BIPM Workshop on Challenges in Metrology for Dynamic Measurement

Dynamic measurements for mechanical quantity standards, from NMIs to industries

Gustavo Ripper

INMETRO / Brazil

15-16 November, 2012

Dynamic measurement - definition

- Dynamic measurement is defined as a measurement made where:

> the physical quantity being measured varies with time and, where this variation may have significant effect on measurement result (the estimate of the measurand) and the associated uncertainty

http://www.npl.co.uk/server.php?show=ConWebDoc.2131

Dynamic Measurement of Mechanical Quantities

Growing industrial demand

- more applications
- variety of measurands
- higher precision

- Formalized
- Not explicitly formalized

NMIs need to be prepared !

Tasks of National Metrology Institutes

- In order to create the scientific bases of measurement, the NMI shall in general accomplish three fundamental tasks, usually by experiments:

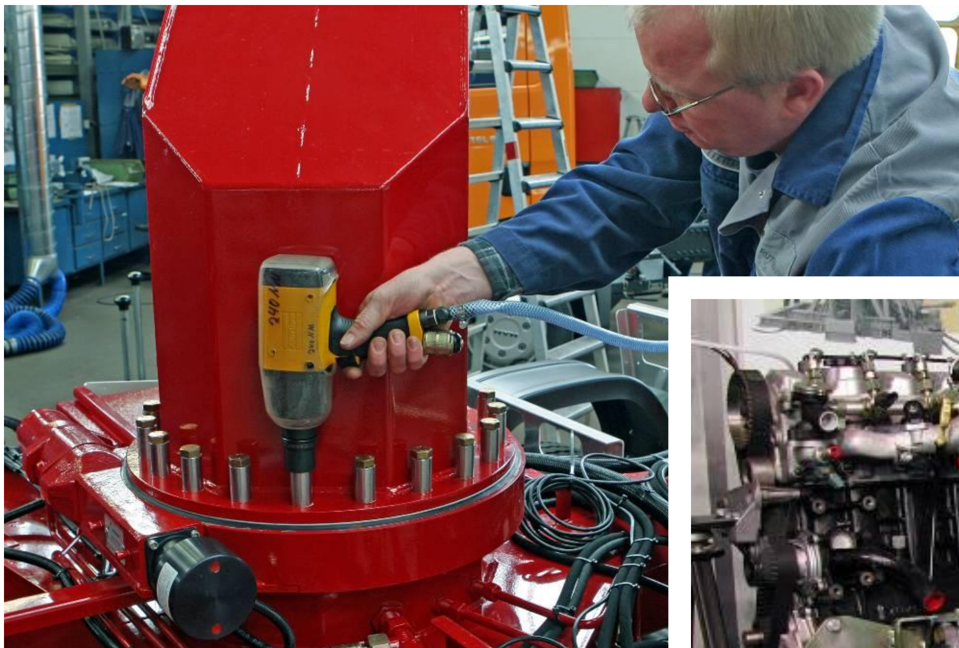
1. Realization of the units in compliance with the definition agreed on the international level.

2. Maintenance of the units by a material measure or measuring device referred to as standard.

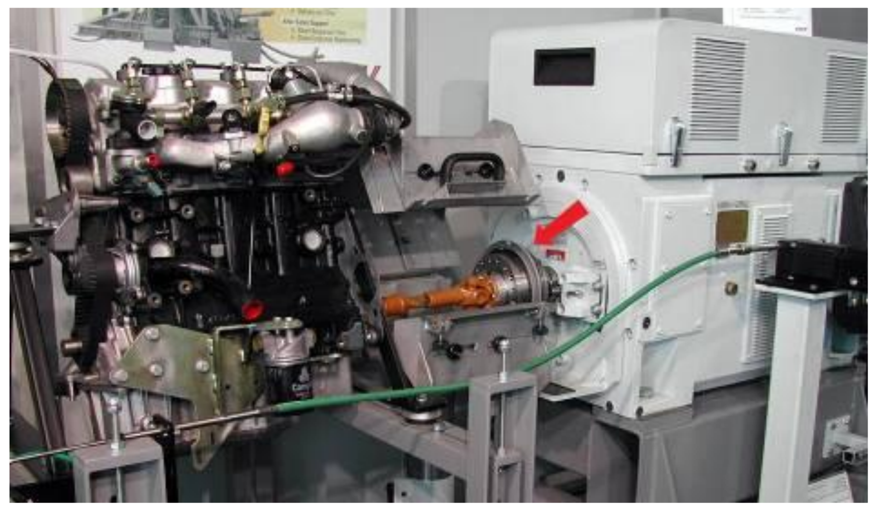
3. Dissemination of the units to the users using reference and working standards.

Why dynamic calibration?

- many applications using dynamic torque



Example:
impulse wrenches,
engine teststands

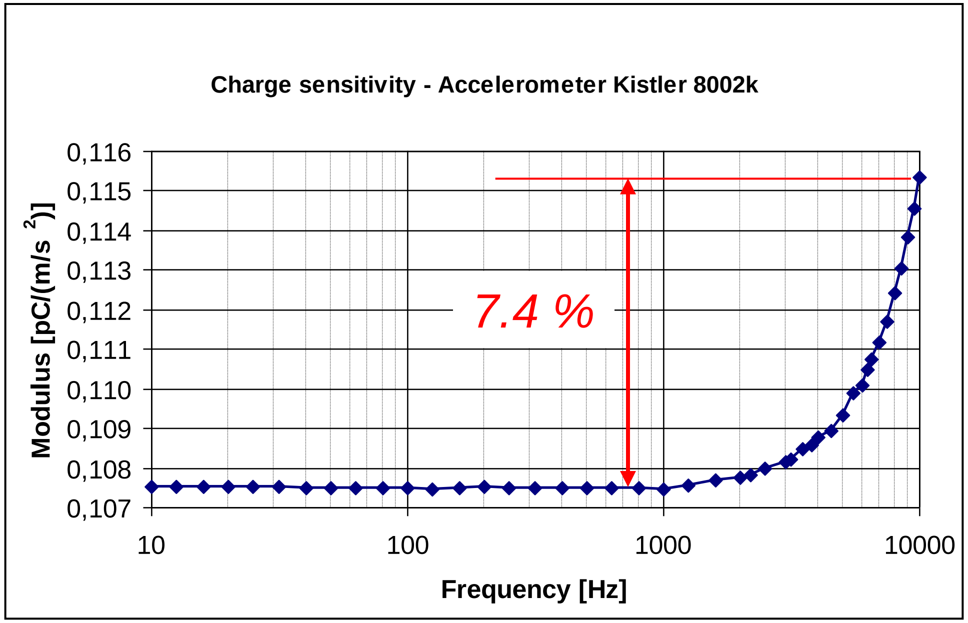


Source: Atlas Copco ↑
Source: HBM →

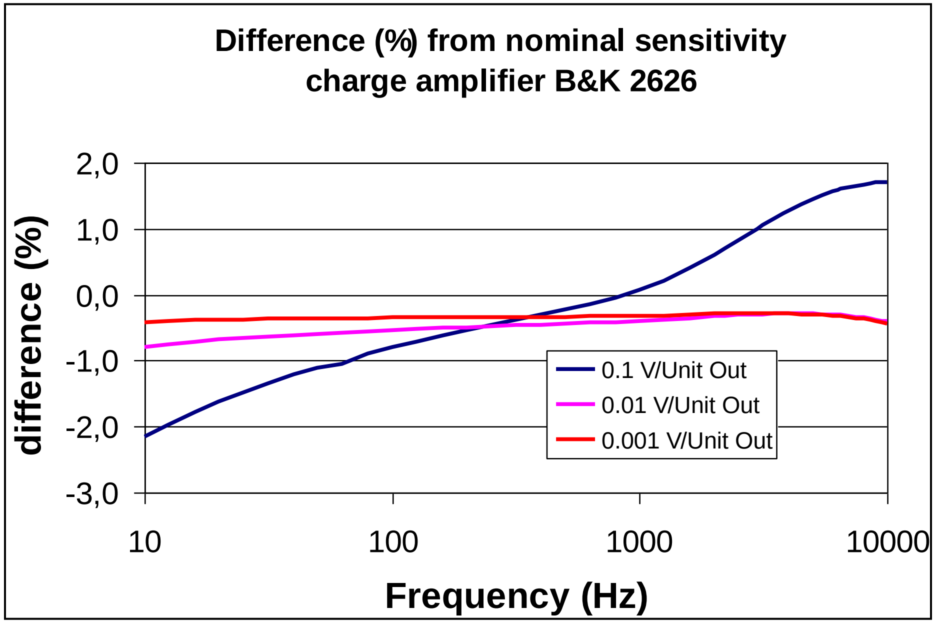
Important for the optimization of engines, transmissions and drive trains with respect to efficiency and emmissions *Source: letter from stakeholder*

Frequency dependency of sensitivity

- In dynamic measurements, the frequency-dependent response of a sensor cannot be described by a single parameter (sensitivity) obtained from static calibration



Transducer sensitivity



Signal conditioner

Current traceability situation

- At present traceability exists for static realizations of the mechanical quantities force, torque and pressure

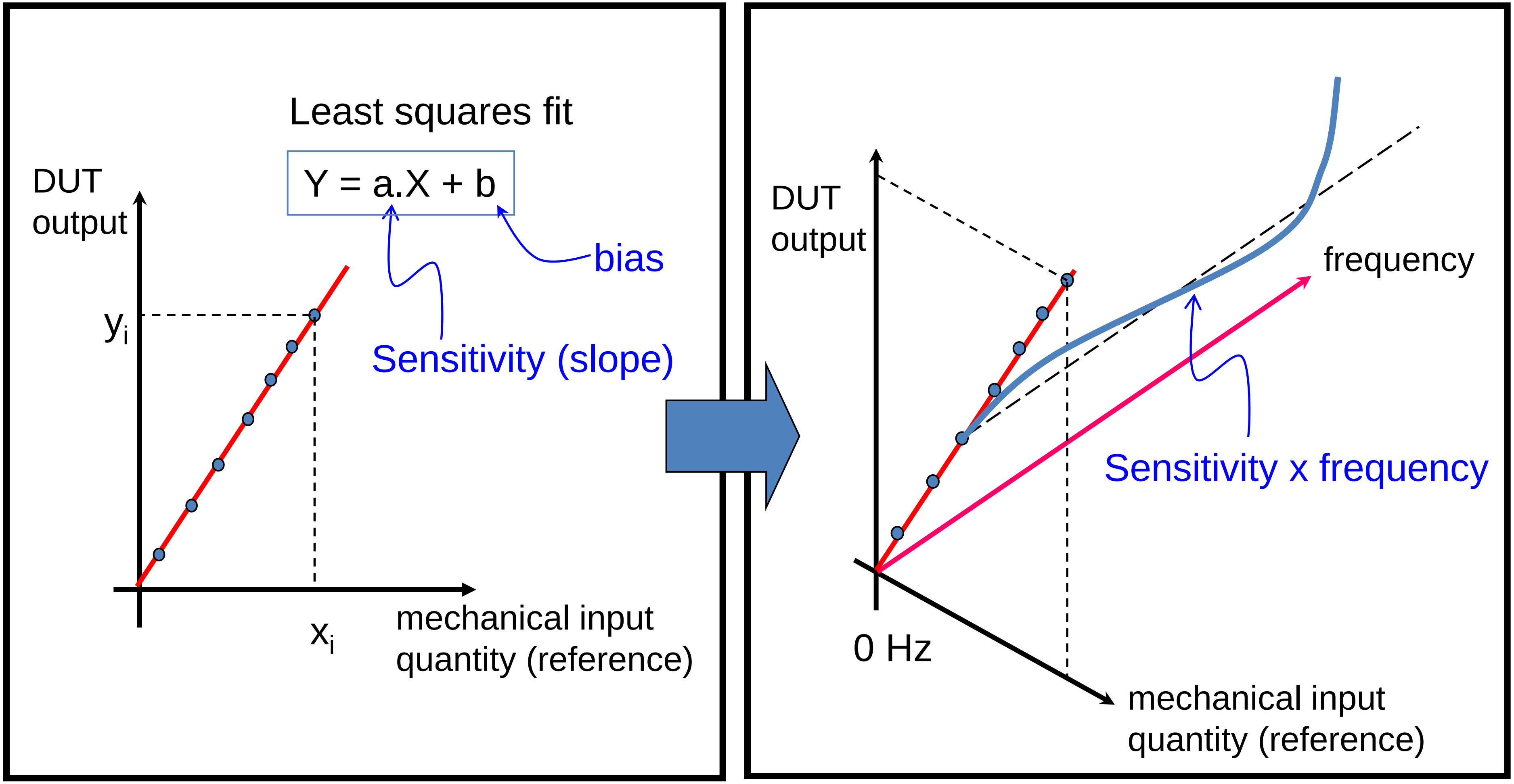
Dead weight force machine of INMETRO
100 kN direct, 1000 kN transfer

Pressure balance
of PTB

Dead weight torque machine of INMETRO
1 N·m up to 3 kN·m

From static to dynamic calibration

STATIC (2 Dimensions) ***DYNAMIC*** (3 Dimensions)



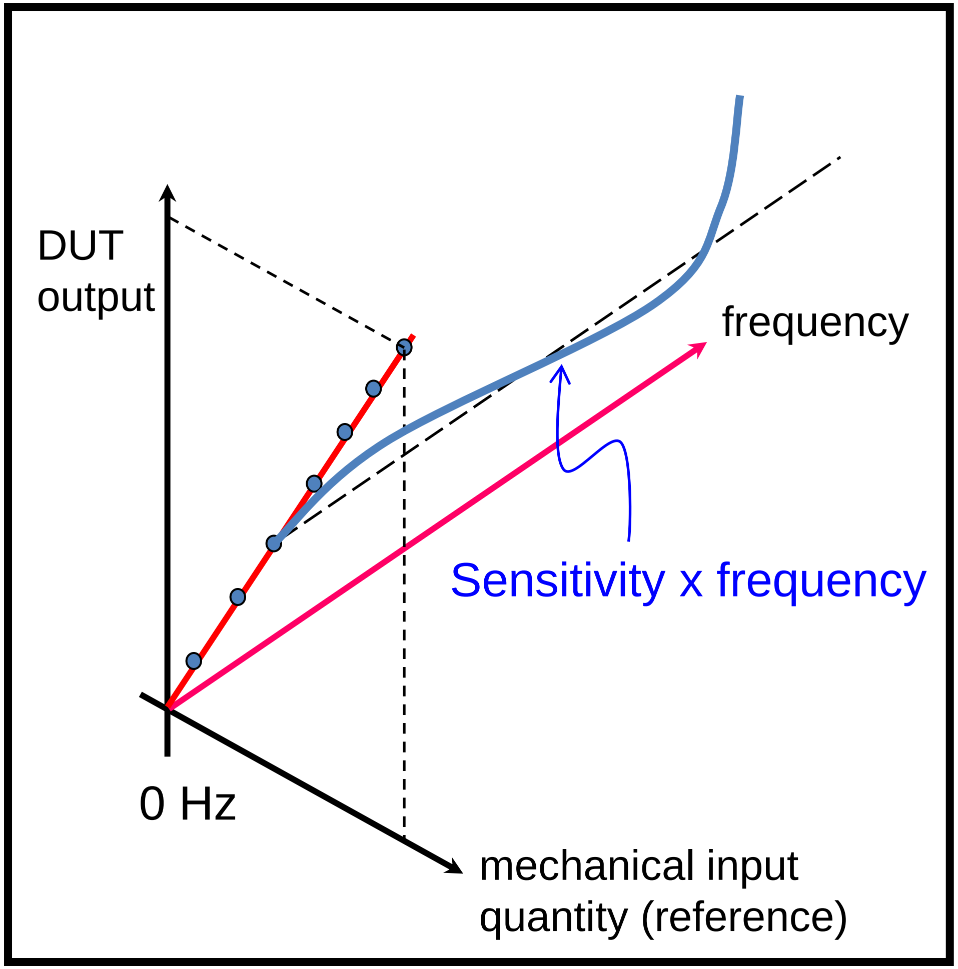
From static to dynamic calibration

- Dynamic metrology is a complete new field for many static experts

New

- Methods / procedures
- Instrumentation
- Transducers
- Signal processing techniques
- etc.

DYNAMIC (3 Dimensions)

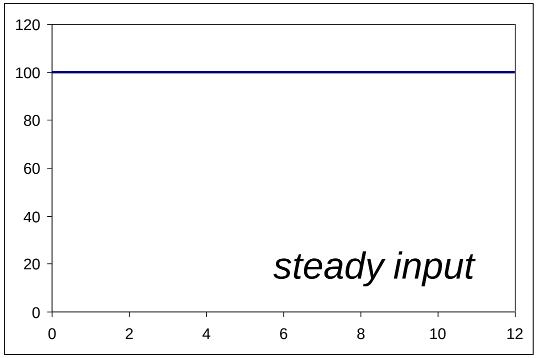


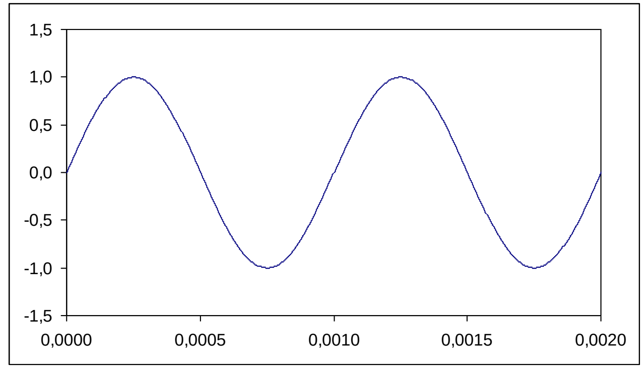
Dynamic calibration

- Static calibration
  - Primary Reference => local gravity
  - Secondary Reference => calibrated transducer
- Dynamic calibration
  - Primary Reference => laser interferometry to measure motion
  - Secondary Reference => calibrated transducer
- Usually defined by the type of dynamic excitation (frequency content, amplitude level)
  - Continuous velocity
  - Sinusoidal
  - Impact
  - Step

Examples of types of excitation

static

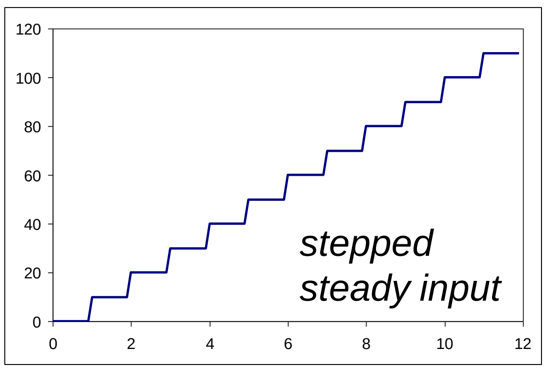


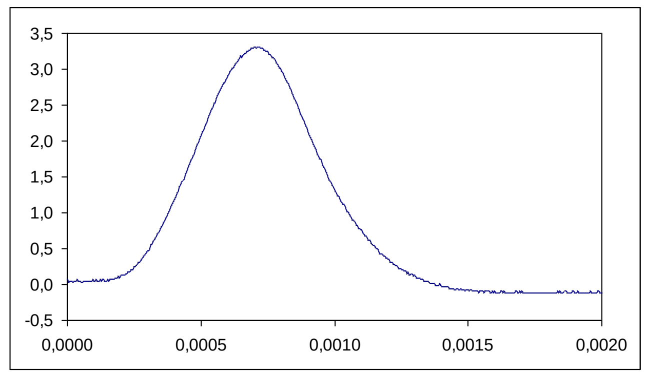


sinusoidal

single frequency
acceleration
varying input

quasi-static

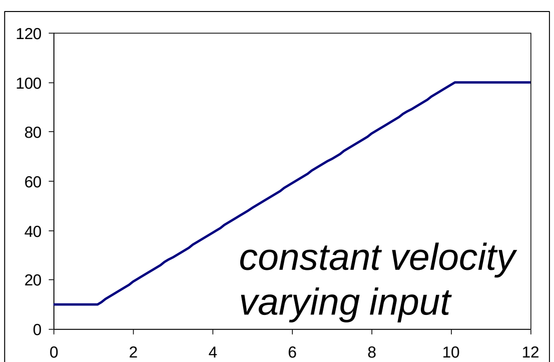


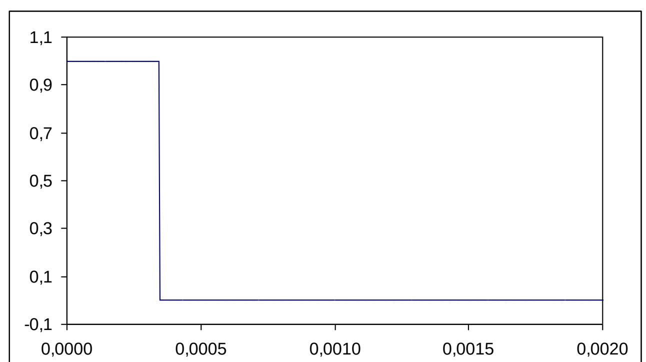


shock

broadband
acceleration
varying input

continuous





step

broadband
acceleration
varying input

Current distribution of CMCs in the KCDB

(source: KCDB, updated on 28/Oct/2012)

Metrology Area: Mass and related quantities

- Force – 33 countries (compression, tension, comp. & tension)
  - Dynamic force* – 0
- Torque – 12 countries (torque)
  - Dynamic torque* – 0
- Pressure – 44 countries (absolute, differential, dynamic, gauge)
  - Dynamic Pressure – 0
- Gravity – 4 countries

* Services not included in the document:

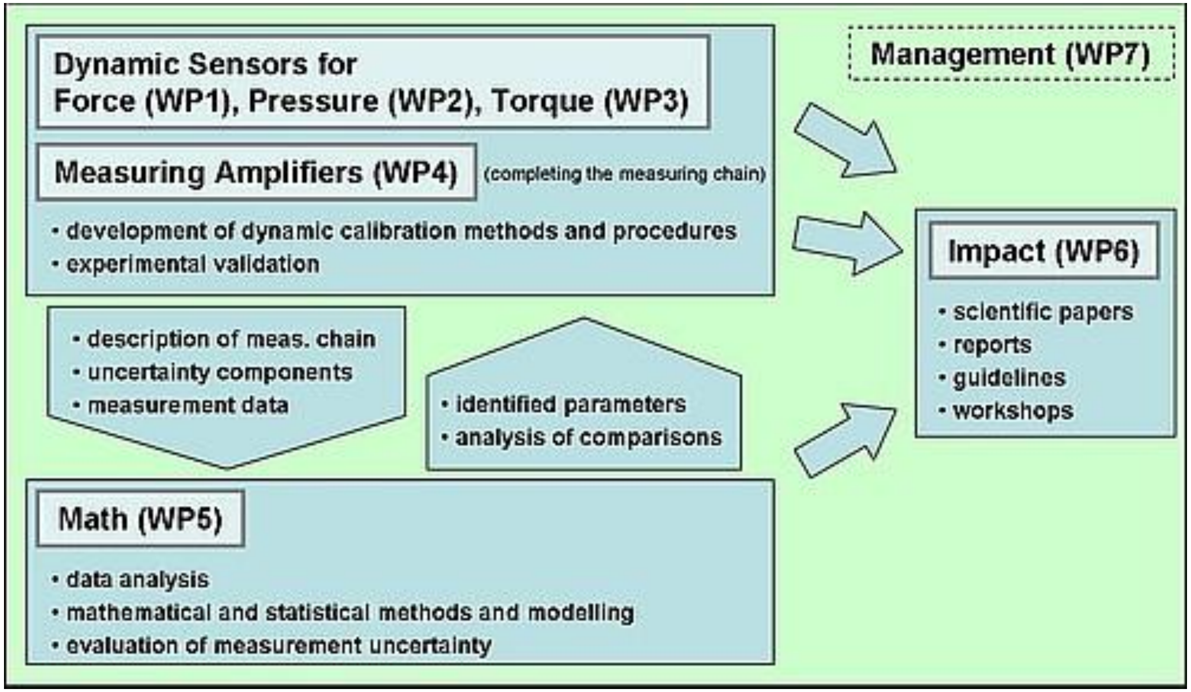
"*Classification of services in mass and related quantities*", dated 21 October 2003

EMRP European Metrology Research Programme ▸ Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

JRP-IND09: Traceable Dynamic Measurement of Mechanical Quantities

Aim: *To establish traceability for three dynamic mechanical quantities*
force, torque and pressure



Funded partners (9 NMIs):
PTB, NPL, LNE, MIKES, CEM, SP, INRIM, CMI, UME

Colaborators:
HBM, SPEKTRA, VW, Porsche

Duration = 3 years
Total amount = 3.6 million Euros

Synergetic approach to create the foundation for a European infrastructure for traceable dynamic measurements

Letters of support

Broad range of applications:

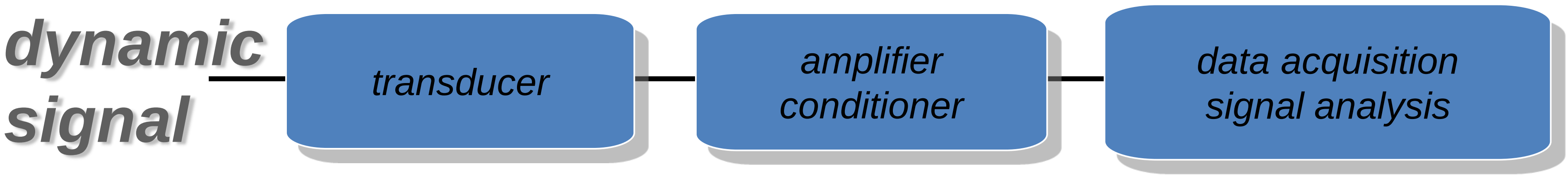
- Automotive industry
- Transducer manufacturers
- Pumps manufacturer
- Manufacturer of testing equipment
- Software developer
- Engineering Consultants
- Energy generation and aircraft engines
- Hazard properties of explosives
- Air blast pressure measurement
- Turbomachinery
- Airline company
- Defense
- Repair shop
- Etc.

