58</td>
<td>0.87</td>
<td>0.71</td>
<td>0.62</td>
<td>0.62</td>
<td>0.62</td>
<td>0.63</td>
<td>0.90</td>
<td>0.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPL-DUT 4809</td>
<td>0.58</td>
<td>0.62</td>
<td>0.62</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.64</td>
<td>0.66</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>OPL+DUT 4809</td>
<td>0.61</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.75</td>
<td>0.77</td>
<td>1.20</td>
<td></td>
</tr>
</tbody>
</table>

+/- DUT means with or without transverse and temperature influence
HPL means Highest Precision Laser cal. at all points
OPL means One Point Laser calibration only at 160 Hz, plus known resonance frequency and no slope
Thank you for your attention!!

QUESTIONS?