Static x dynamic calibration

- Static
  - Well established
  - High accuracy, very low uncertainties
  - Sensitivity may vary with amplitude
  - Applicable only to transducers that respond to static inputs

- Dynamic
  - Needs developments
  - Lower accuracy, higher uncertainties
  - Sensitivity may vary with amplitude & frequency
  - Applicable to transducers that respond to dynamic inputs, which may not respond to static inputs
    - For example: piezoelectric transducers

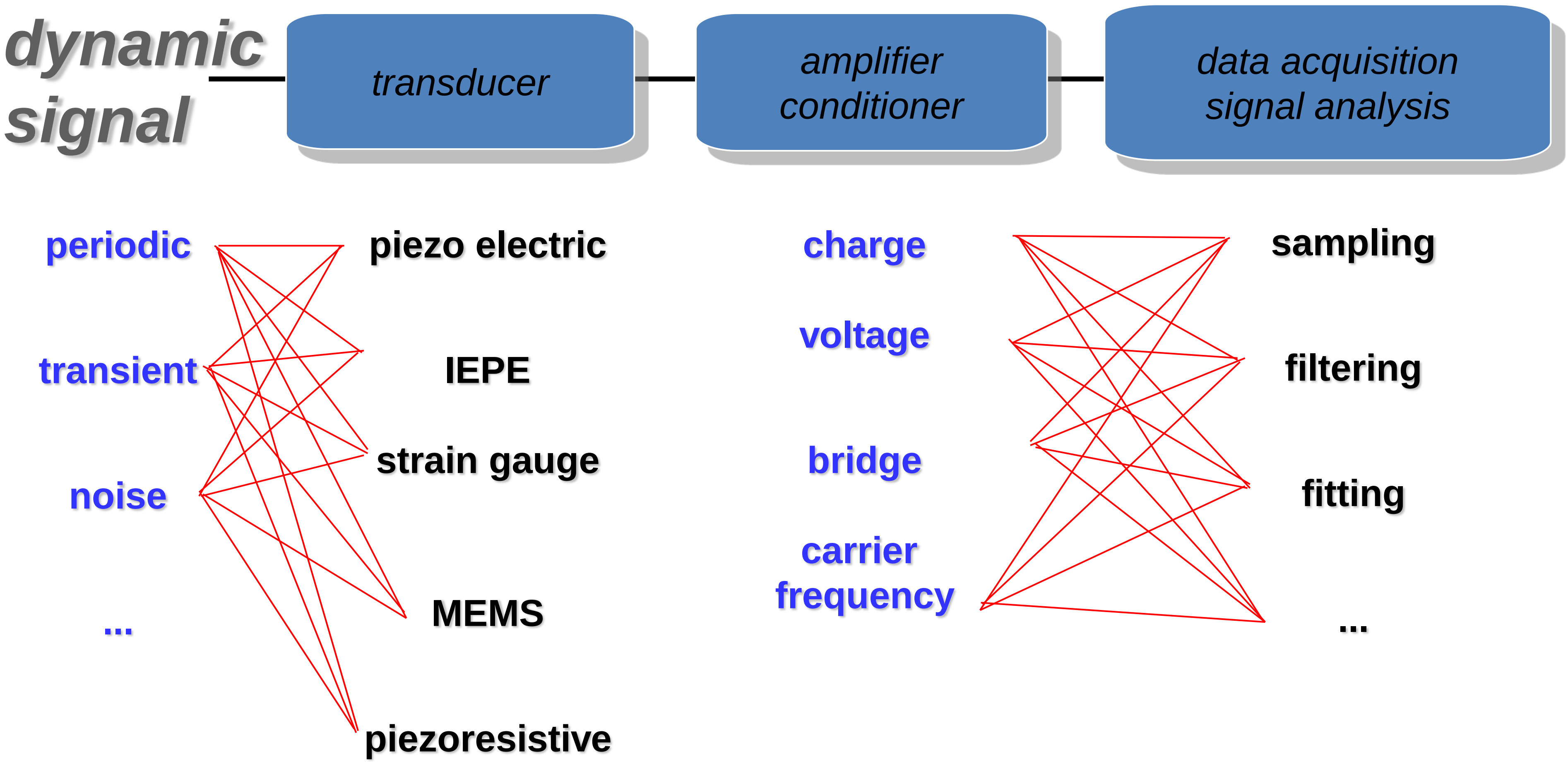
How to take advantage of synergy



periodic	piezo electric	charge	sampling
transient	IEPE	voltage	filtering
noise	strain gauge	bridge	fitting
...	MEMS	carrier frequency	...
	piezoresistive		

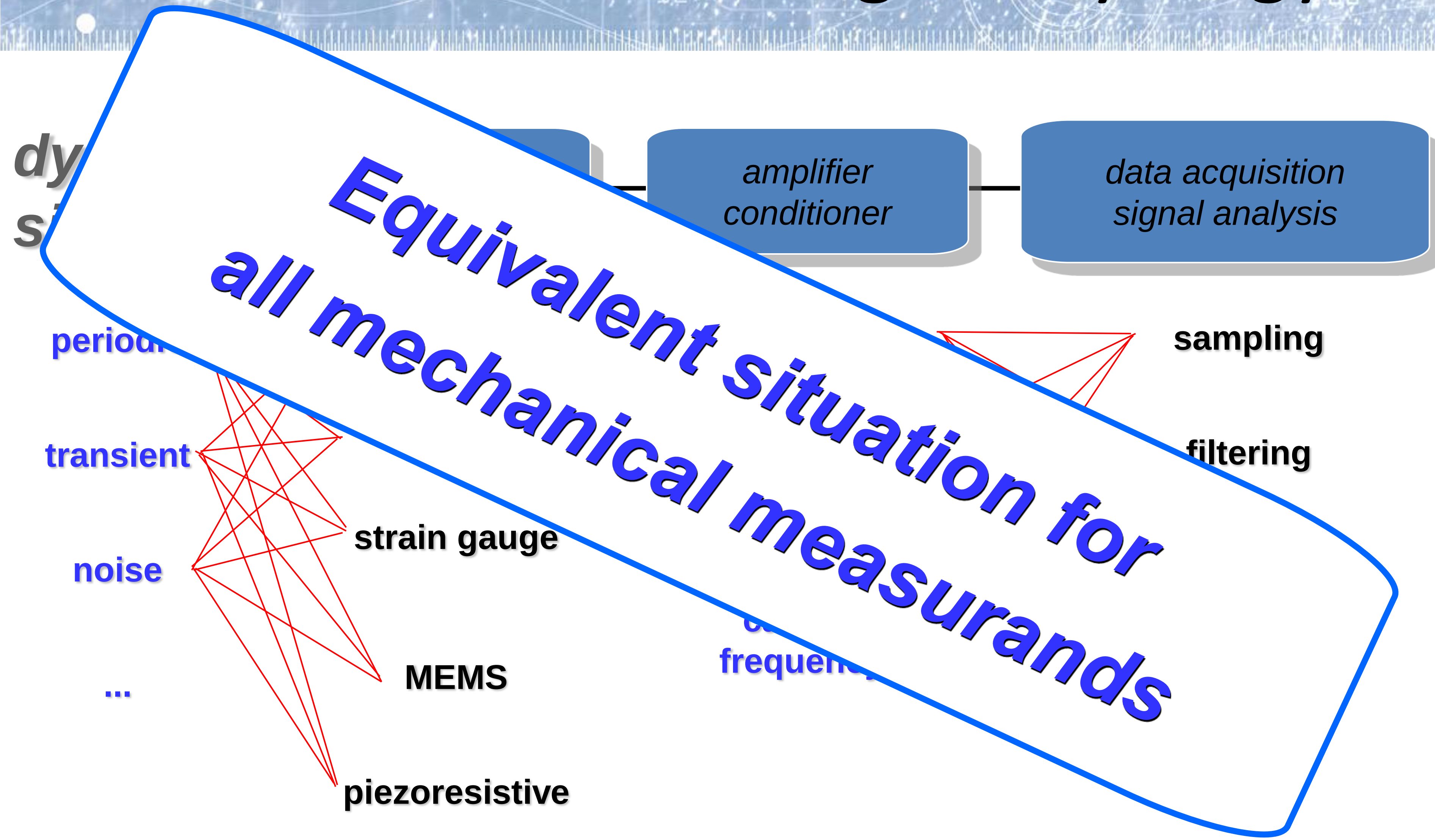
Many similarities between force, torque, pressure and vibration

How to take advantage of synergy

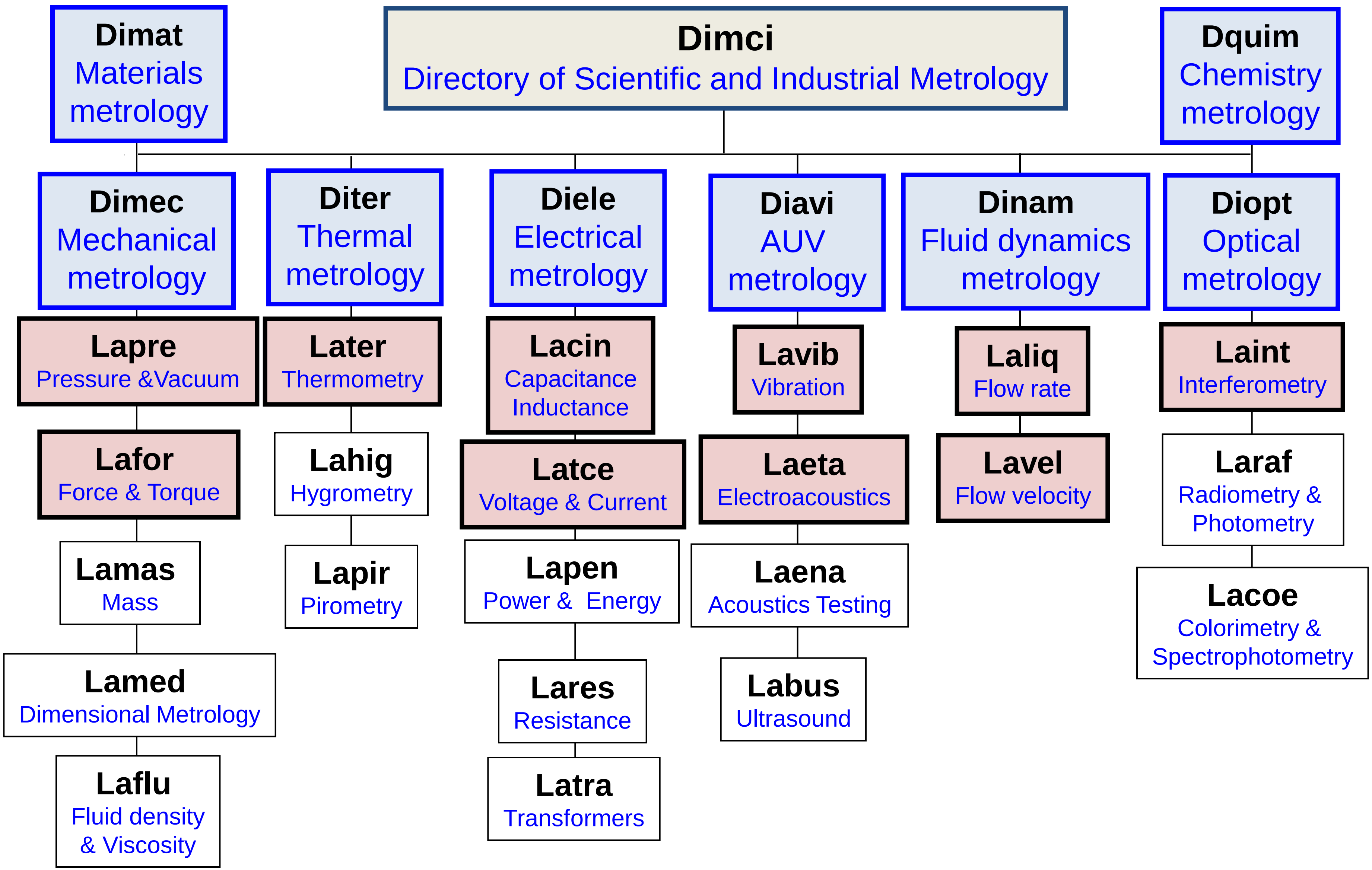


It is worthwhile to join forces across fields

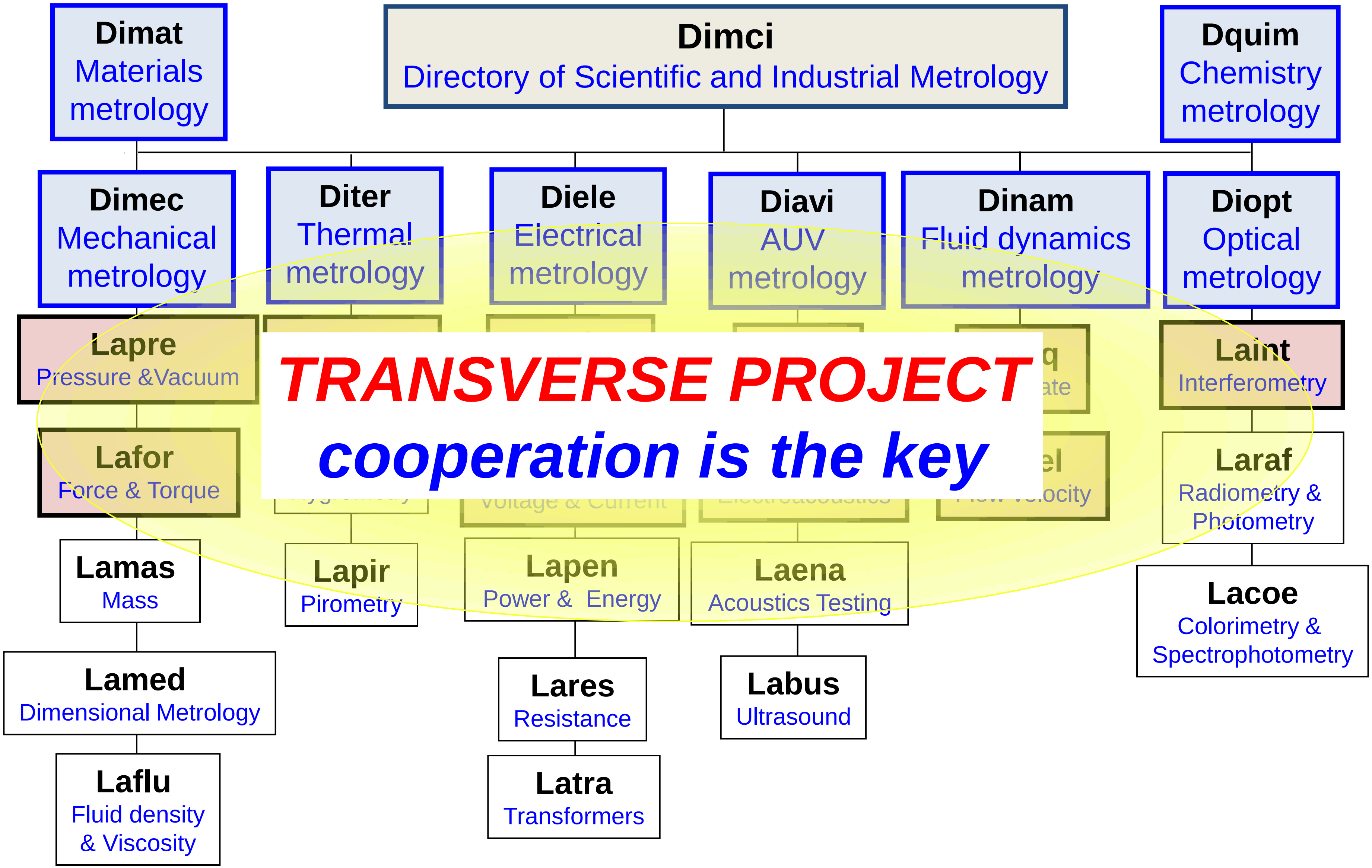
How to take advantage of synergy



Dynamic measurements in a typical NMI structure



Dynamic measurements in a typical NMI structure



Mechanical units related to dynamic mechanical measurements

- Acceleration in metre per second squared (m/s^2)
- Force measured in newton (N) ($kg \cdot m/s^2$)
- Torque measured in newton·metre (N·m) ($kg \cdot m/s^2 \cdot m$)
- Pressure measured in pascal (Pa) ($kg \cdot m/s^2 \cdot m^{-2}$)
- Signal conditioner sensitivity in
  - V/(mV/V) or
  - V/pC or
  - …

All in terms of frequency response or dynamic system parameters

Measurands and calibration methods

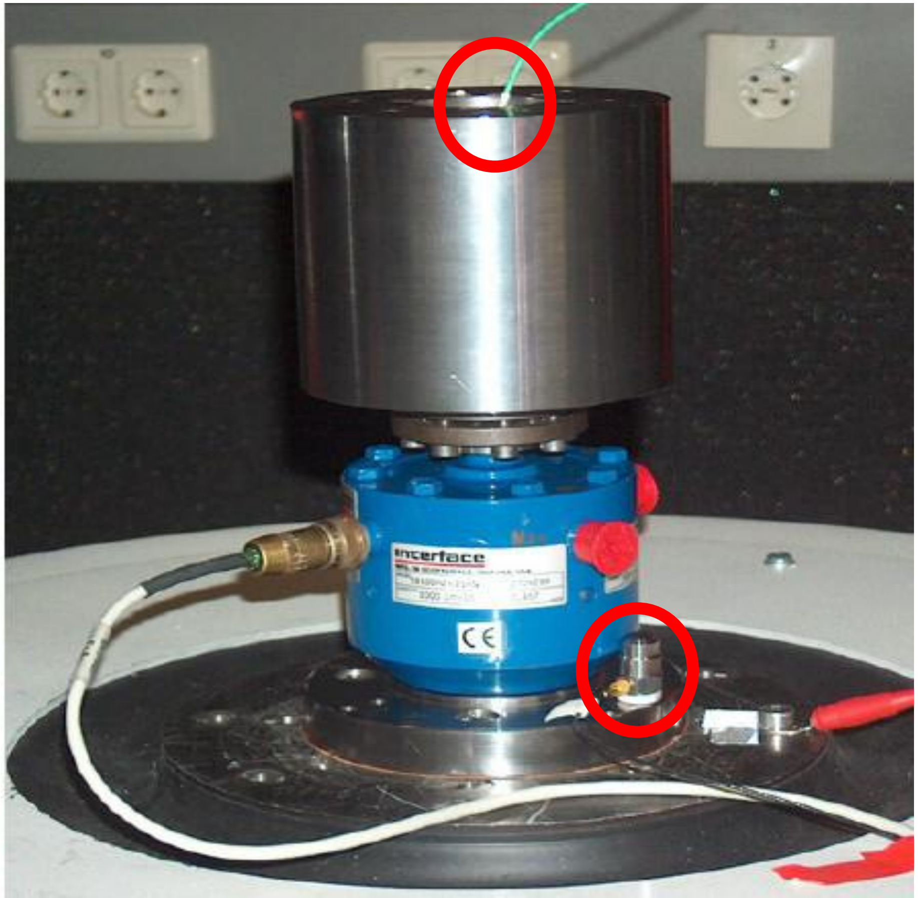
Dynamic Measurands (shock, sinusoidal)

- Acceleration
- Force
- Pressure
- Angular acceleration
- Torque

Calibration Methods

- Primary methods (laser interferometer reference)
- Secondary methods (comparison with reference transducer)

Sinusoidal force as example



Ch Schlegel *et al*., Traceable periodic force calibration**,** Metrologia **49** (2012) 224–235

Force as

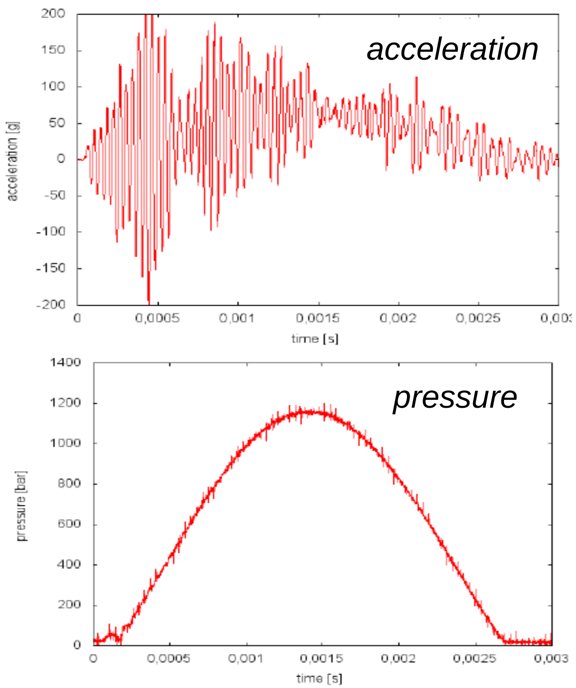
mass times acceleration

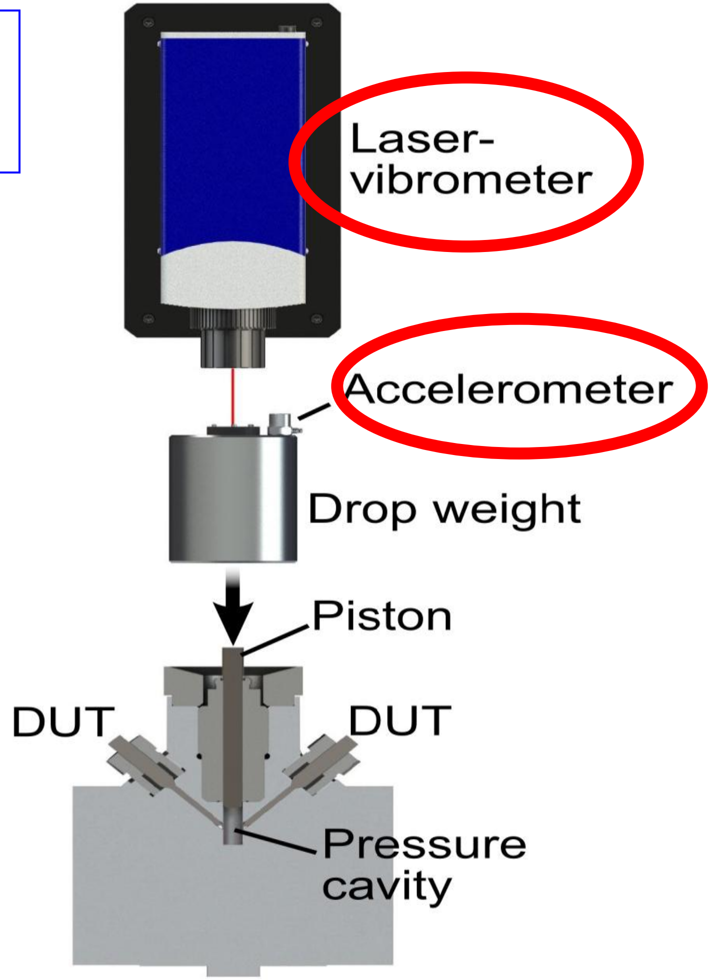
- Mass is one-time calibration
- Acceleration is the dynamic quantity
  - Acc. needs traceability
  - Acc. needs methodical consultancy
  - Acc. needs analysis experience

Dynamic shock pressure as example

MIKES / Finland

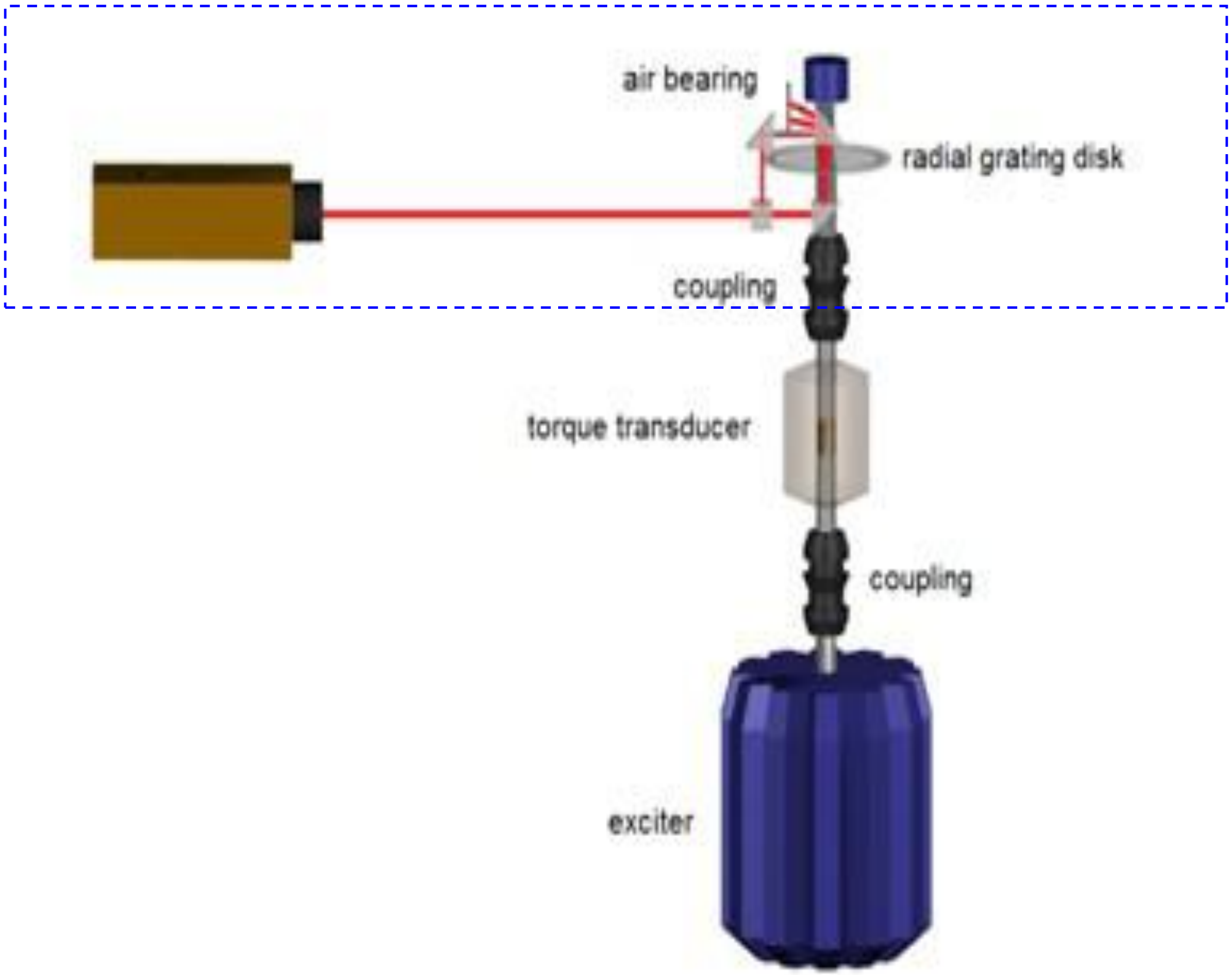
Pressure is determined via:
- Force and cross section of cavity
- Displacement and compressibility





Sinusoidal torque as example

Primary angular acceleration measurement



Dynamic force calibration in vibration laboratories

- Some smaller size force transducers are already calibrated by vibration laboratories

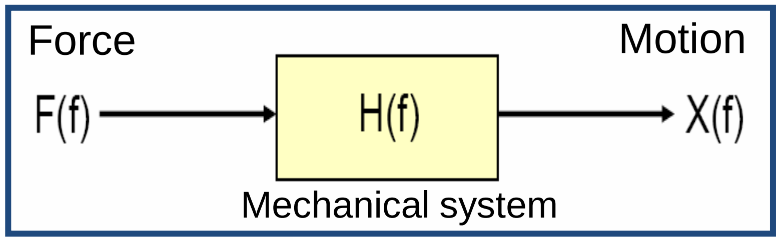
- Basic principle used: Newton's 2nd law

- Examples:
  - force transducers
  - Impedance heads
  - Impact hammers

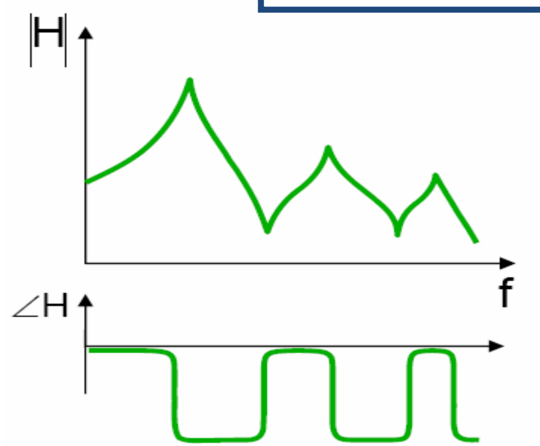
Example: Experimental modal analysis

Dynamic measurement of input and output quantities

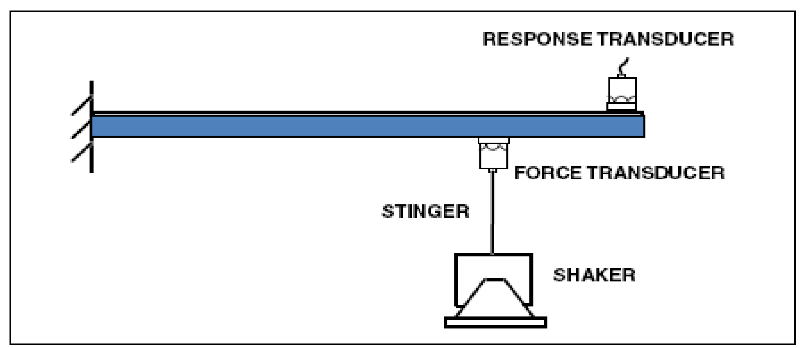
input

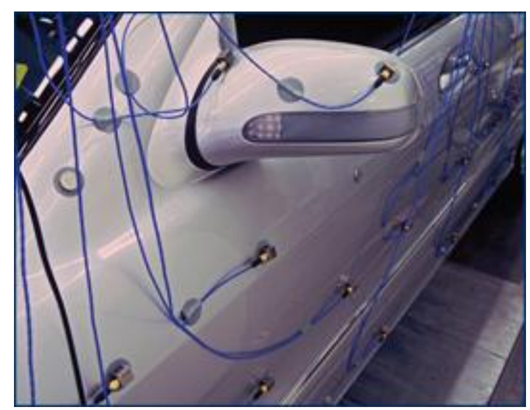


output



$$H(f) = \frac{X(f)}{F(f)}$$





Frequency Response Functions → Magnitude x frequency

Phase x frequency

Quality of experimental modal analysis

Good FRF measurements

Tips and Tricks for Best Results

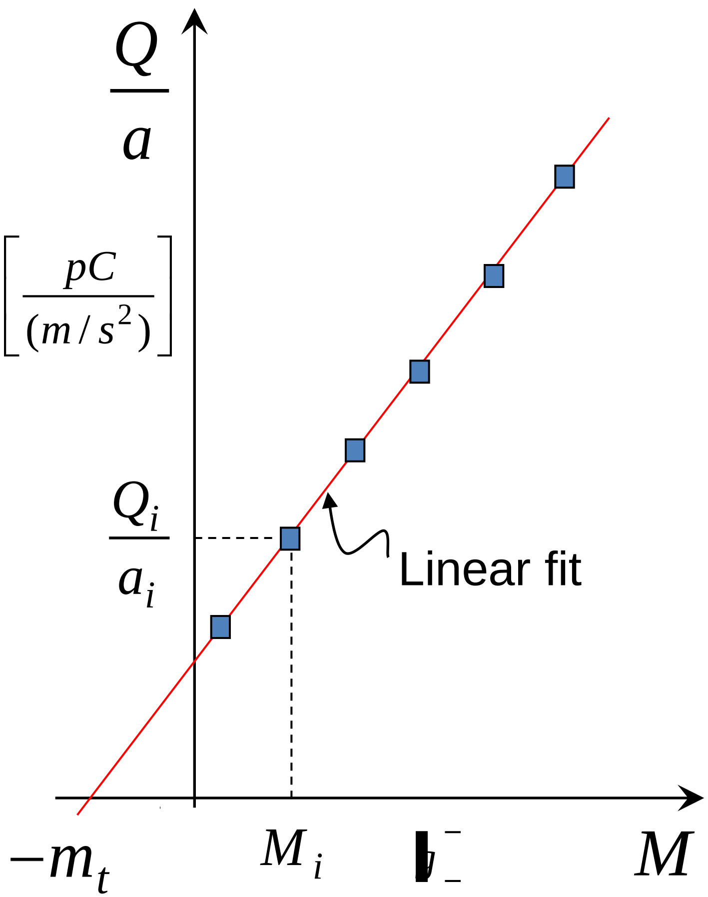
- **Verify measurement chain integrity prior to test:**
  - Transducer calibration
  - Mass Ratio calibration
- **Verify suitability of input and output transducers:**
  - Operating ranges (frequency, dynamic range, *phase* response)
  - Mass loading of accelerometers
  - Accelerometer mounting
  - Sensitivity to environmental effects
  - Stability
- **Verify suitability of test set-up:**
  - Transducer positioning and *alignment*
  - Pre-test: rattling, boundary conditions, rigid body modes, signal-to-noise ratio, linear approximation, excitation signal, repeated roots, Maxwell reciprocity, force measurement, exciter-input transducer-stinger-structure connection

Calibration in laboratory environment

Operational check: Considers the whole measuring system

Quality FRF measurements are the foundation of experimental modal analysis!

Calibration of Piezoelectric force transducer



Load mass

$$F = (M + m_t)a$$

Tip or End mass of the force transducer

Charge output

$$Q = S_F \cdot F = S_F (M + m_t)a$$

Considering a set of load masses M_i

$$\frac{Q_i}{a_i} = S_F M_i + S_F m_t$$

Fit slope → ***Force Sensitivity***

intercept → ***End mass***

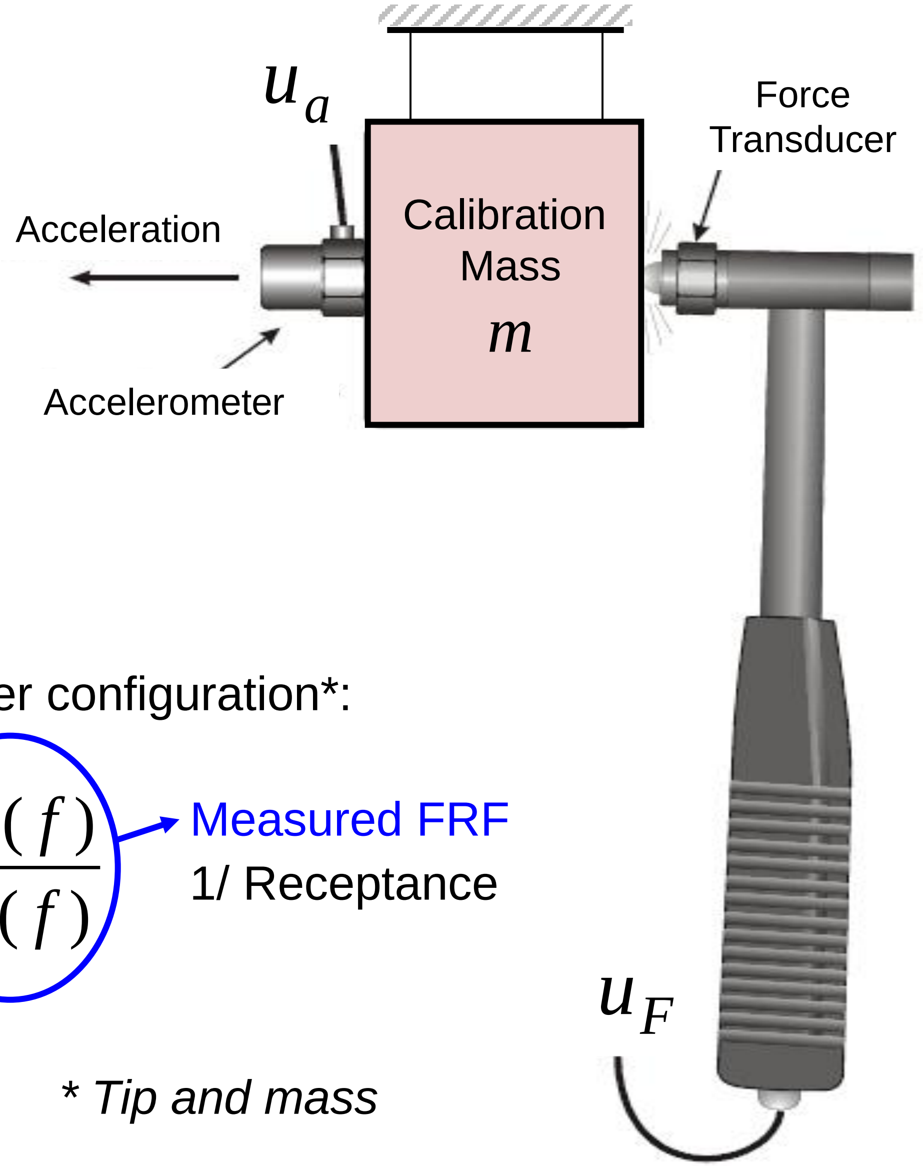
G. Lauer, Development of methods for dynamic force calibration, Part II Absolute calibration of piezoelectric force transducers by laser interferometry,Final Report EUR 12933/2, bcr information, 1990

Impact hammer calibration

$$F = m \cdot a$$

$$\frac{a}{F} = \frac{1}{m} \quad \text{(constant)}$$

$$\frac{S_F(f)}{S_a(f)} \cdot \frac{u_a(f)}{u_F(f)} = \frac{1}{m}$$



Force sensitivity for a given hammer configuration*:

$$S_F(f) = S_a(f) \cdot \frac{1}{m} \cdot \frac{u_F(f)}{u_a(f)}$$

Measured FRF

1/ Receptance

Accelerometer sensitivity

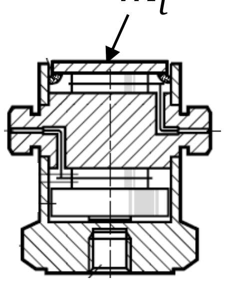
* *Tip and mass*

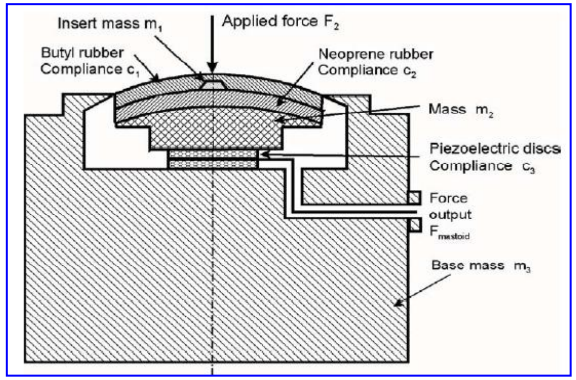
Impedance head calibration

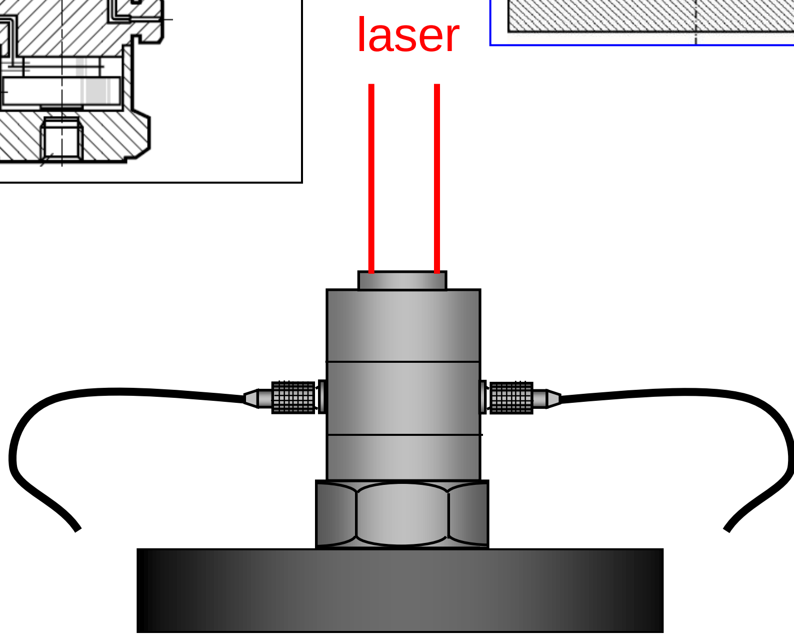
B&K 8000 is a impedance head specifically designed to test an artificial mastoid as specified in IEC 60373

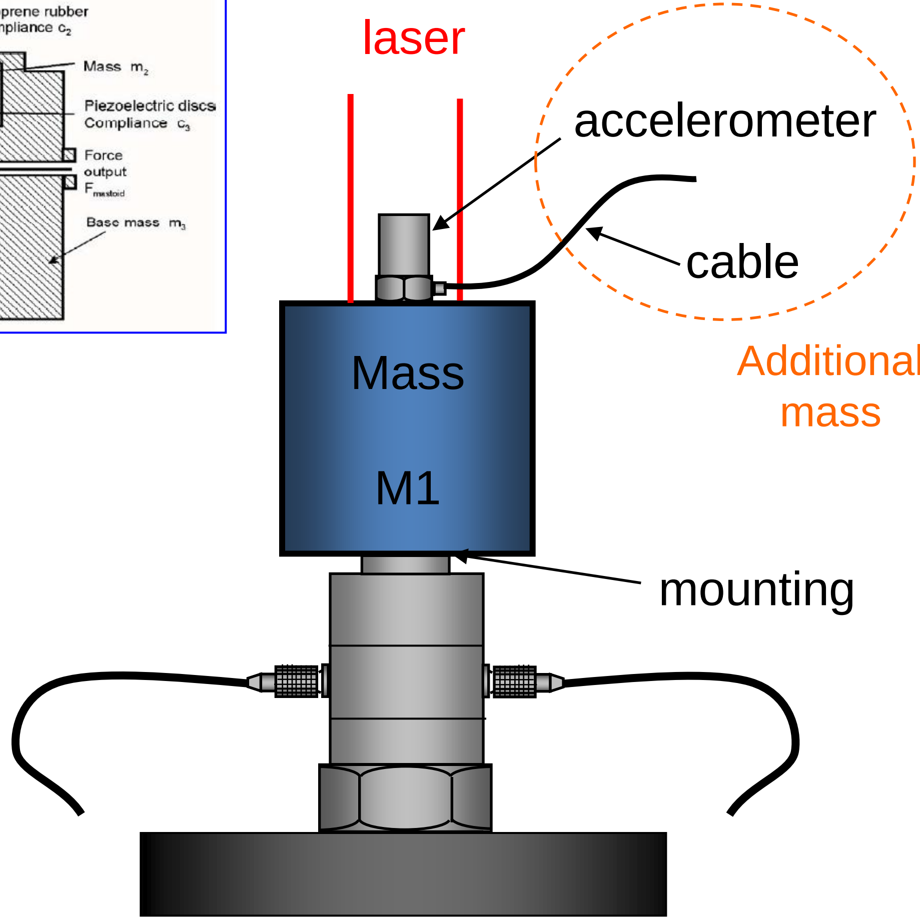
B&K 8000 Flat tip

$$m_t = 1.3\,\mathrm{g}$$



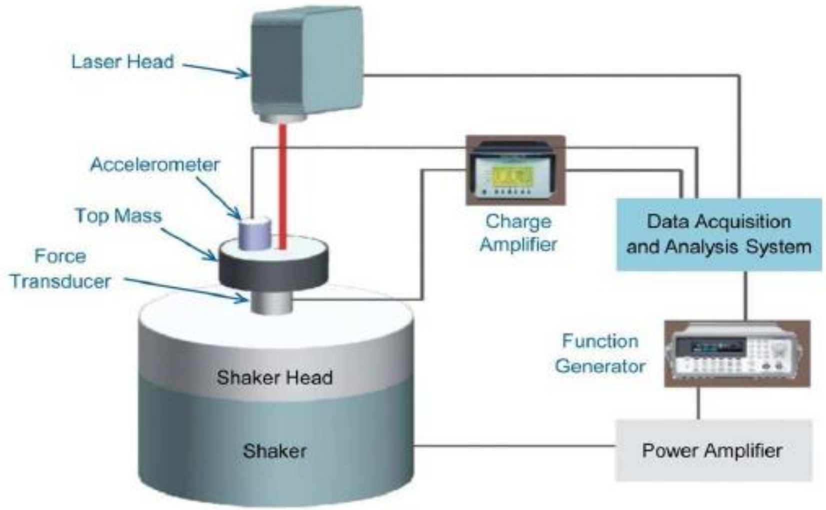


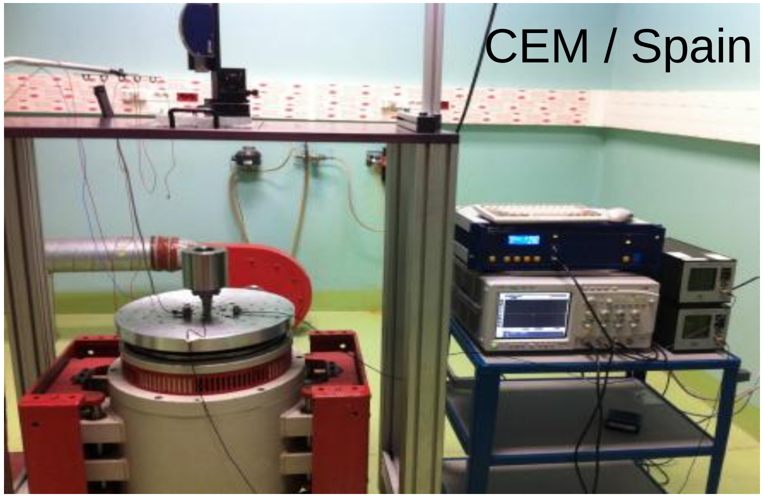


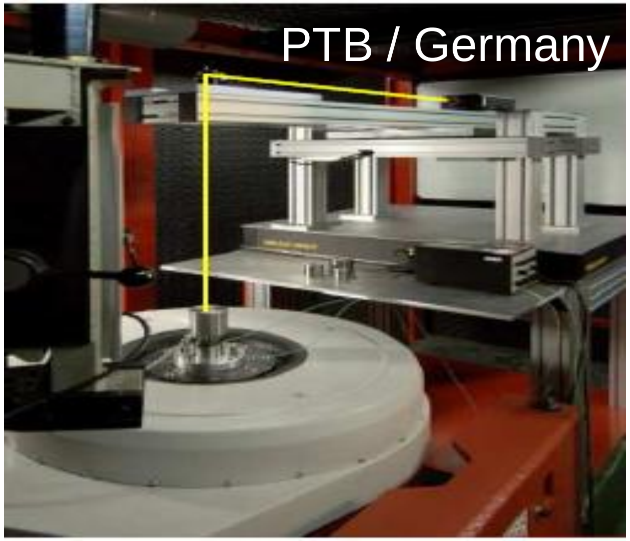


Knud Rasmussen, Calibration of Artificial Mastoids and Impedance Transducers, EUROMET Project 401, Report PL-15, 2000

Sinusoidal force calibration







EMRP JRP-IND09 WP-1

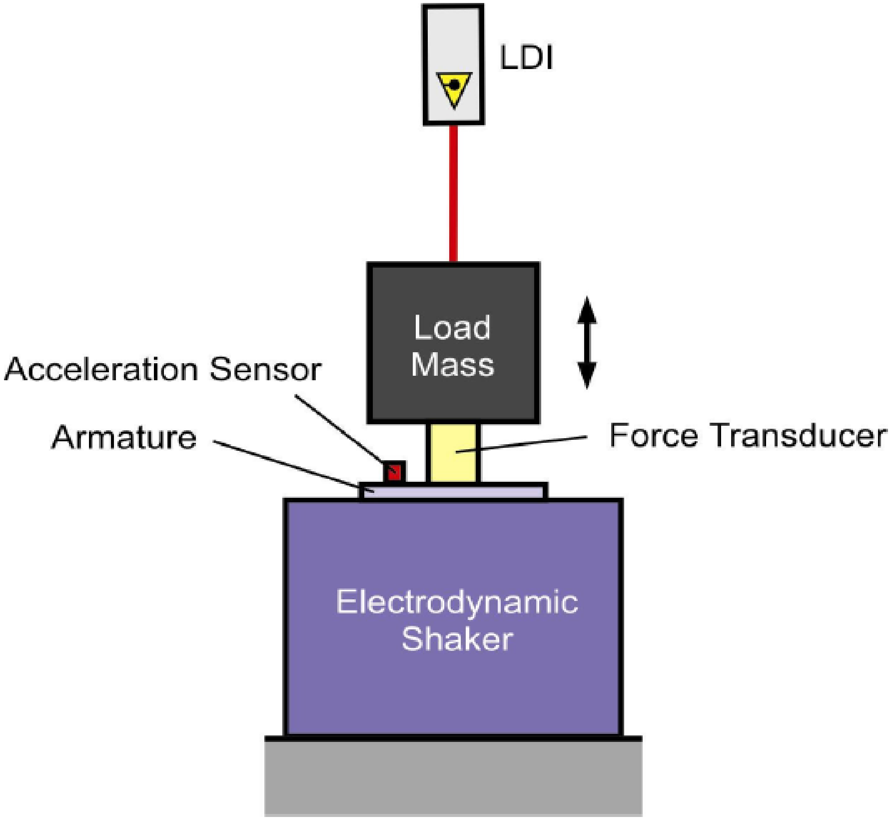
CEM / Spain
- Shaker LDS 726, up to 5 kN

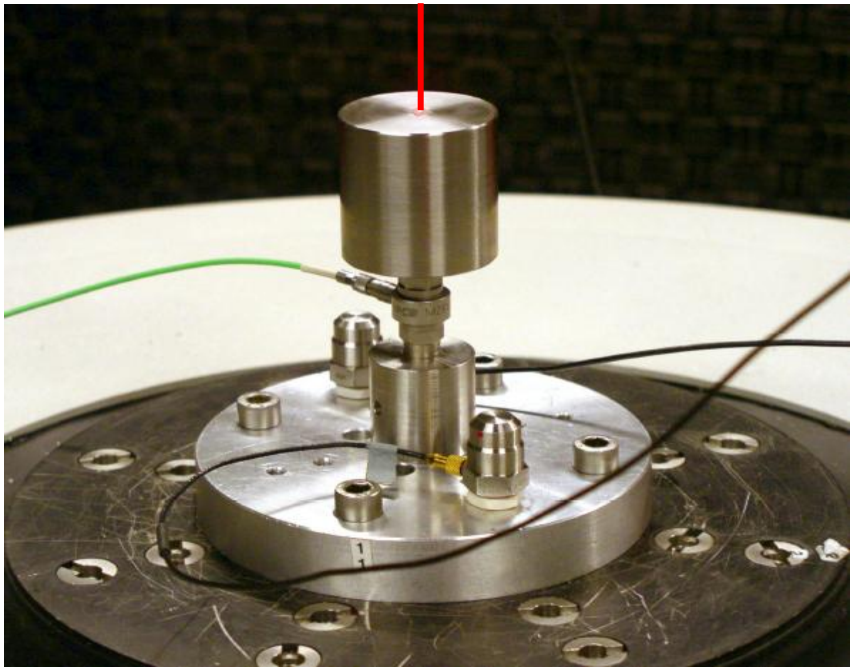
LNE / France
- Shaker LDS 721, up to 2.9 kN

PTB / Germany (3 systems)
- Shaker B&K, up to100 N, 10 Hz to 2 kHz
- Shaker R&S, up to 800 N, 10 Hz to 3 kHz
- Shaker LDS, up to 10 kN, 10 Hz to 2 kHz

C. Bartoli *et al*., Traceable dynamic measurement of mechanical quantities: Objectives and first results of the European Project, In: Proc. of IMEKO World Congress 2012.

PTB 10 kN dynamic force device





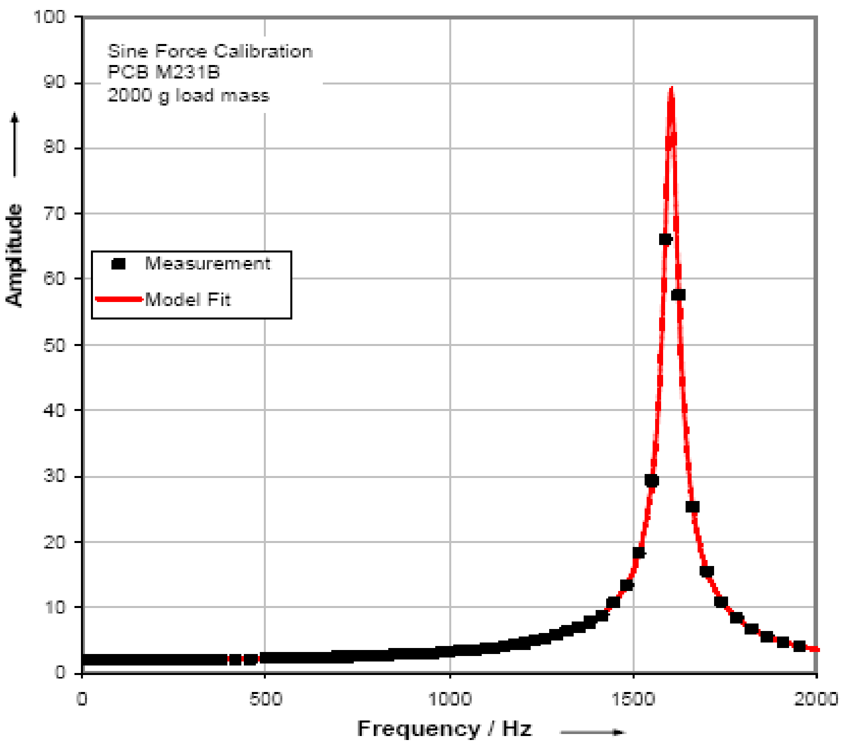
Sine force calibration of a piezoelectric force transducer

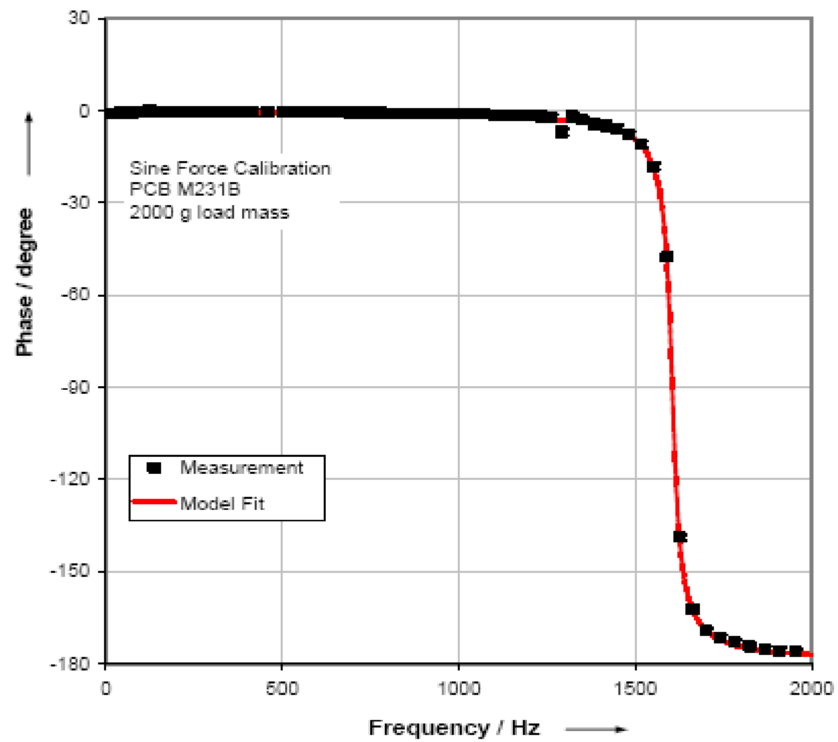
Load masses:
250 g, 500 g, 1000 g and 2000 g

M. Kobusch, A. Link, A. Buss, T. Bruns, Comparison of Shock and Sine Force Calibration Methods, In: Proc. of IMEKO 20th TC3, 3rd TC16 and 1st TC22 Intl. Conf., Merida, 2007

Sine force calibration results

Force transducer PCB M231B, 2000g load mass





Measured data and 2nd order Model Fit

Spring constant *k*,
Damping constant *d*

M. Kobusch, A. Link, A. Buss, T. Bruns, Comparison of Shock and Sine Force Calibration Methods, In: Proc. of IMEKO 20th TC3, 3rd TC16 and 1st TC22 Intl. Conf., Merida, 2007

For larger forces

$$F = (M + m_t)a$$

- This simple equation does not take into account the effects of the relative motion of the load mass and the influences of side forces

- Side forces – can be reduced by air bearing guides

- Relative motion – force must be determined from the acceleration distribution $a(x,t)$ and mass distribution with density ρ

$$F = \int_V \rho \cdot a(x,t) \cdot dV$$

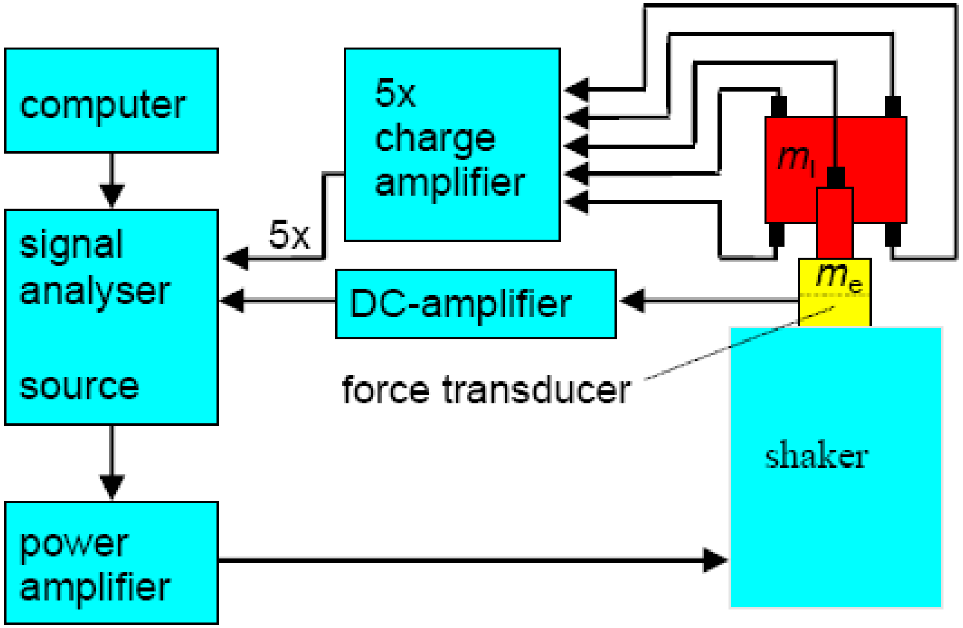
Measurement of acceleration distribution

At higher frequencies and with greater masses the load masses can no longer be considered to be rigid bodies

$$F = \int_V \rho \cdot a(x,t) \cdot dV$$

acceleration distribution

Multiple acceleration measurements

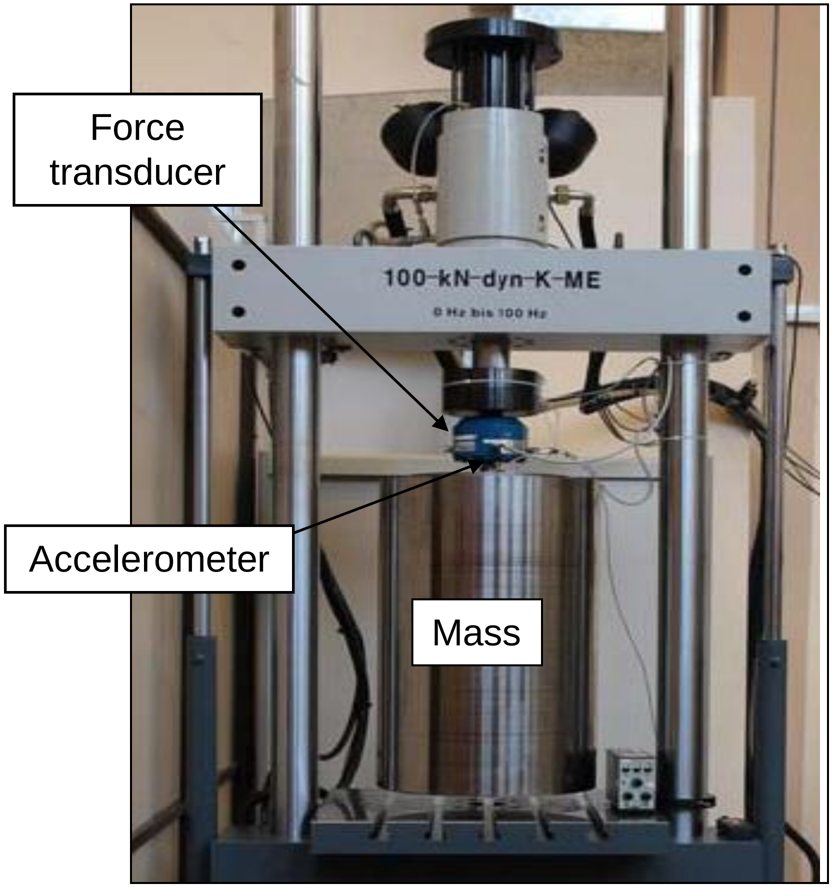


Rolf Kumme, **A NEW CALIBRATION FACILITY FOR DYNAMIC FORCES UP TO 10 kN A NEW CALIBRATION FACILITY FOR DYNAMIC FORCES UP TO 10 kN,** **In: Proc.** *XVII IMEKO World Congress 2003, Croatia*

Dynamic force calibration

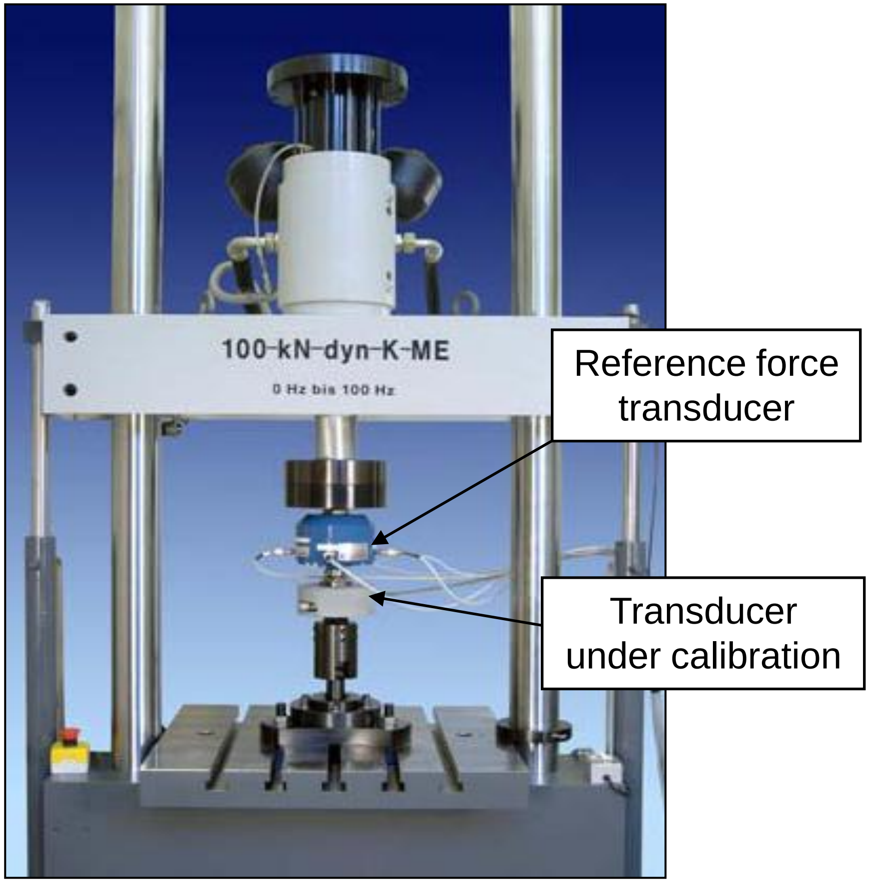
Hydraulic exciter – 0 to 100 kN

- Continuous
- Sinusoidal (0.125 to 100 Hz)



by Inertia forces

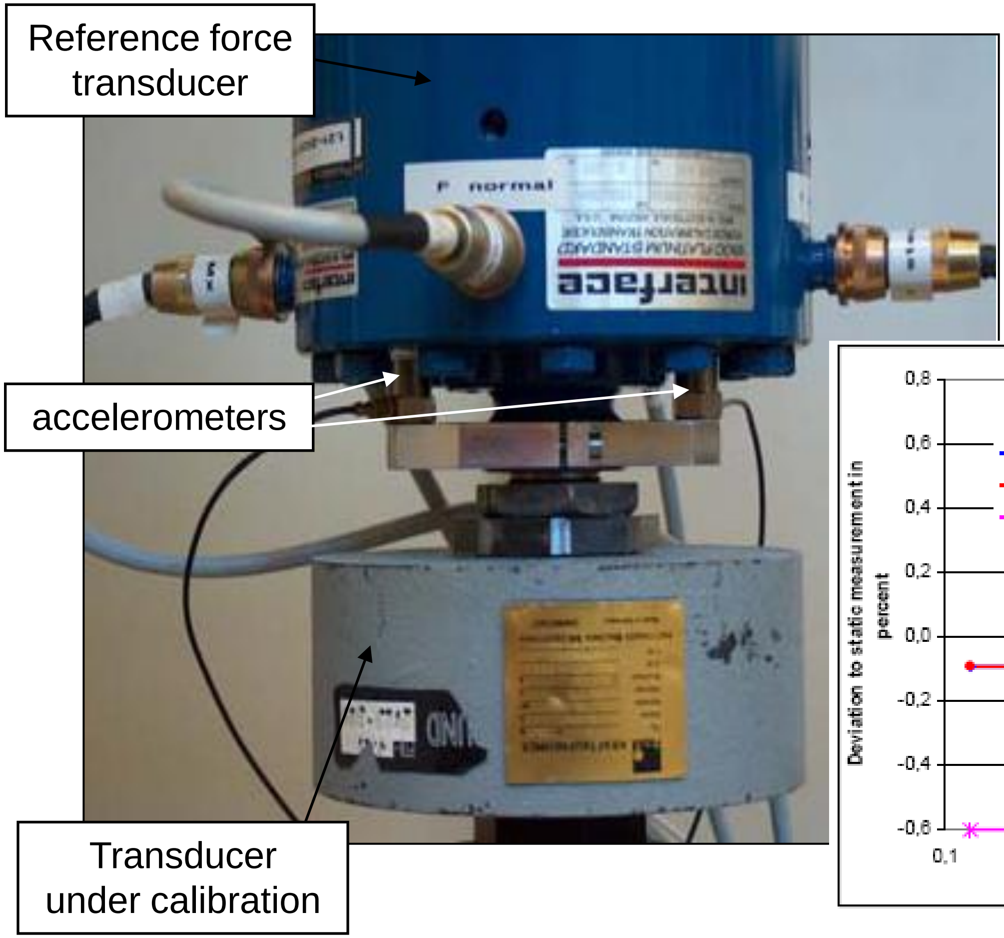
$$F = m\,a$$



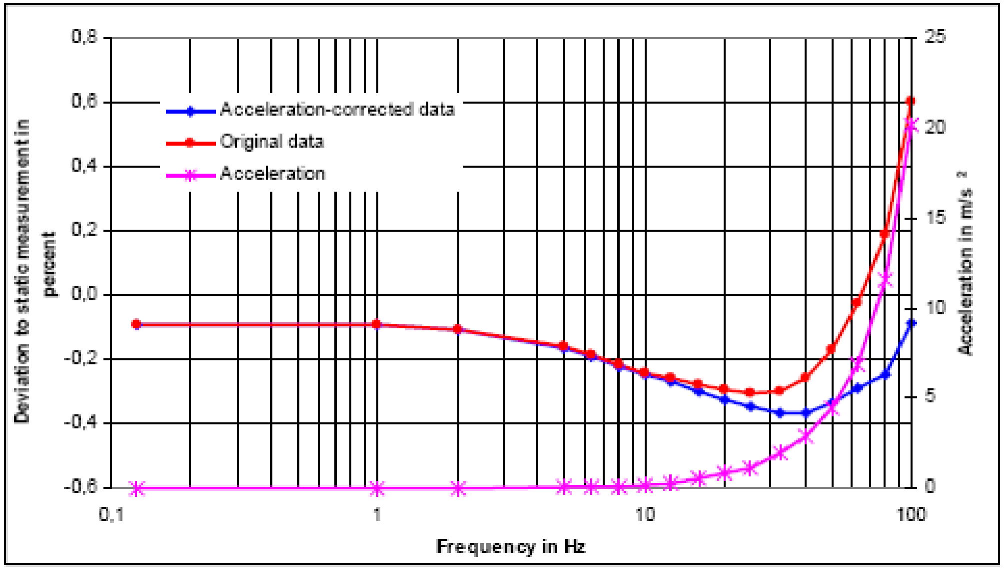
by Direct comparison

Rolf Kumme et al, A NEW FACILITY FOR CONTINUOUS AND DYNAMIC FORCE CALIBRATION WITH FORCES UP TO 100 KN, In: Proc. IMEKO 2010 TC3, TC5 and TC22 Conferences

Direct dynamic force comparison



Accelerometers for compensation of inertia forces of parasitic mass between transducers (estimated as 3.5 kg)

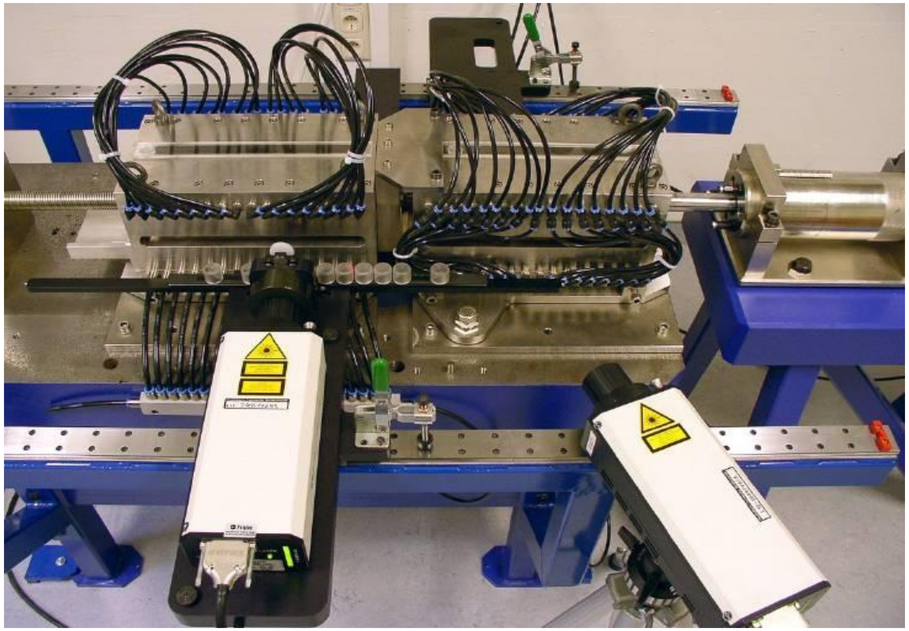


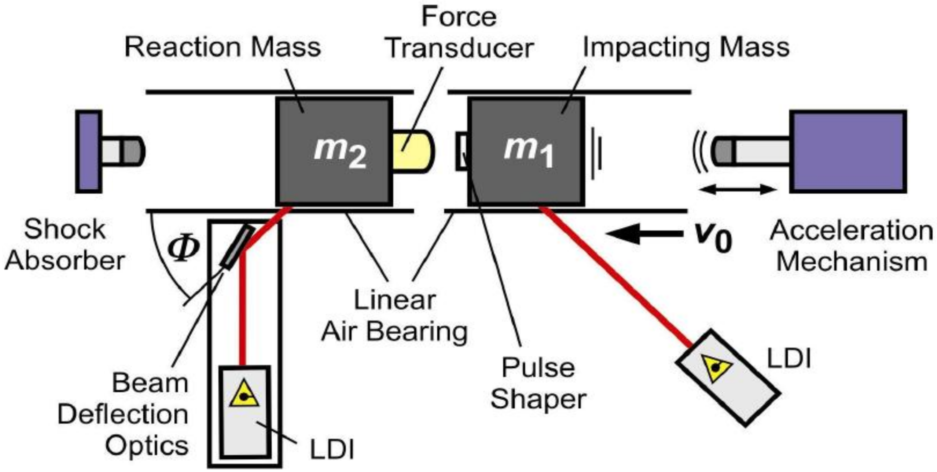
Rolf Kumme et al, A NEW FACILITY FOR CONTINUOUS AND DYNAMIC FORCE CALIBRATION WITH FORCES UP TO 100 KN, In: Proc. IMEKO 2010 TC3, TC5 and TC22 Conferences

PTB 20 kN force impact device

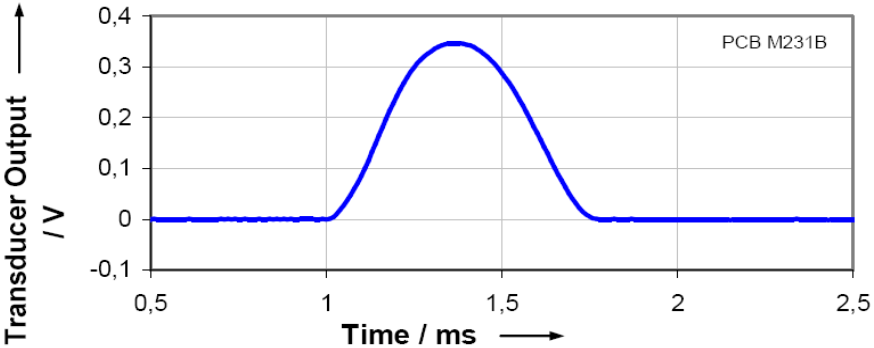
Shock calibration of force transducers

m_1 and m_2 = 10 kg



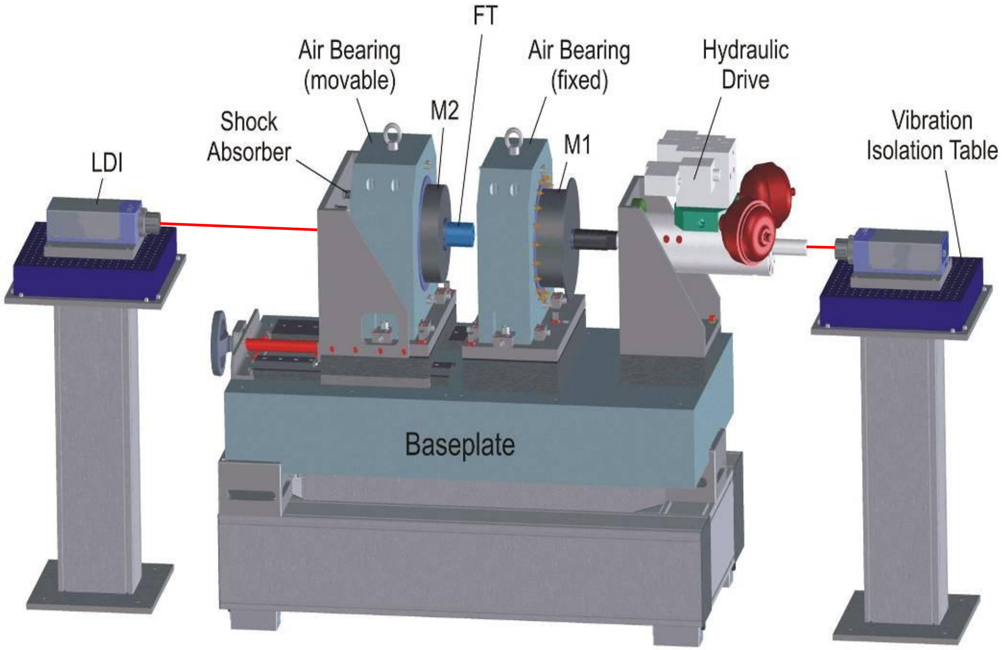


Peak ratio method



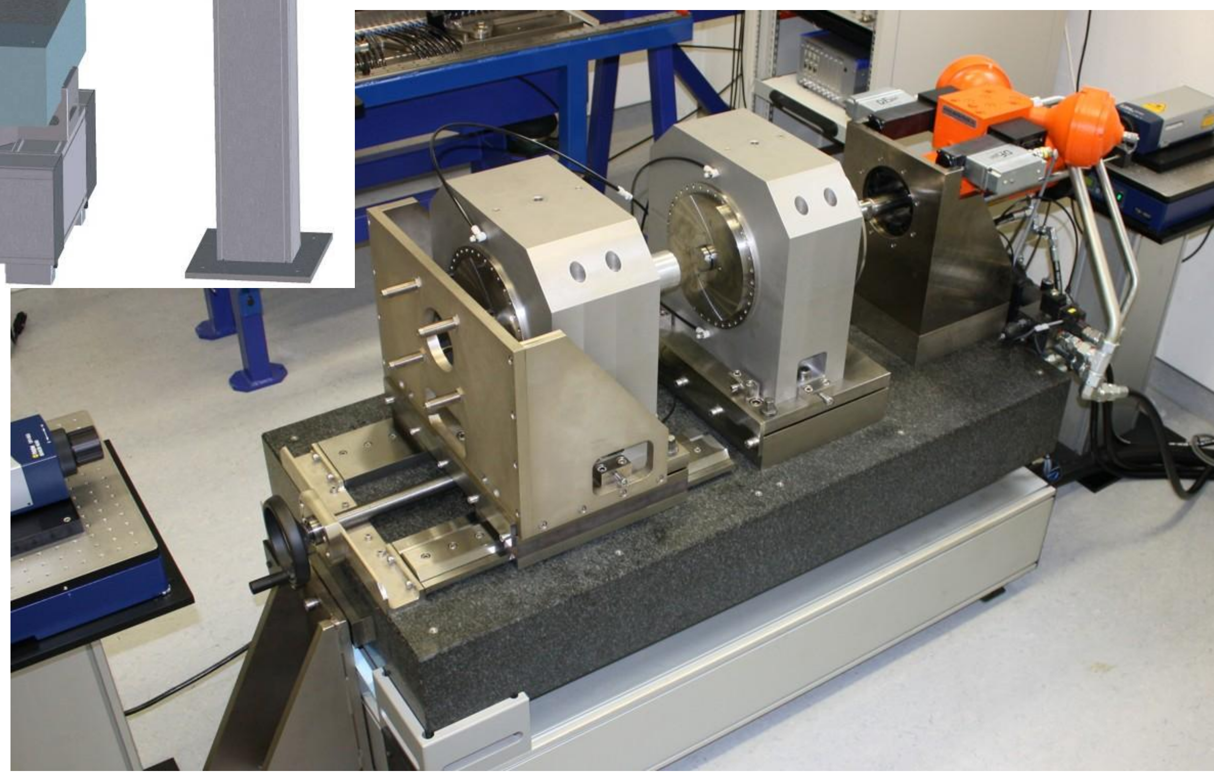
M. Kobusch, A. Link, A. Buss, T. Bruns, Comparison of Shock and Sine Force Calibration Methods, In: Proc. of IMEKO 20th TC3, 3rd TC16 and 1st TC22 Intl. Conf., Merida, 2007

Force shock calibration



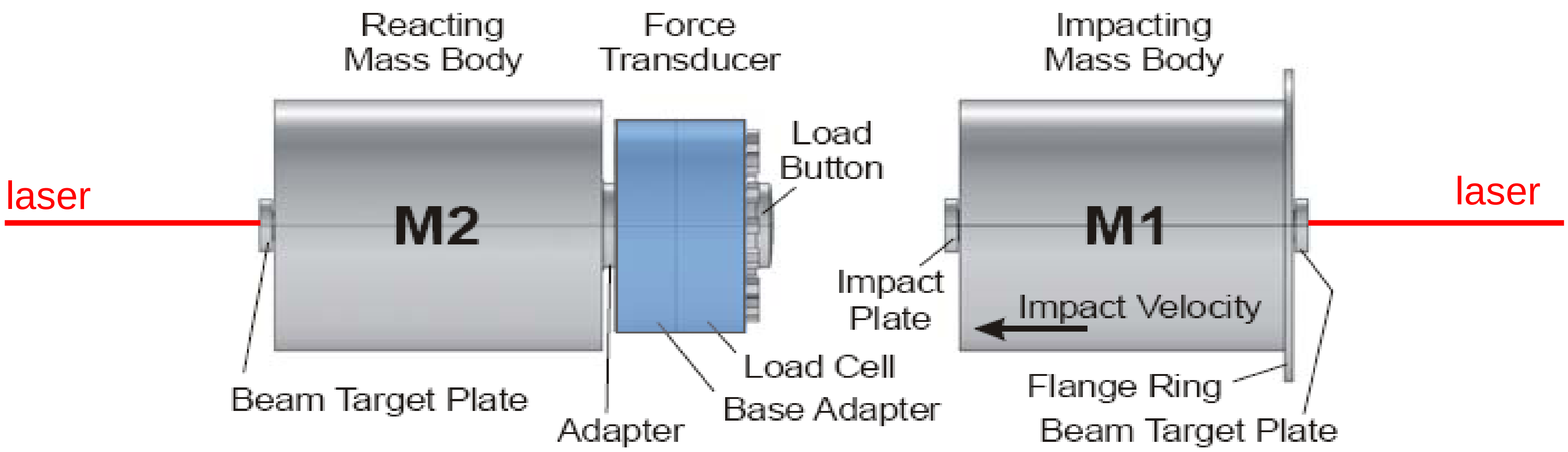
250 kN Force shock Calibration Device

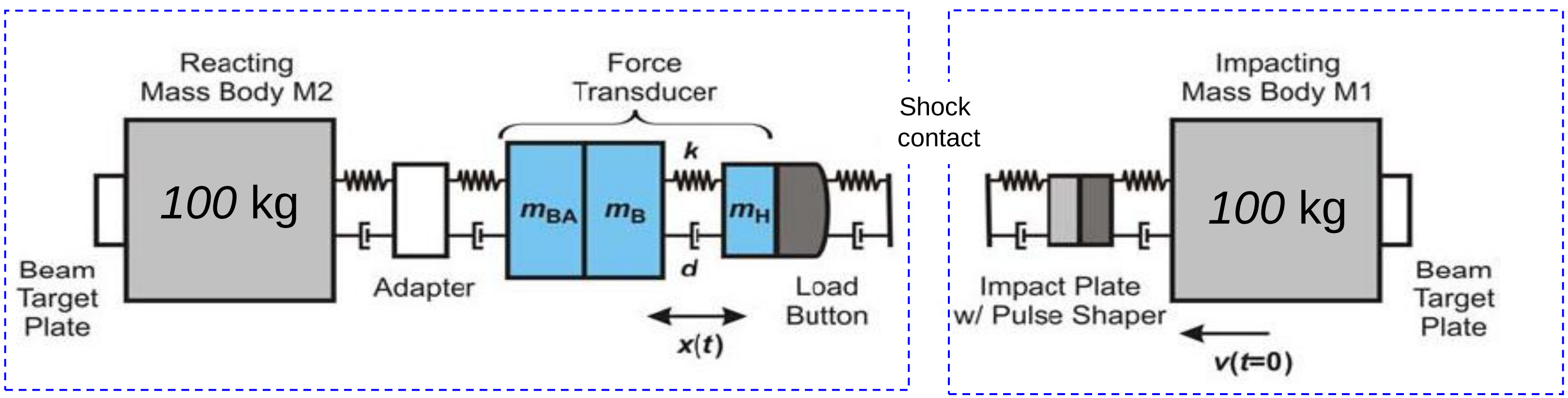
PTB / Germany



Thomas Bruns, Leonard Klaus, Michael Müller, **THE 250 KILONEWTON PRIMARY SHOCK FORCE CALIBRATION DEVICE AT PTB**, In: Proc. IMEKO 2010 TC3, TC5 and TC22 Conferences.

Mechanical configuration of the PTB's 250kN force shock calibration device





Multi-body model of the shock force device

Michael Kobusch, Leonard Klaus, and Thomas Bruns, MODEL-BASED ANALYSIS OF THE DYNAMIC BEHAVIOUR OF A 250 KN SHOCK FORCE CALIBRATION DEVICE, In: Proc. XX IMEKO World Congress, 2012

First experiments

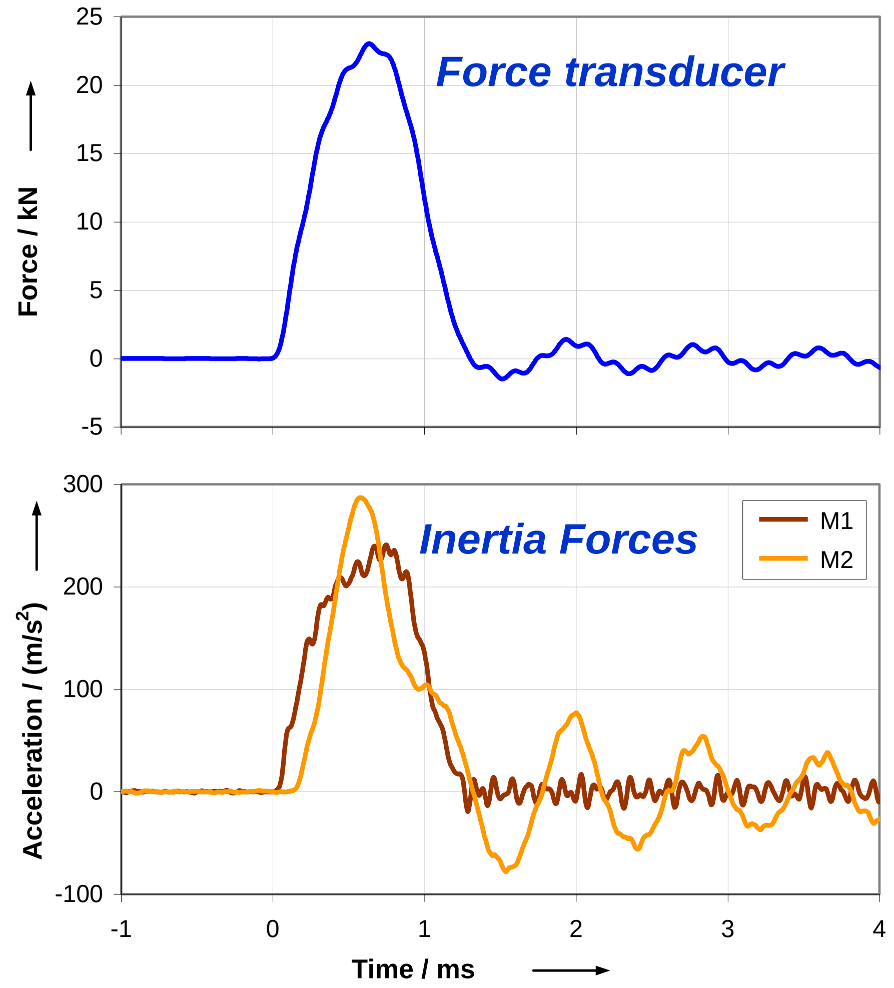
Measurements of Strain Gauge Transducer

- **Example**
  - 23 kN (10% max. load)
  - hard contact
  - 1.2 ms pulse
  - impact velocity 0.17 ms
  - 5 kHz LP filter

- **Result**
  - modal forms excited
  - no good agreement for such short pulses

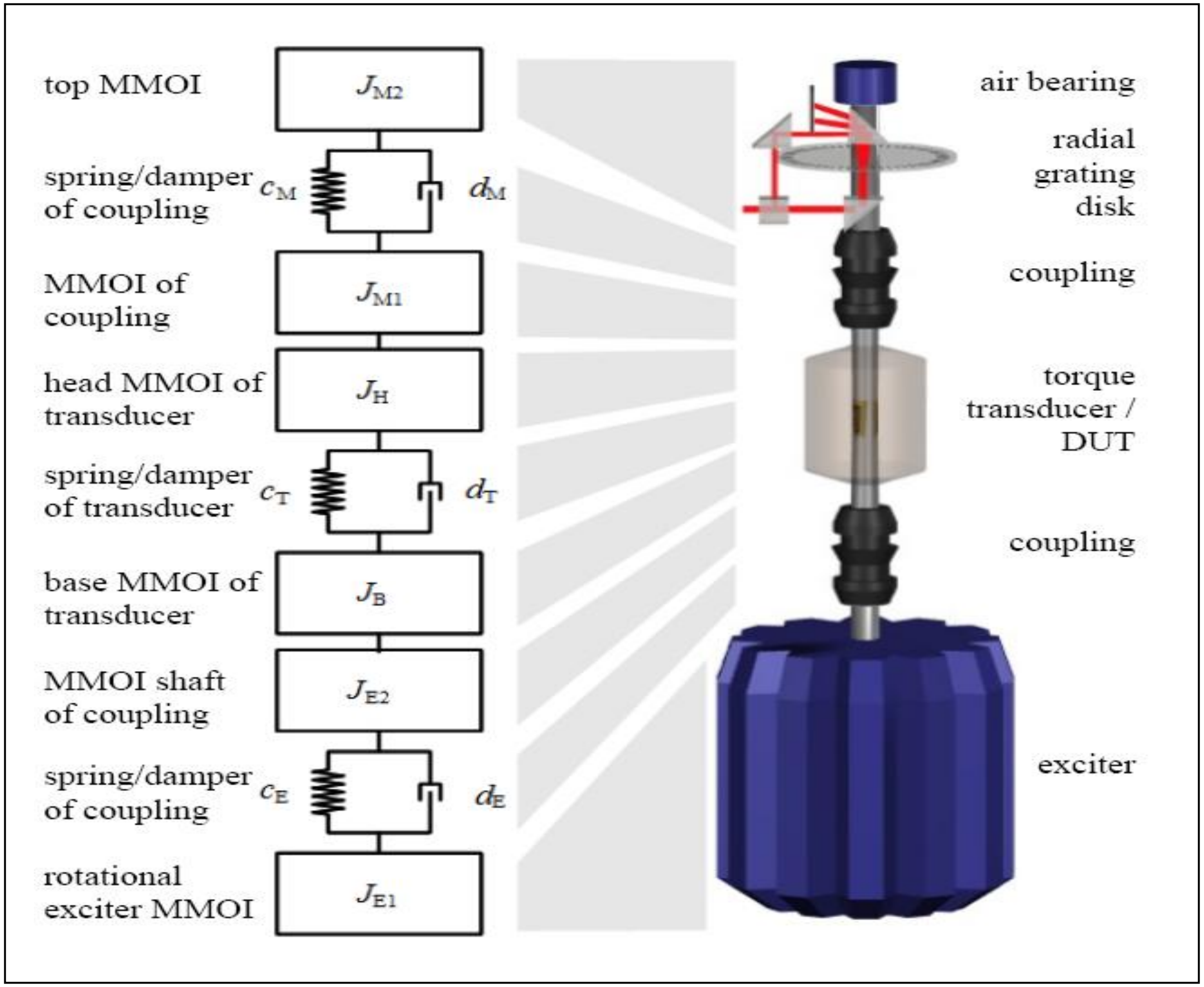
Analysis / Optimisation of device and methods needed!

250 kN Force shock Calibration Device



Dynamic torque calibration

Mechanical model | Measuring device



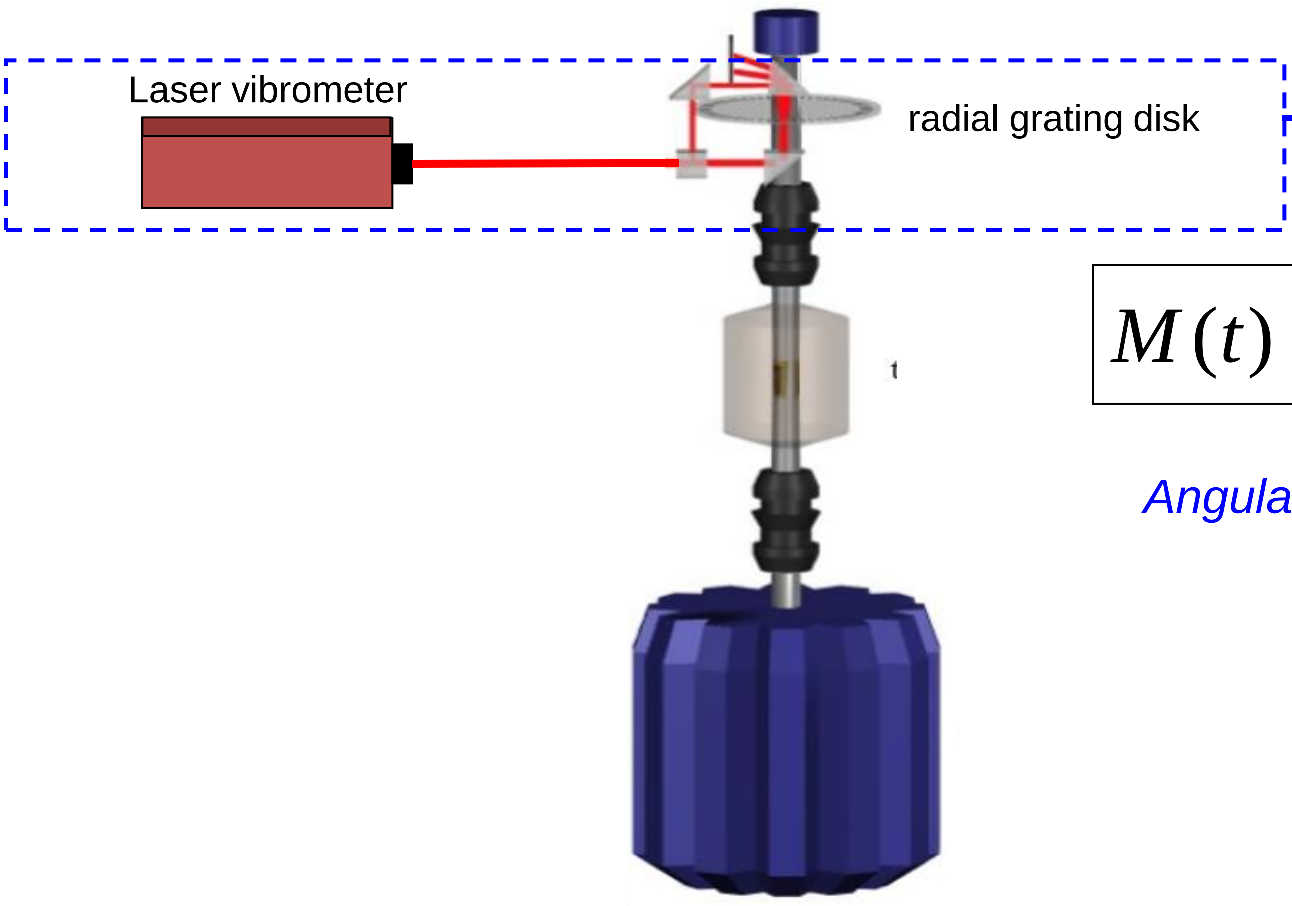
The measurement principle is in analogy to periodic force excitation based on the Newton's second law

$$M(t) = \ddot{\phi}(t) \cdot J$$

Dynamic torque as: Angular acceleration times Mass moment of Inertia

Sinusoidal torque

Primary angular acceleration measurement

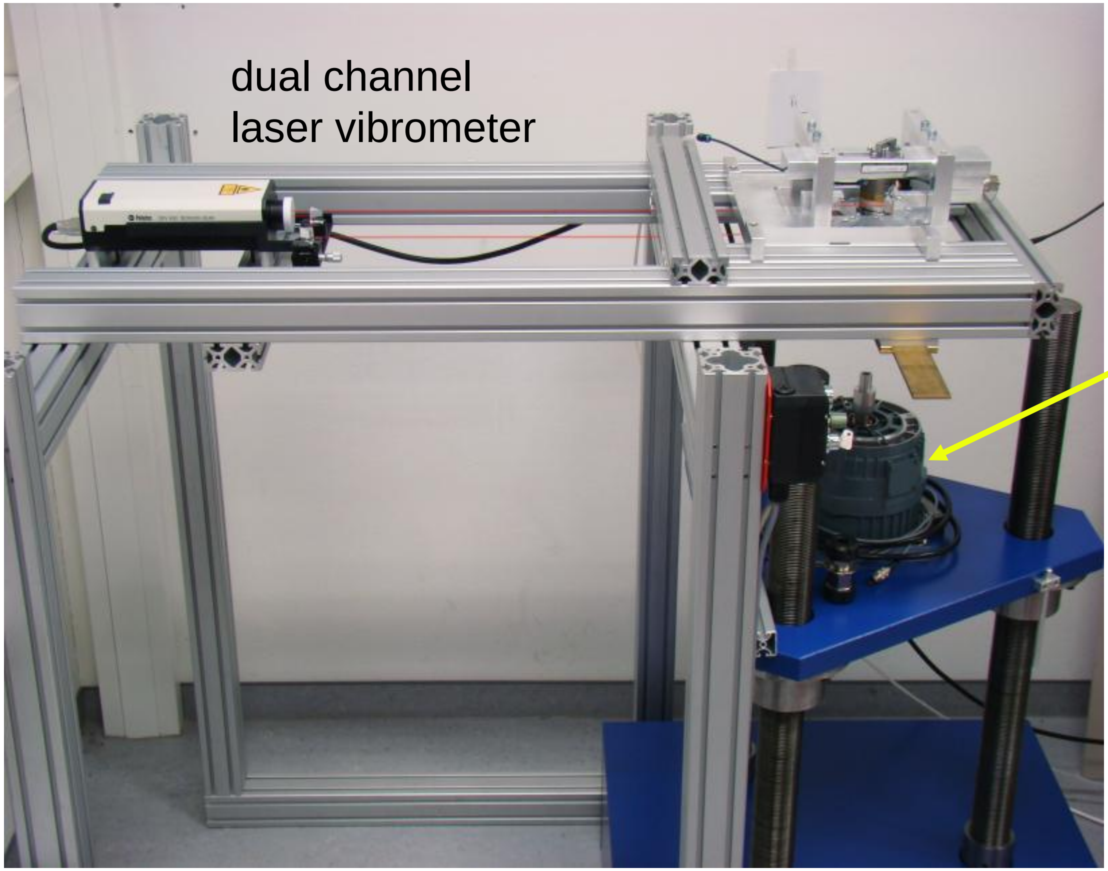


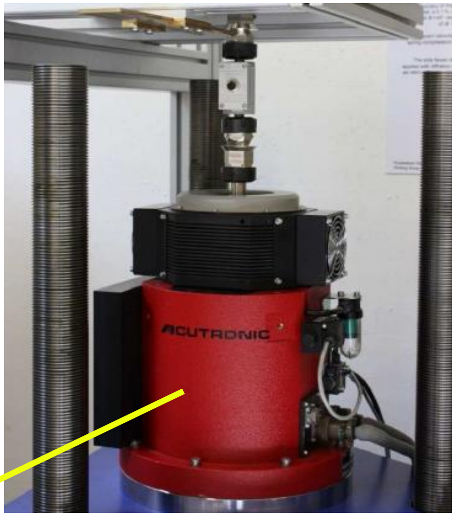
$$M(t) = \ddot{\phi}(t) \cdot J$$

Angular acceleration

PTB primary torque prototype

primary traceability on the units
mass moment of inertia, wavelength, time



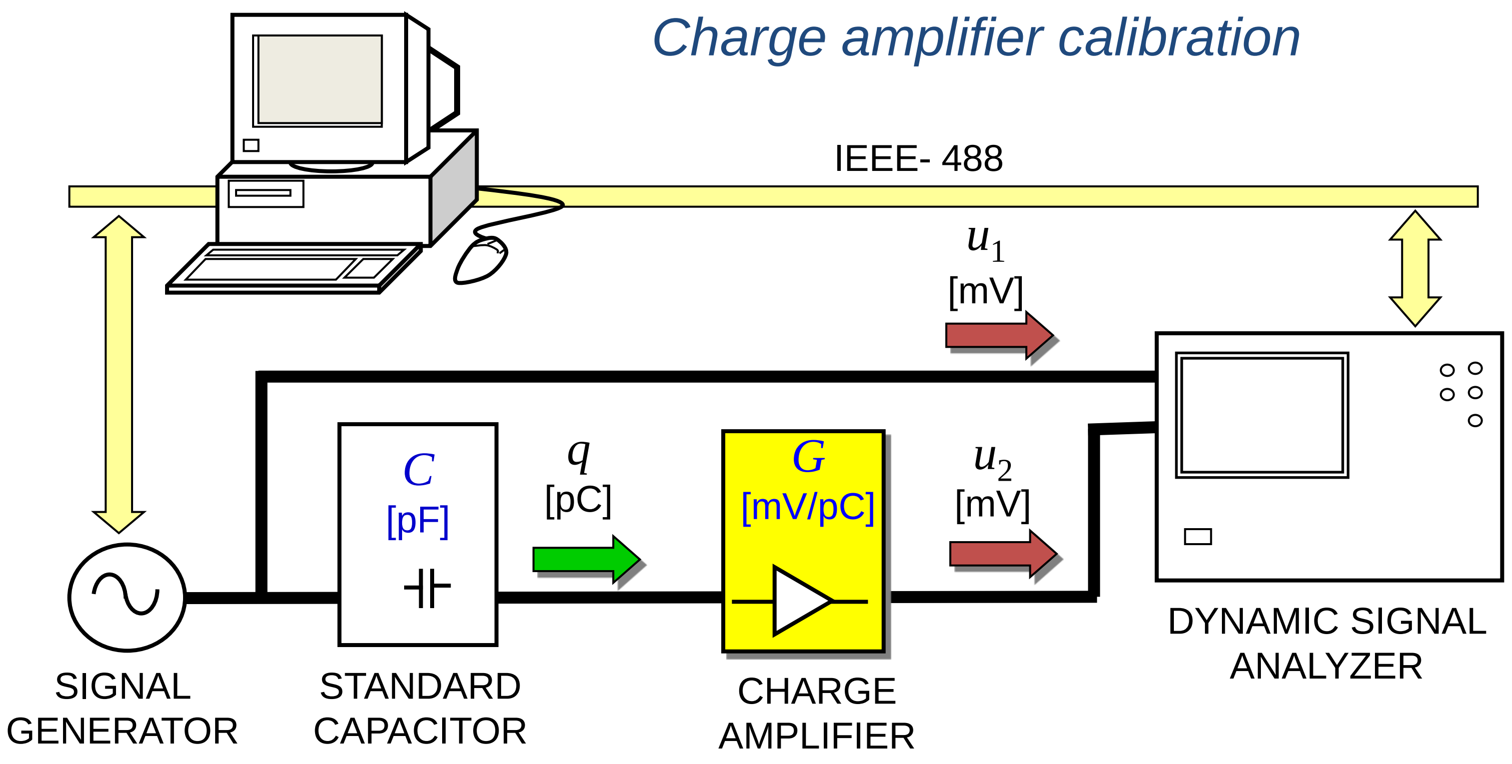


- New rotational exciter and controller
- New air bearing

<u>Goal:</u>
Torque amplitude - 20 N·m
Frequency – up to 1 kHz

Claire Bartoli et al, TRACEABLE DYNAMIC MEASUREMENT OF MECHANICAL QUANTITIES: OBJECTIVES AND FIRST RESULTS OF THIS EUROPEAN PROJECT, In: Proc. XX IMEKO World Congress, 2012

Electrical calibration of signal conditioners



magnitude $$G = \frac{u_2}{q} = \frac{u_2}{u_1 C}$$

phase $$\varphi(G) = \varphi(u_2) - \varphi(u_1)$$

Calibration of signal conditioners

Charge amplifiers

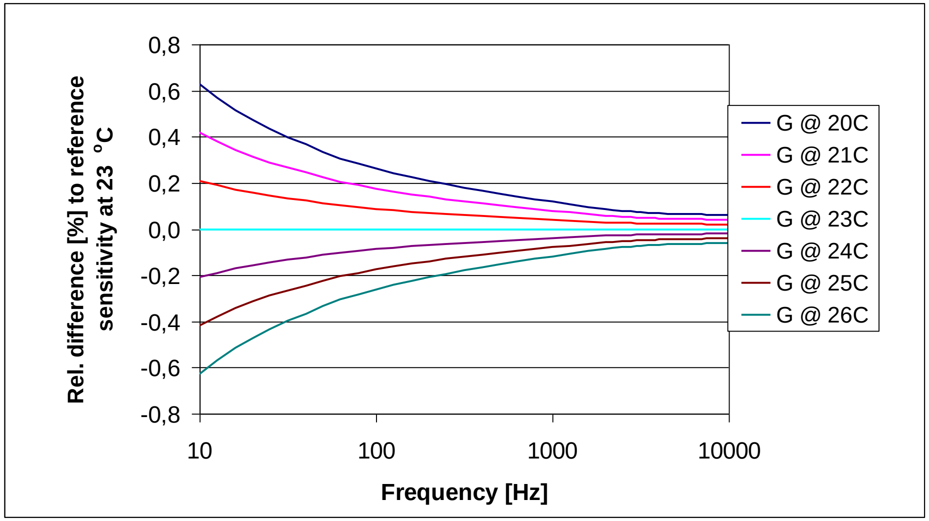
- Formal traceability of reference capacitances for the entire frequency range of interest
- New challenges due to
  - the improvement of uncertainties and,
  - broadening of measurement ranges.
- Calibration with non-periodic input for use in shock
- Effects at extreme frequencies
- Loading effects at high frequencies

Charge amplifier calibration

Effect of environmental temperature

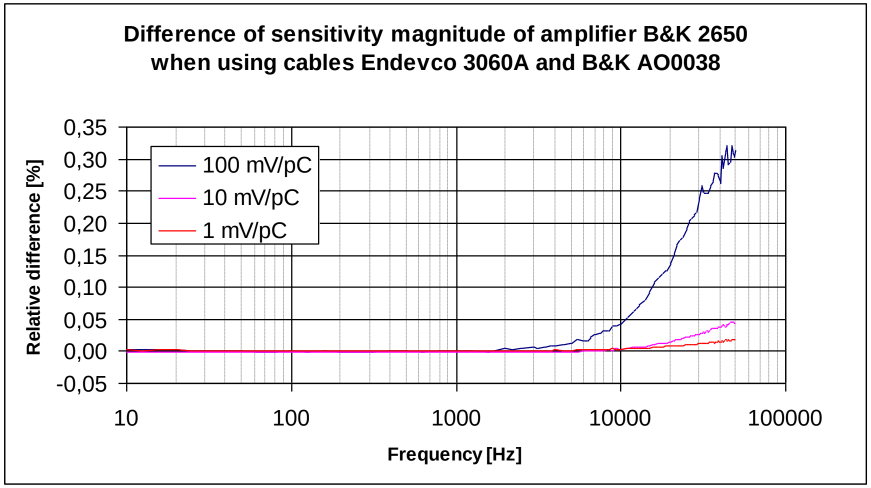
Relative difference [%] of the sensitivity magnitude depending on temperature

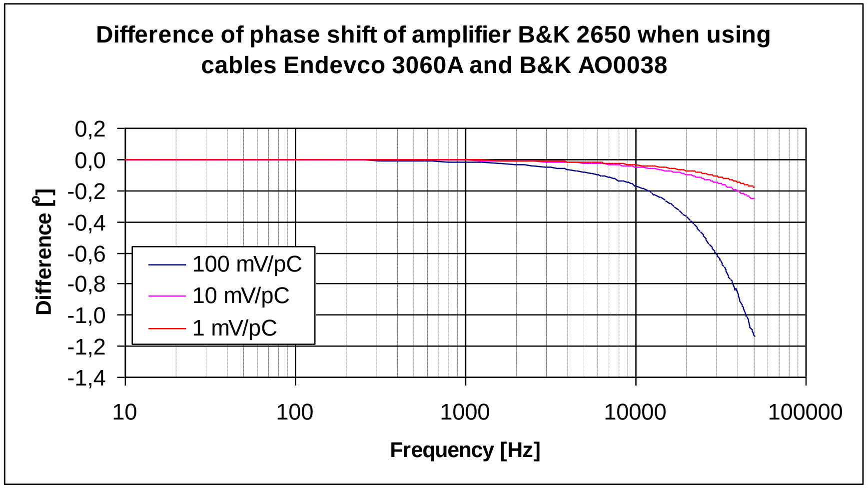
Example: charge amplifier B&K 2626
(Settings: Sens 1.00, 0.1 V/Unit Out, LFL 0.3Hz, HFL Lin.)



Effect of input cable capacitance

B&K: 110 pF, Endevco: 403 pF





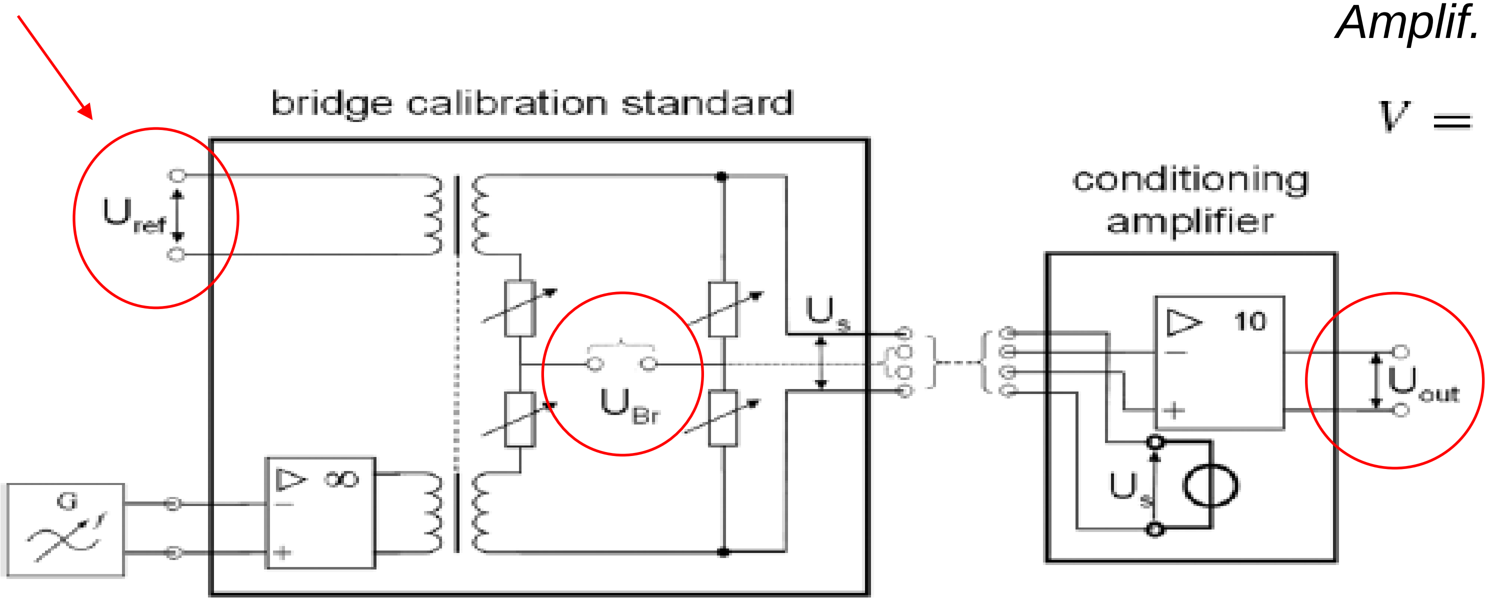
Calibration of bridge conditioning amplifier

The calibration device simulates the conditions of a real force transducer

Inductively, an ac signal is coupled into the bridge and the dynamic bridge detuning is monitored via an auxiliary output.

Amplif. factor

$$V = \frac{U_{out}}{U_{Br}}.$$



schematic circuit of the PTB bridge calibration standard

DUT

$U_{95\%}$ = 0,015 % at 400 Hz

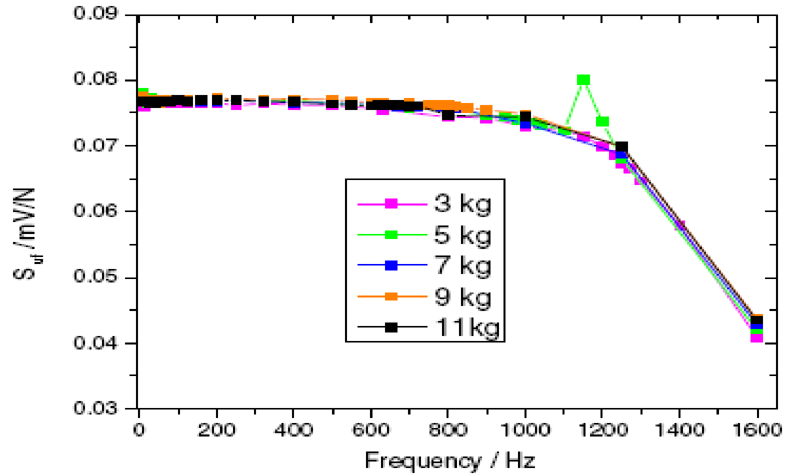
Ch Schlegel *et al.*, Traceable periodic force calibration**,** Metrologia **49** (2012) 224–235

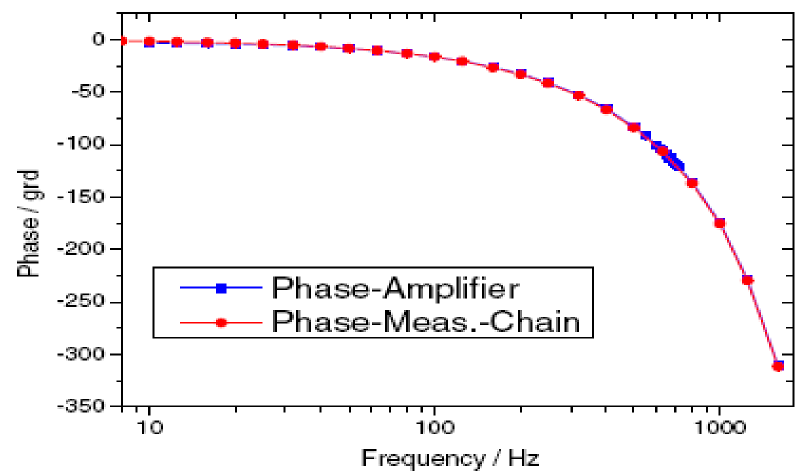
Correction of amplifier response

Magnitude

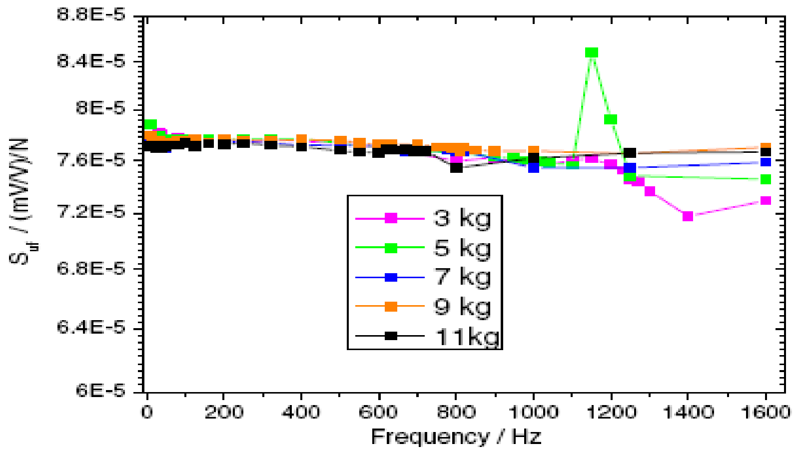
Phase response

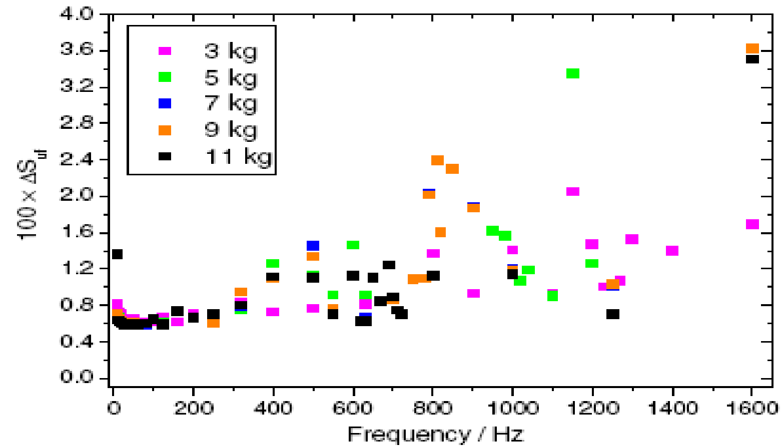
chain





transducer





Ch Schlegel *et al*., Traceable periodic force calibration,
Metrologia **49** (2012) 224–235

Signal conditioners

Type of transducer:

- Strain gauge ⇨ Bridge amplifier
  - Typically ~450 Ohm

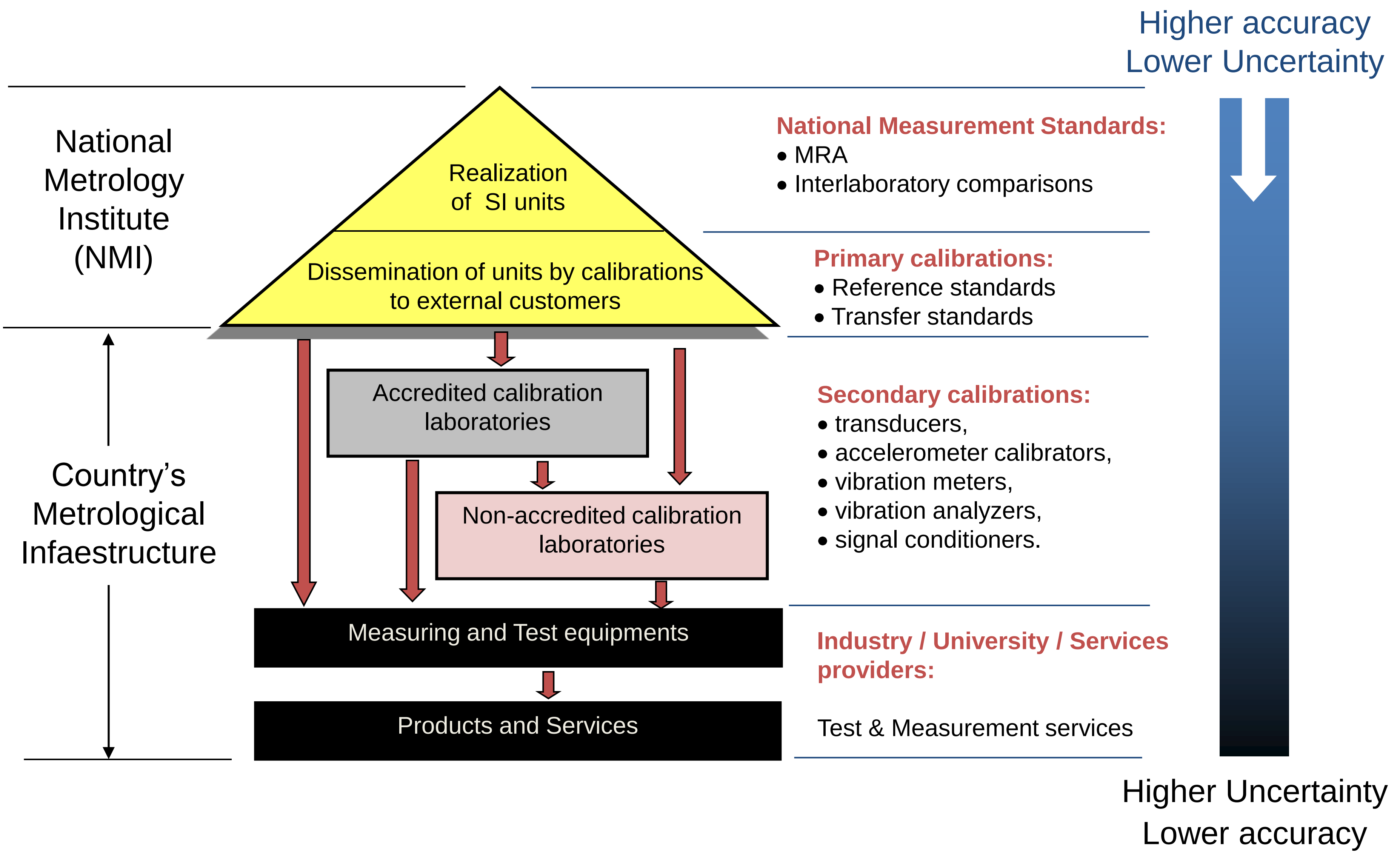
U = 0,05 % (PTB)

- Piezoelectric ⇨ Charge amplifier

U = 0,05 % to 0,1 %

- Other types? Piezoresistive

Metrological hierarchy for Vibration



Documentary Standards

- ISO 5347 - Methods for the calibration of vibration and shock pick-ups

Part 5: Calibration by Earth's gravitation
Part 7: Primary calibration by centrifuge
Part 8: Primary calibration by dual centrifuge
Part 12: Testing of transverse shock sensitivity
Part 13: Testing of base strain sensitivity
Part 14: Resonance frequency testing of undamped accelerometers on a steel block
Part 15: Testing of acoustic sensitivity
Part 16: Testing of mounting torque sensitivity
Part 17: Testing of fixed temperature sensitivity
Part 18: Testing of transient temperature sensitivity
Part 19: Testing of magnetic field sensitivity
Part 22: Accelerometer resonance testing – General methods

Still valid, reviewed and confirmed without revision

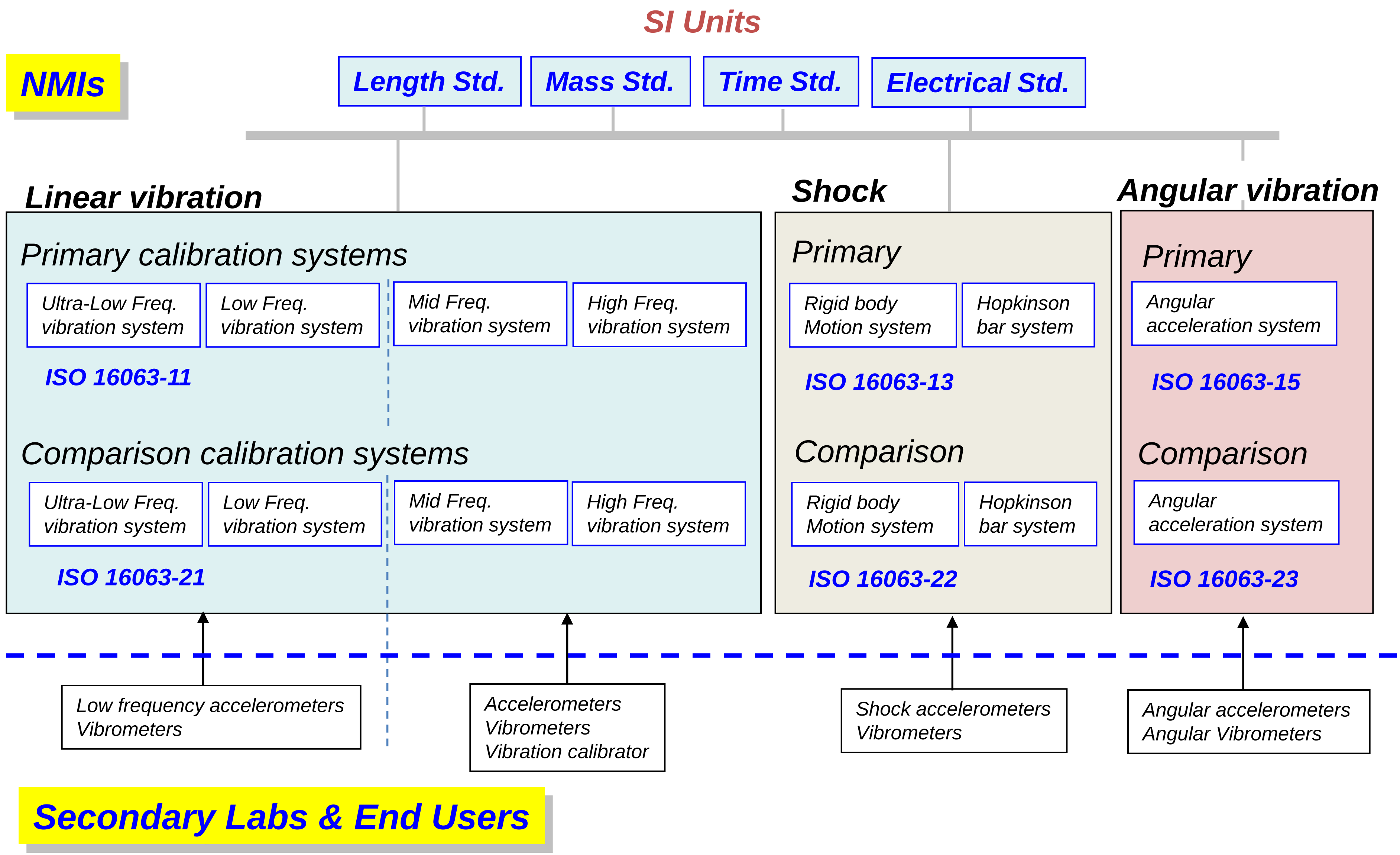
- ISO 16063 - Methods for the calibration of vibration and shock transducers

<u>Structure:</u>

Part 1: Basic concepts
Part 1X: Primary calibration
Part 2X: Secondary calibration
Part 3X: Calibration in severe environment
Part 4X: Other calibration methods

Revised and new

Traceability hierarchy of Vibration laboratories



ISO 16063-11:1999

Methods for the calibration of vibration and shock transducers
Part 11: Primary vibration calibration by laser interferometry

Method 1 - Fringe counting

- freq.: 0.4 - 800 Hz
- amplitudes: s > 2500 nm (4λ)
- constant acceleration

Freq (Hz)	R_f
10	320231
160	1251
800	50
1000	32

a = 100 m/s^2

Method 2 - Minimum point

- freq.: 800 - 10000 Hz
- amplitudes: s > 193 nm (J_1)
- fixed discrete accelerations

Freq (Hz)	a (m/s^2)
800	4.9
1000	7.6
5000	190
10000	762

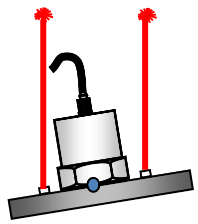
s = 193 nm

Method 3 - Sine approximation

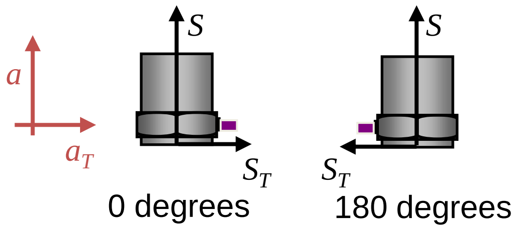
- freq.: 0.4 - 10000 Hz
- amplitudes: s > 316 nm (λ/2)
- constant acceleration

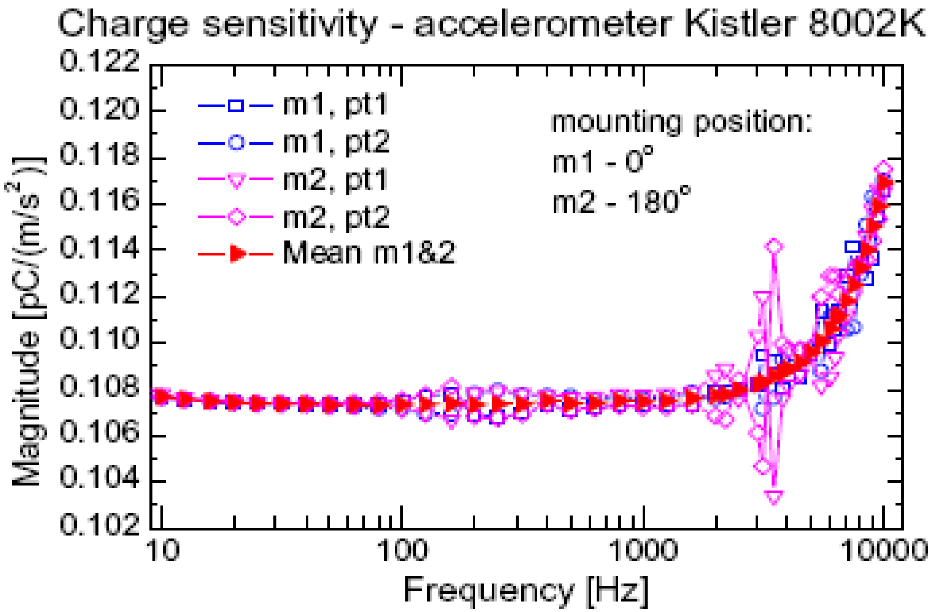
Additional procedures / guides needed to minimize common systematic errors

Rocking motion

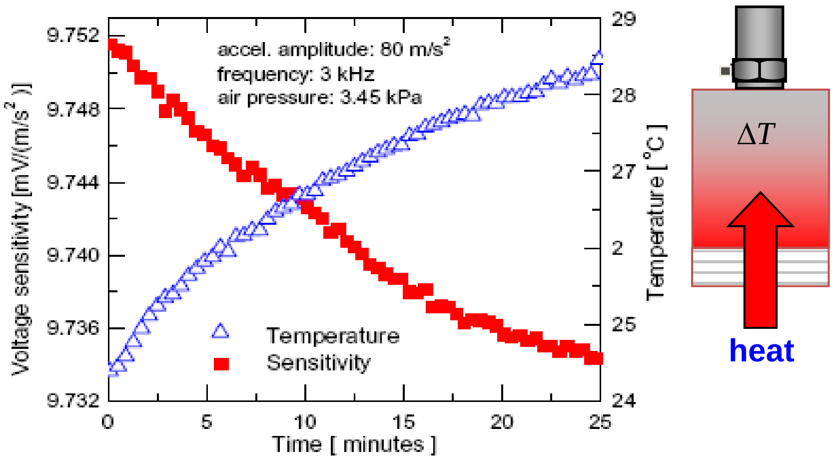


Transverse sensitivity

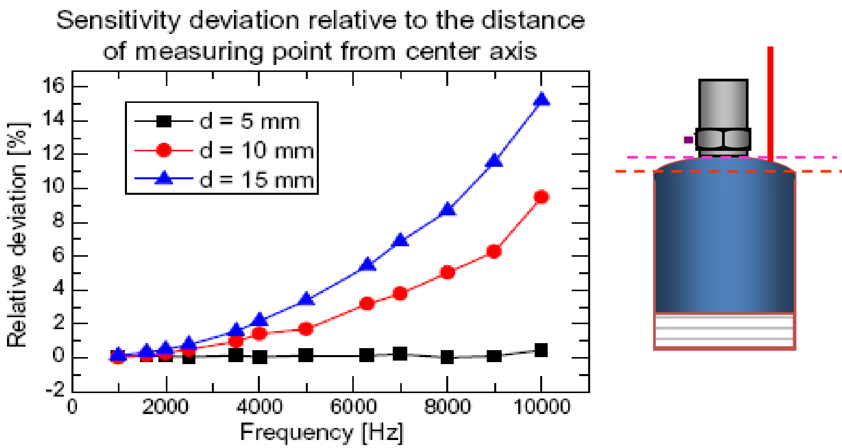




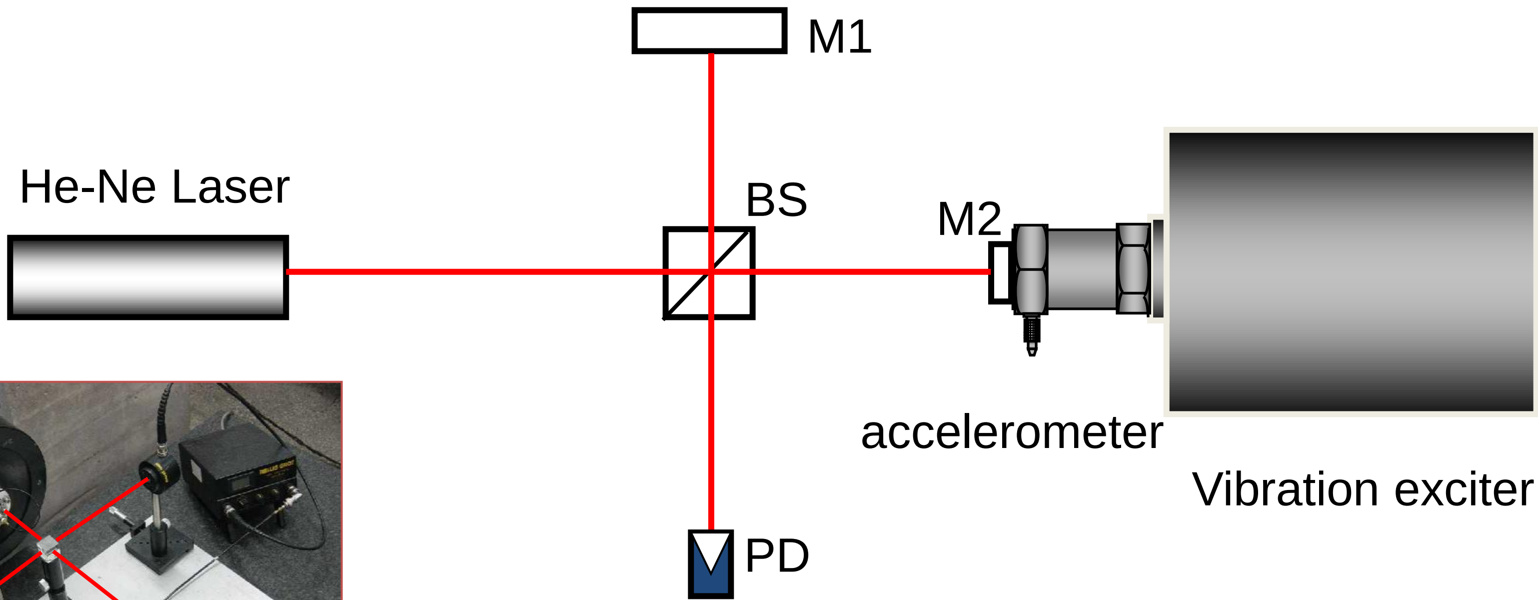
Differential heating

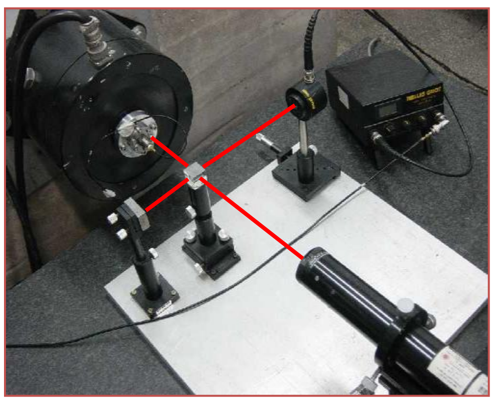


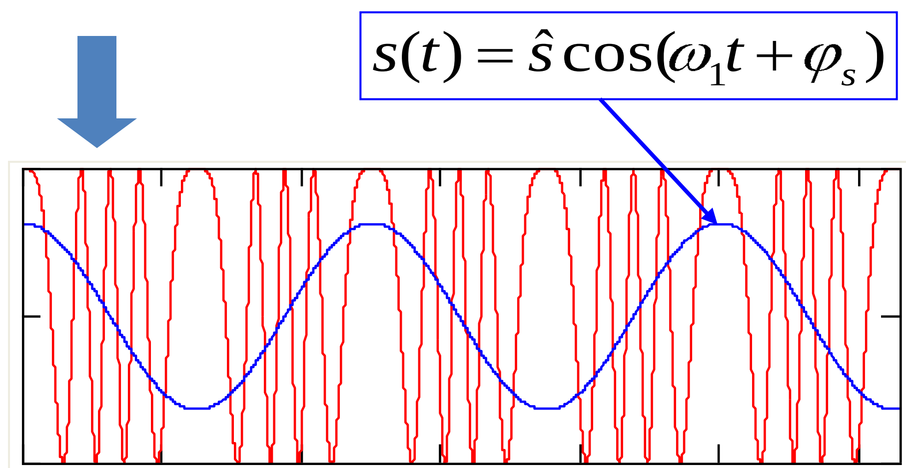
Armature modal deformation



Michelson interferometer





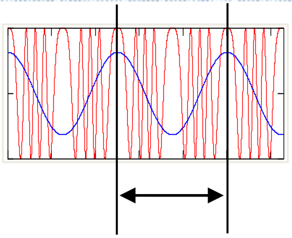


$$s(t) = \hat{s}\cos(\omega_1 t + \varphi_s)$$

BS – 50:50 Non-polarizing beam splitter
BS – Non-polarizing beam splitter
PD – Photodetector and amplifier
M1 – Reference mirror
M2 – Moving mirror

Method 1: Fringe counting method

Number of fringes maxima per vibration period: $$R_f = \hat{s}\,\frac{8}{\lambda}$$



$T_1 = 1/f_1$

Frequency ratio: $$R_f = \frac{f_{fot}}{f_1}$$

Displacement amplitude: $$\hat{s} = R_f\,\frac{\lambda}{8}$$

$$\hat{s} = \left(0{,}0791 \cdot R_f\right)\mu\text{m}$$

He-Ne laser

λ = 632,8 nm

Acceleration amplitude: $$\hat{a} = \left(2\pi f_1\right)^2 \hat{s}$$

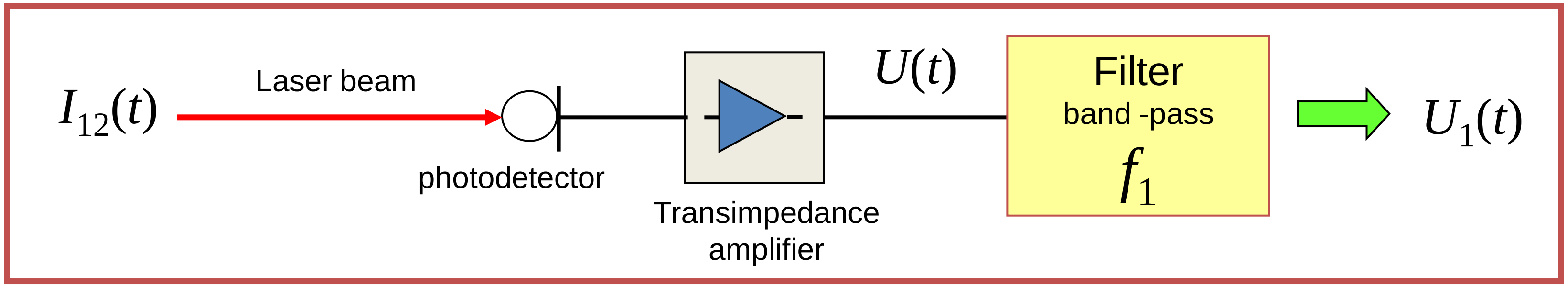
Voltage sensitivity of an acceleration measuring chain:

$$S_{ua}(f_1) = \frac{\hat{u}}{(2\pi f_1)^2\,\hat{s}} = \frac{8\sqrt{2}\,u_{rms}}{(2\pi f_1)^2 R_f \lambda}$$

Charge sensitivity of an accelerometer: $$S_{qa} = \frac{S_{ua}}{G}$$

Method 2: Minimum point method (J_1)

Filtering the voltage signal output from the photodetection unit with a band-pass filter centered at the excitation frequency f_1:



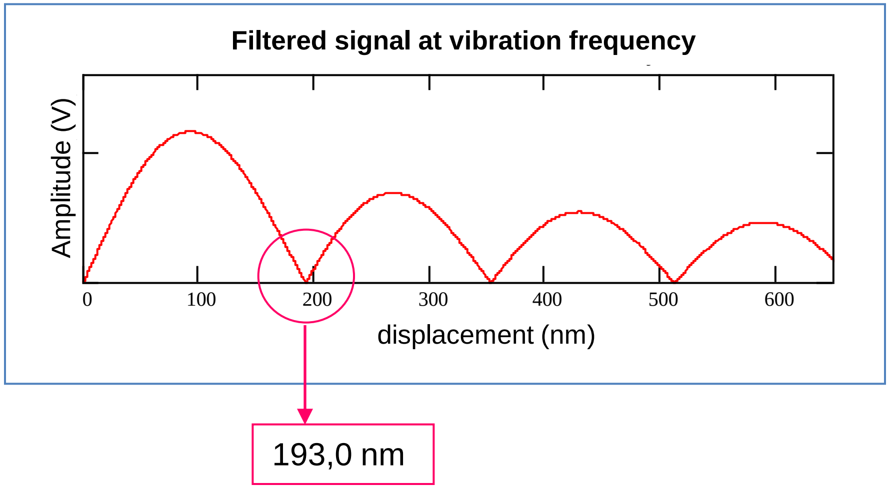
<u>Filtered AC signal:</u>

$$U_1(t) = -2BK_T \sin\varphi_0 \, J_1\left(\frac{4\pi\hat{s}}{\lambda}\right)$$

After adjusting L so that $|\sin\varphi_0| = 1$

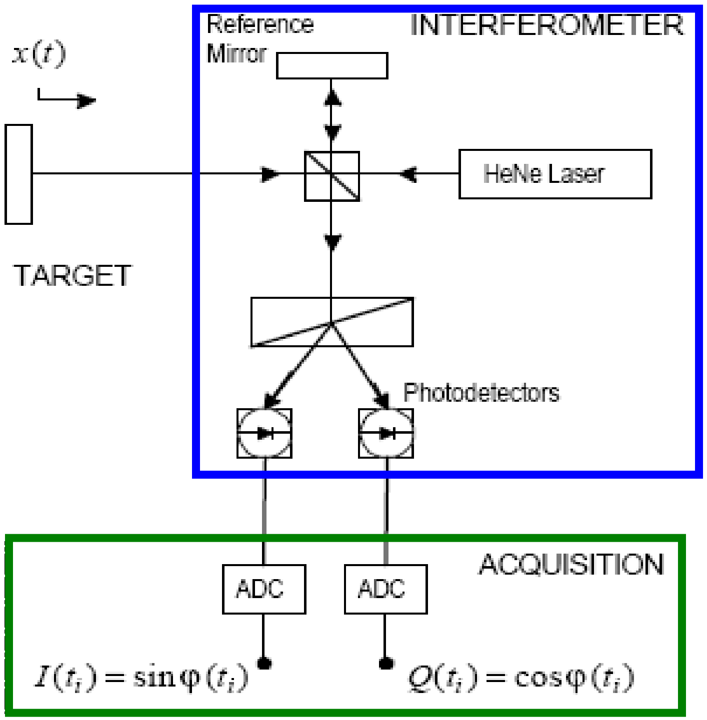
$$U_1(t) = -2BK_T \, J_1\left(\frac{4\pi\hat{s}}{\lambda}\right)$$

$$J_1(\hat{\varphi}_M) = 0 \quad \Rightarrow \quad \hat{s} = \frac{\lambda}{4\pi}\hat{\varphi}_M$$

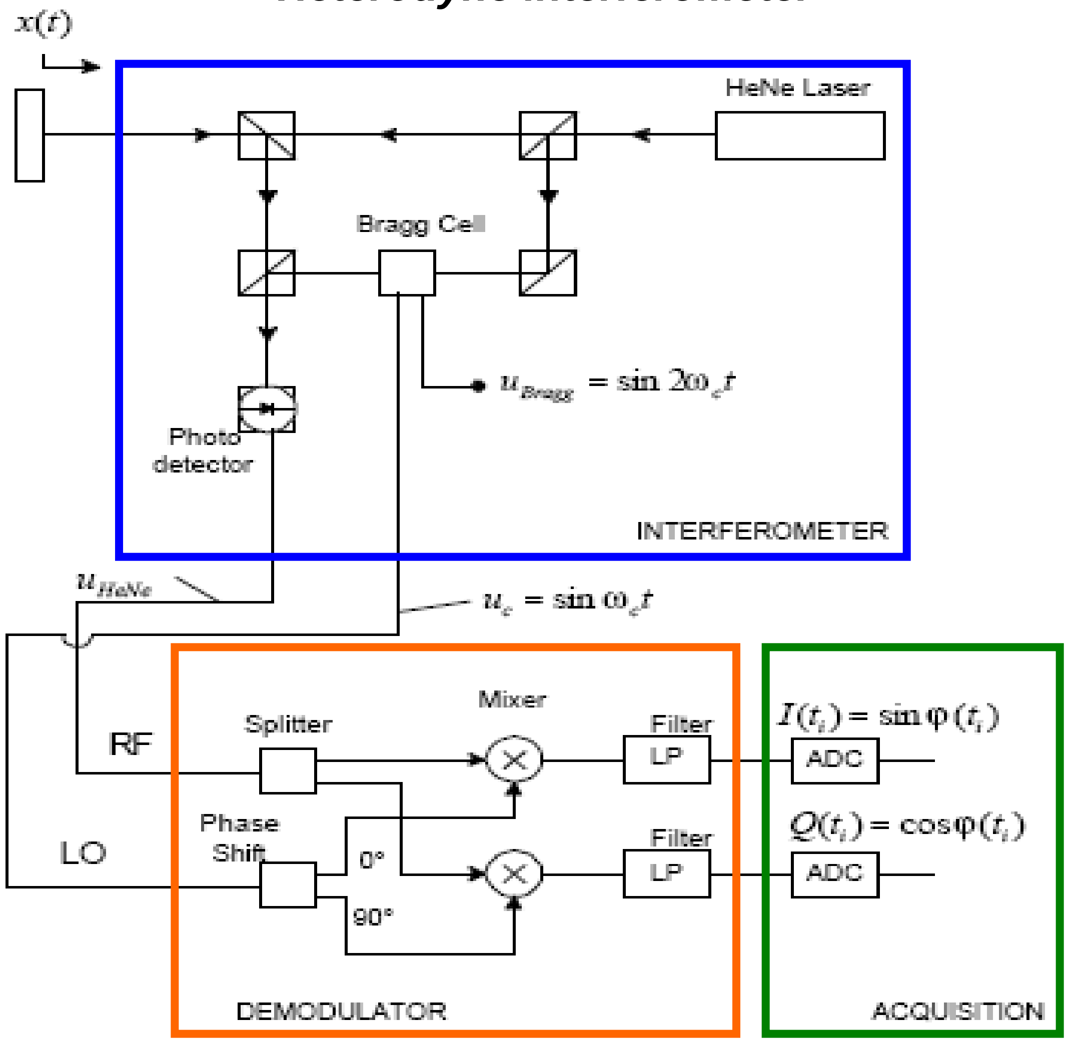


Laser interferometers for Method 3

Homodyne quadrature interferometer



Heterodyne interferometer



We can obtain I&Q output signals from both types of interferometers

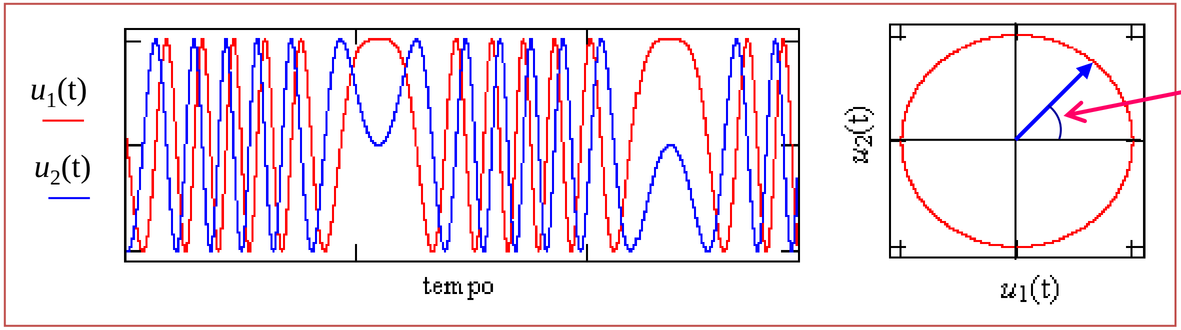
Theory of the method 3

Given a sinusoidal displacement: $s(t) = \hat{s}\cos(\omega_1 t + \varphi_s)$

Photodetectors I&Q output:

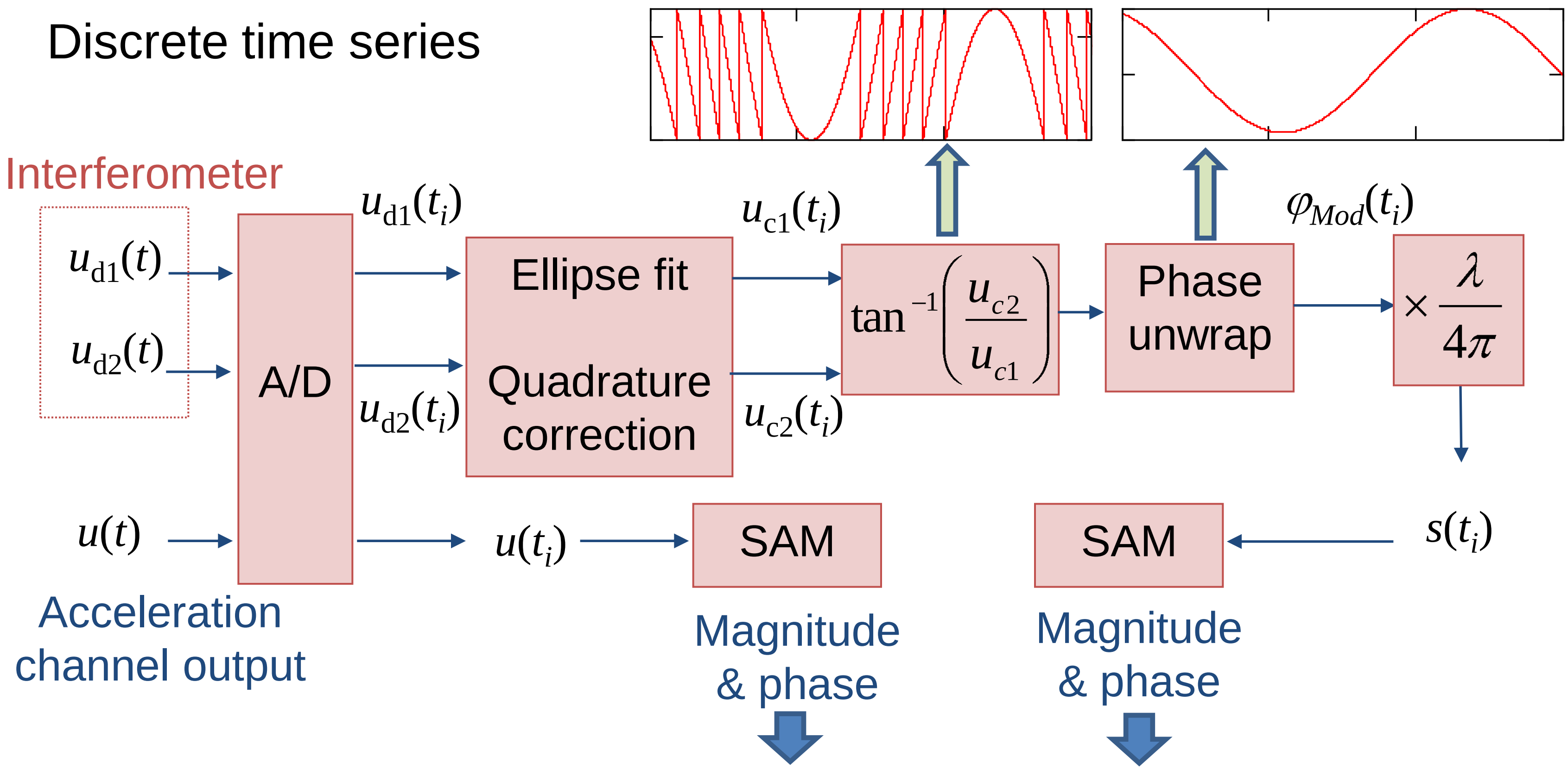
$$u_1(t) = \hat{u}_1 \cos\varphi_{Mod}(t)$$
$$u_2(t) = \hat{u}_2 \sin\varphi_{Mod}(t)$$

The total interferometric phase can be obtained by an arctangent demodulation



$$\varphi_{Mod}(t) = \tan^{-1}\left(\frac{u_2(t)}{u_1(t)}\right)$$

Method 3: Sine approximation method



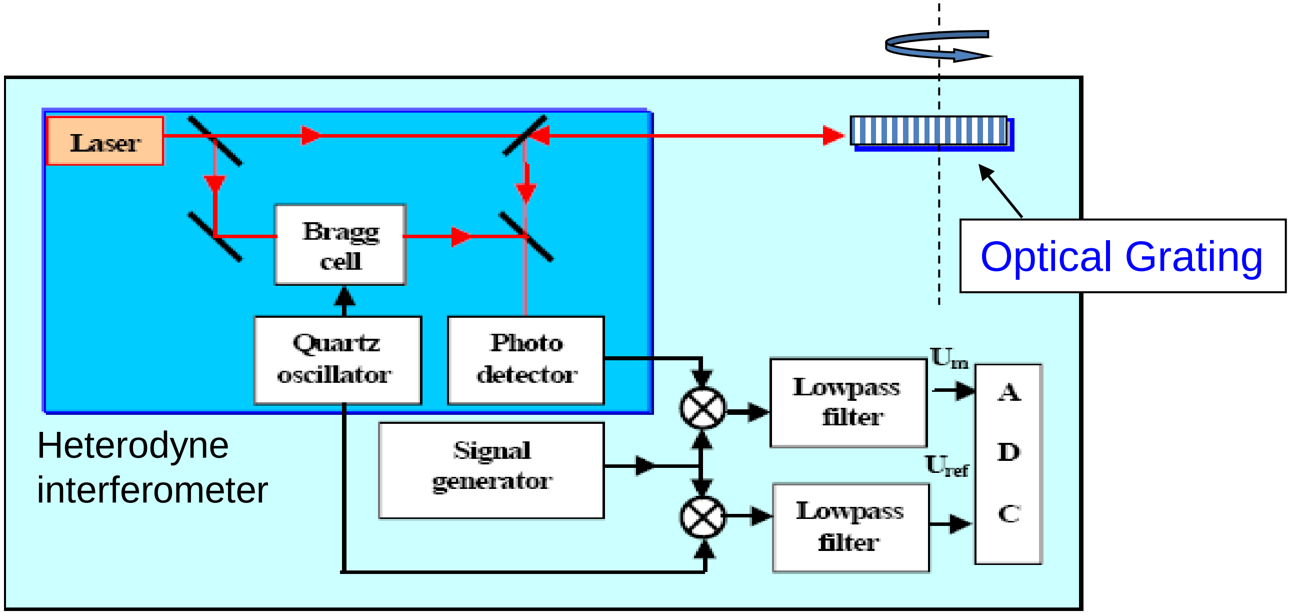
Sensitivity:

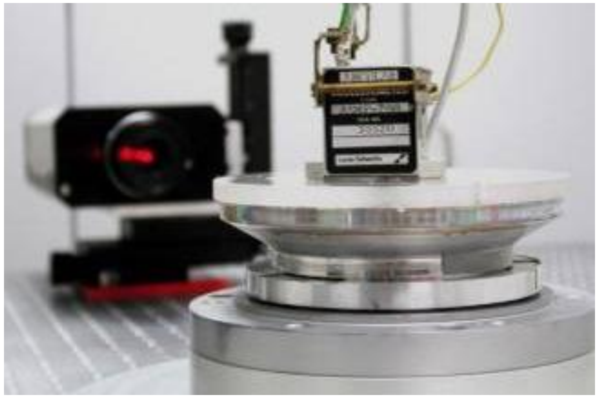
Amplitude: $\hat{S}_{ua} = \frac{\hat{u}}{\hat{a}}$

Phase shift: $\Delta\varphi = \varphi_u - \varphi_a$

Angular vibration

Flat mirror is substituted by an Optical grating





Angular motion quantities

Modulation phase

$$\varphi_{\text{mod}}[n] = \tan^{-1}\frac{U_2[n]}{U_1[n]} + k\pi$$

U_1 and U_2 are the quadrature signals

Rotation angle

$$\Phi[n] = \frac{g}{2\pi}\varphi_{\text{mod}}[n]$$

g is the grating angle constant in radian

Rotation angle of the sinusoidal vibration

$$\Phi[n\Delta t] = \hat{\Phi}\cos(\omega \times n\Delta t + \varphi_\Phi) + C$$

Angular velocity

$$\hat{\Omega} = 2\pi f \times \hat{\Phi}, \quad \varphi_\Omega = \varphi_\Phi - \pi/2$$

Angular acceleration

$$\hat{\alpha} = (2\pi f)^2 \times \hat{\Phi}, \quad \varphi_\alpha = \varphi_\Phi - \pi$$

Output voltage of a transducer

$$U[n\Delta t] = \hat{U}\cos(\omega \times n\Delta t + \varphi_u) + C_u$$

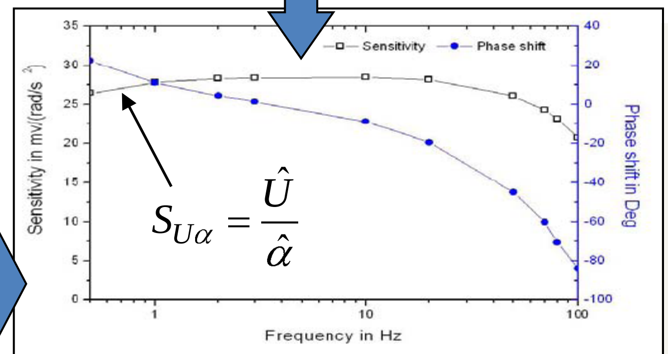
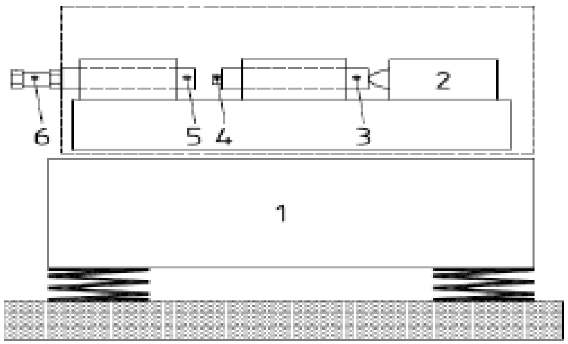


Fig.7. Calibration result of an angular accelerometer

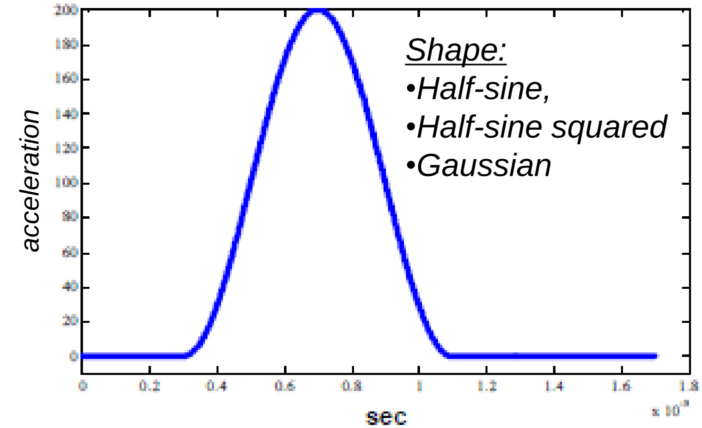
Shock calibration – ISO 16063-13

Rigid Body Motion Shock Source

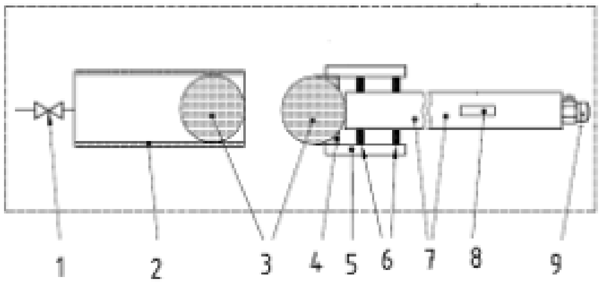


Low intensity

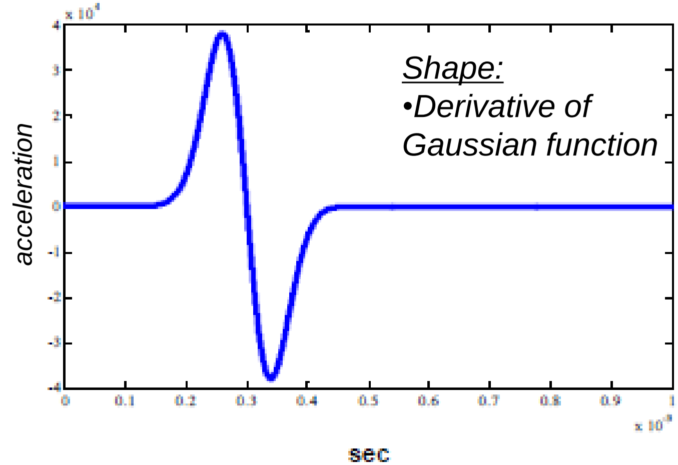
Acceleration shock pulses



Hopkinson Bar Shock Source



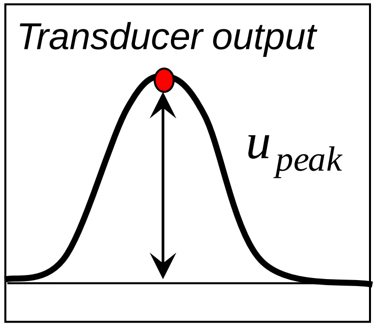
High intensity

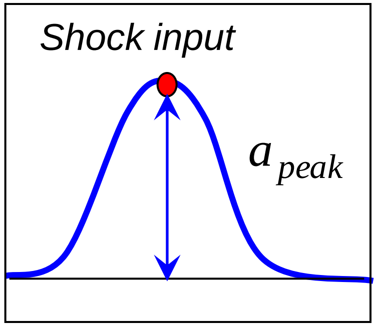


Wave propagation inside a long thin bar

Gaussian velocity shock pulses

Shock calibration - ISO 16063-13





Data processing

- Without DFT (double differentiation)
- With DFT of velocity values
- With DFT of displacement values

- Peak value method

Shock sensitivity

$$S_{sh} = \frac{u_{peak}}{a_{peak}}$$

Limits of uncertainty:

1 % of the reading at reference conditions

- *peak acceleration value of 1000* m/s^2
- *pulse duration of 2* ms

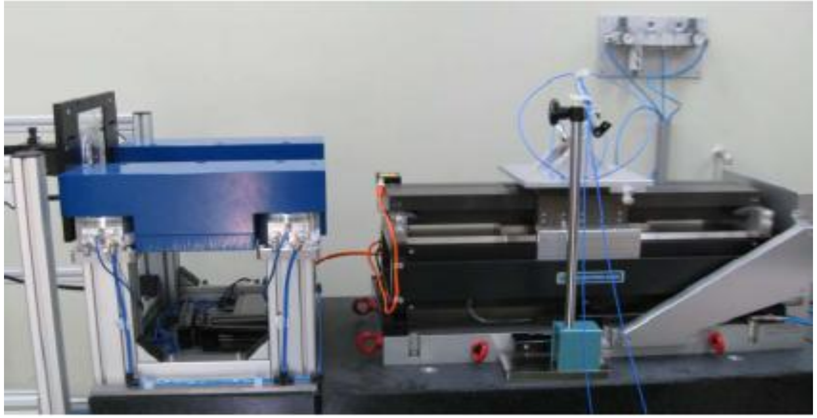
2 % for all other conditions

Primary calibration at ultra-low frequency

PTB / Germany (0.1 to 20 Hz)

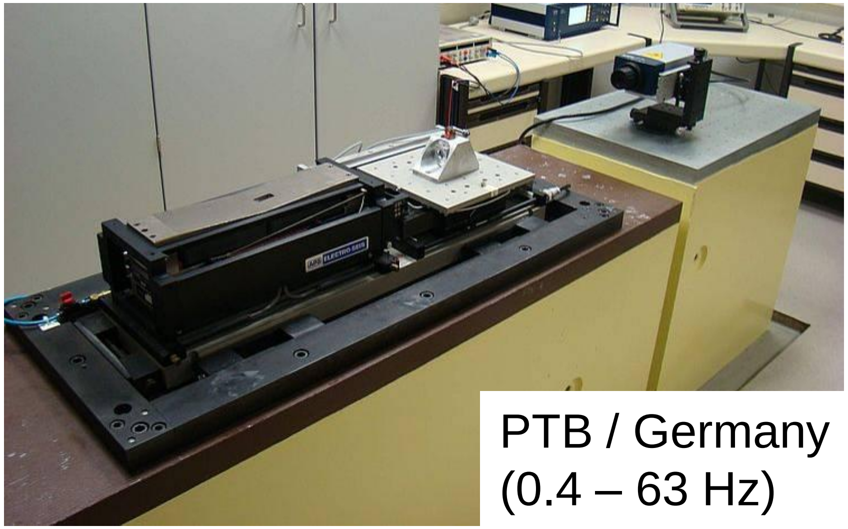
NIM / China (0.1 to 20 Hz)

NMIJ / Japan (0.1 to 2 Hz)

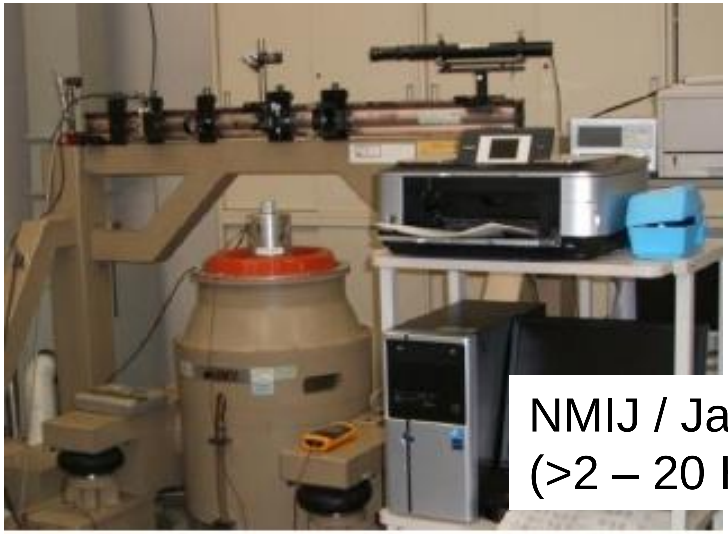


KRISS / Korea (0.1 to 100 Hz)

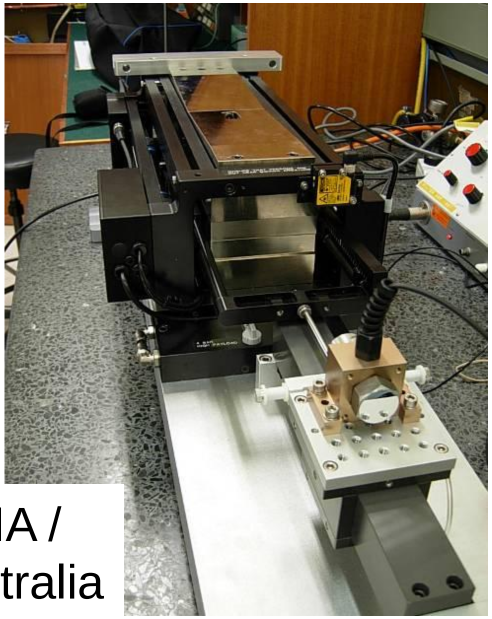
Primary calibration at Low frequency



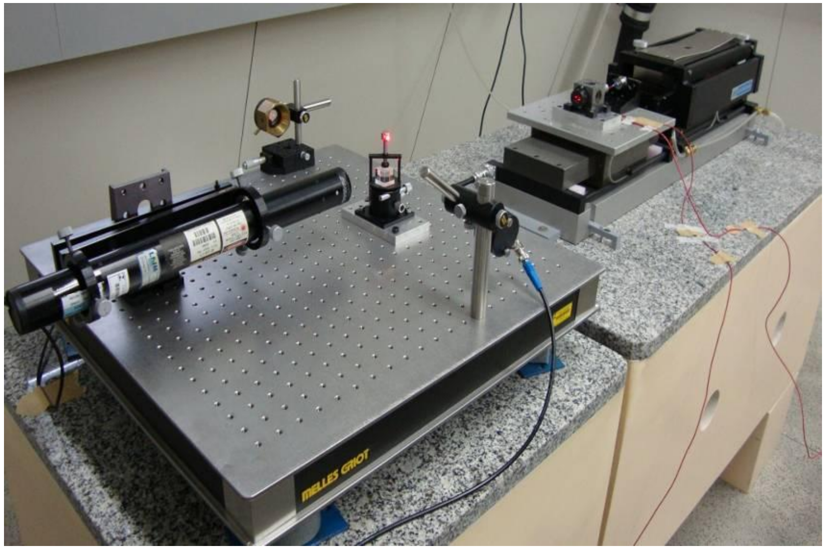
PTB / Germany (0.4 – 63 Hz)



NMIJ / Japan (>2 – 20 Hz)

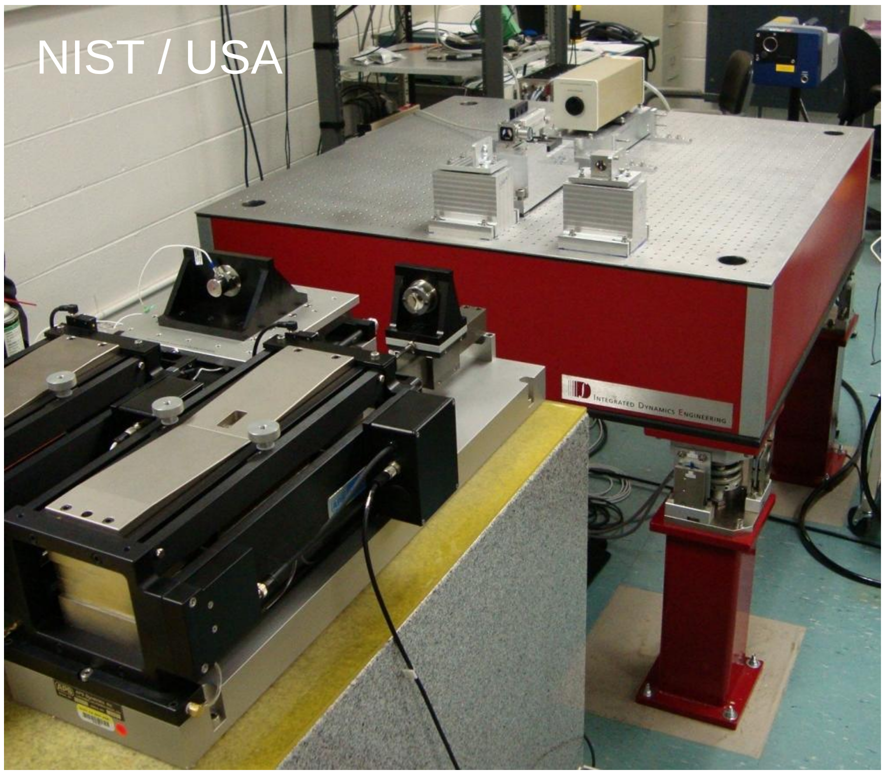


NMIA / Australia

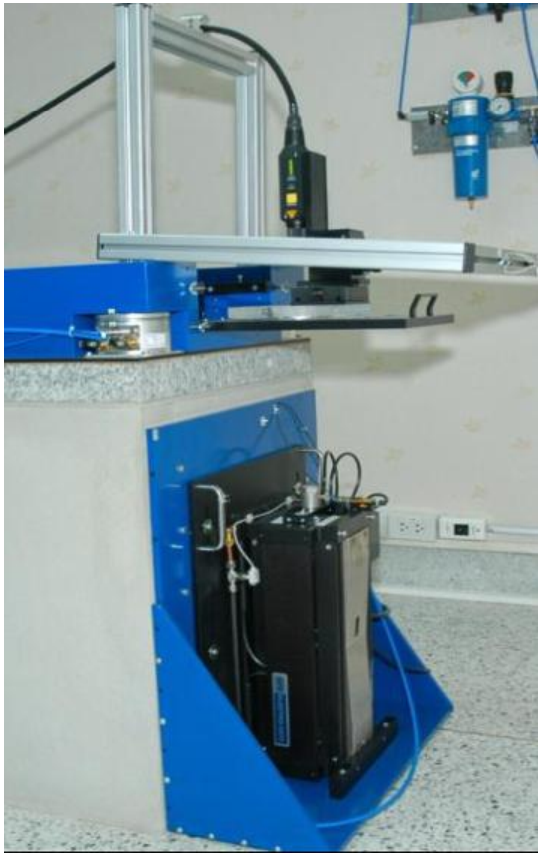


INMETRO / Brazil (0.4 – 100 Hz)

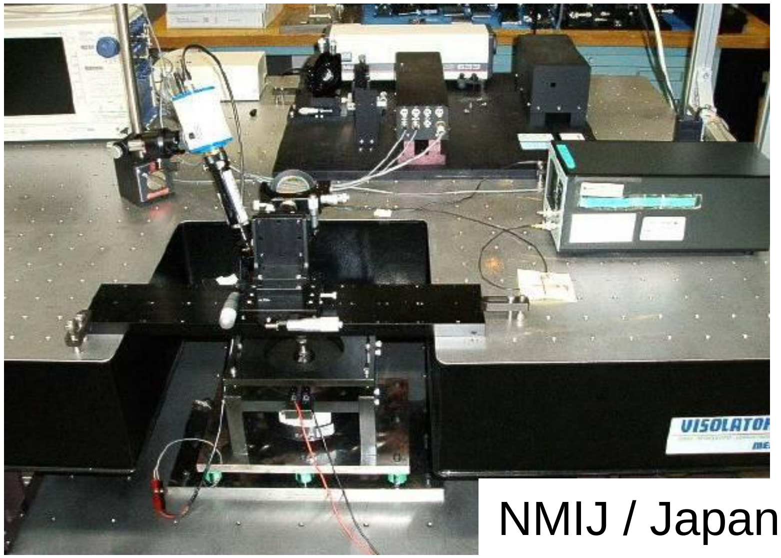
Primary calibration at Low frequency



NIST / USA

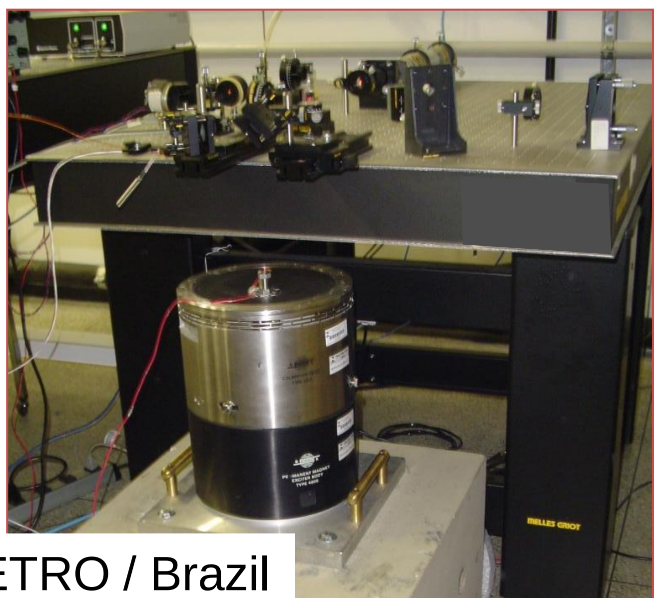

NIMT / Thailand

Primary mid-frequency systems



NMIJ / Japan

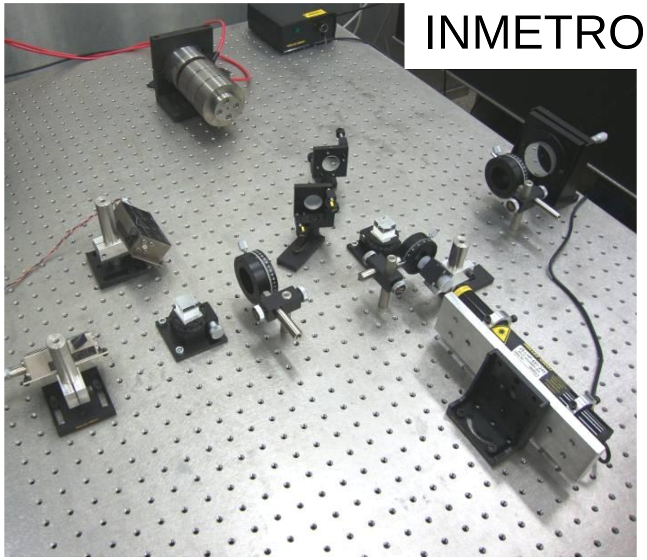
LNE / France



INMETRO / Brazil

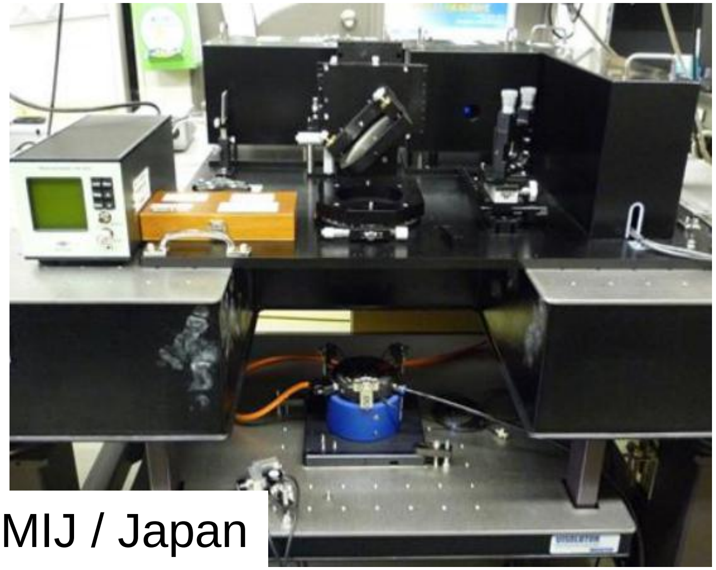
KIM-LIPI / Indonesia

Primary high frequency vibration calibration systems

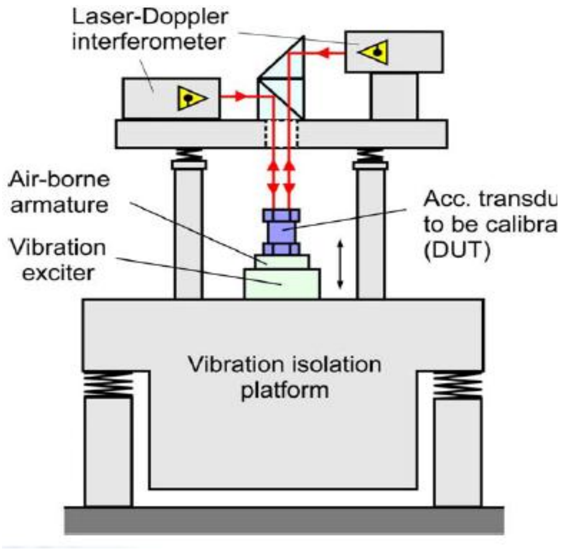


INMETRO / Brazil

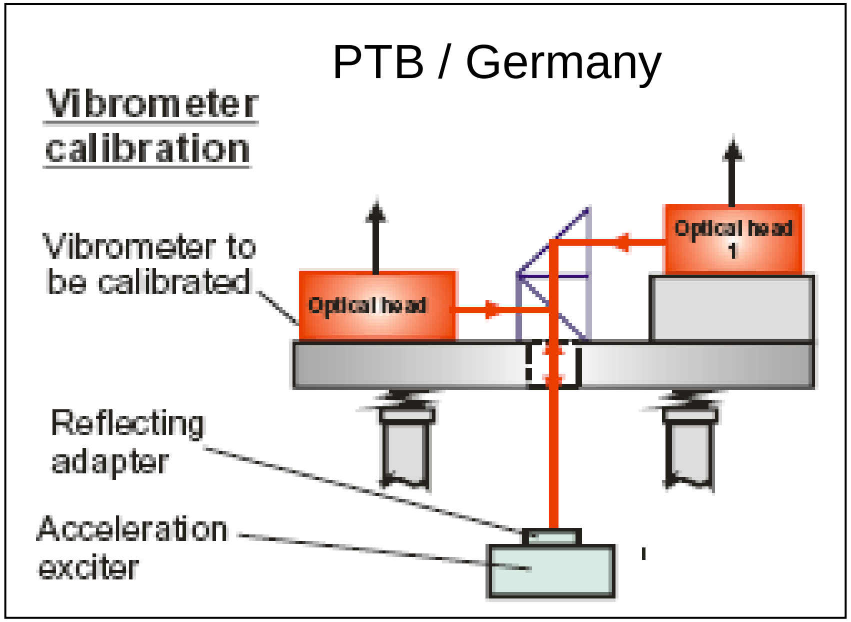
PTB / Germany

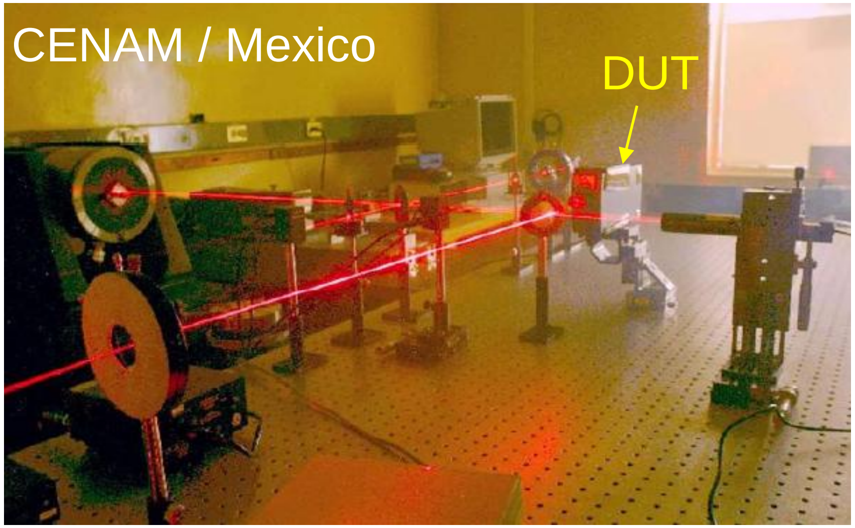


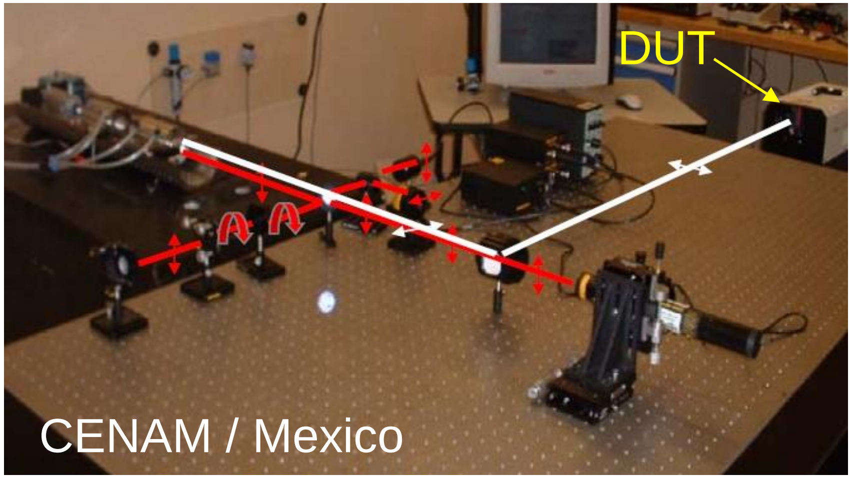
NMIJ / Japan



Primary calibration of vibrometers

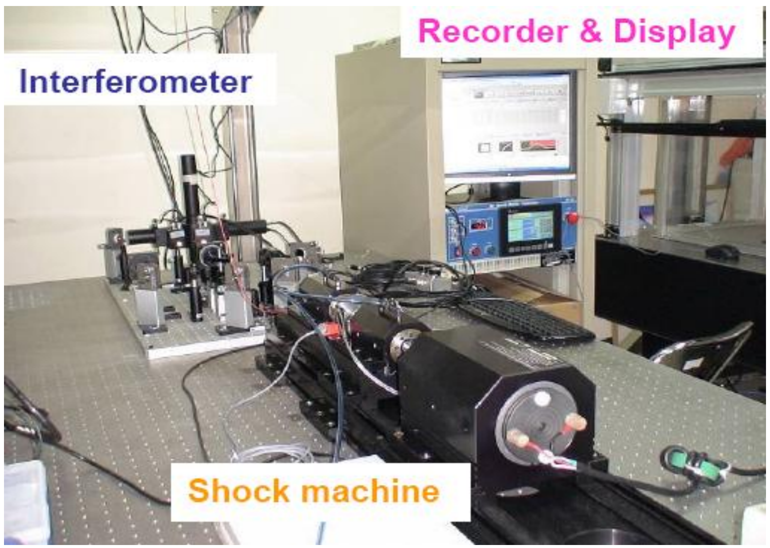


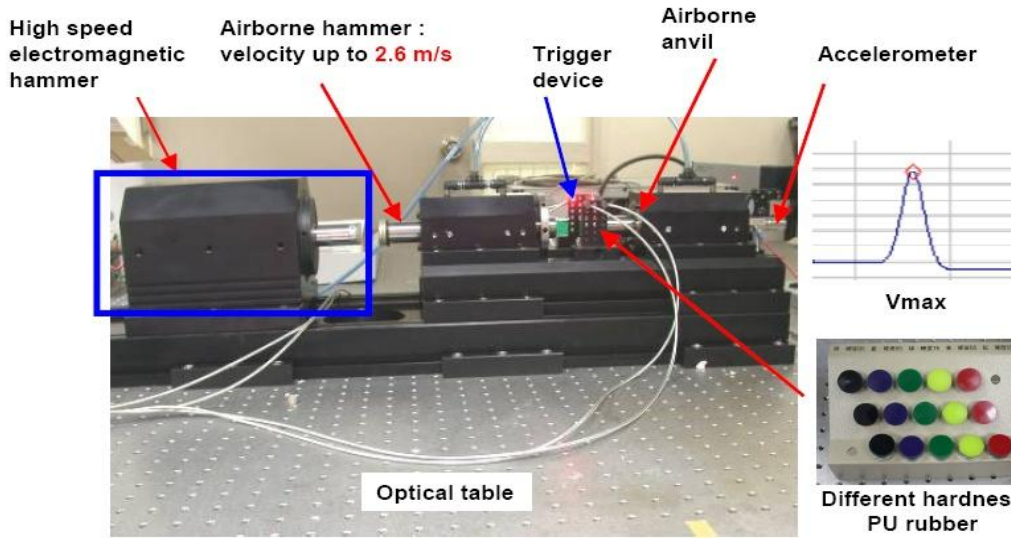




Low intensity shock

- **Hammer-anvil principle with air-borne mass bodies**





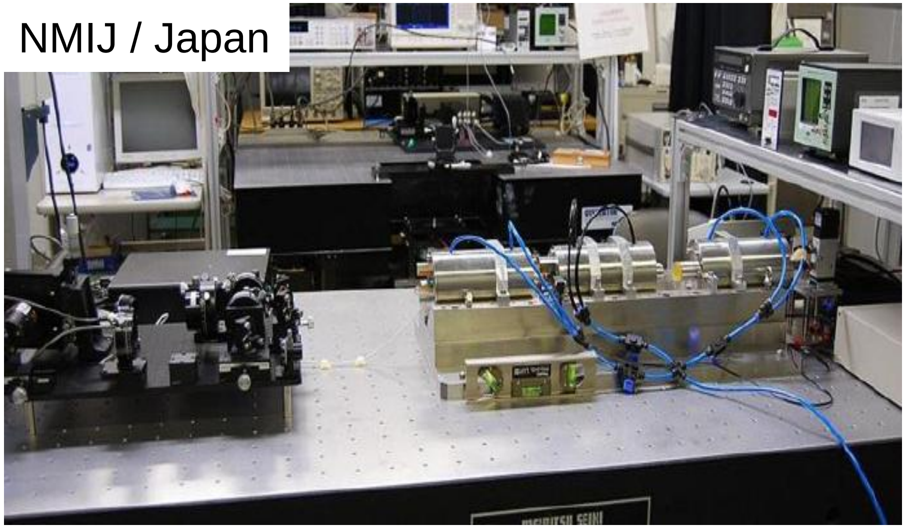
Range : $200\ m/s^2$ to $10000\ m/s^2$

Duration time : < 3.0 ms

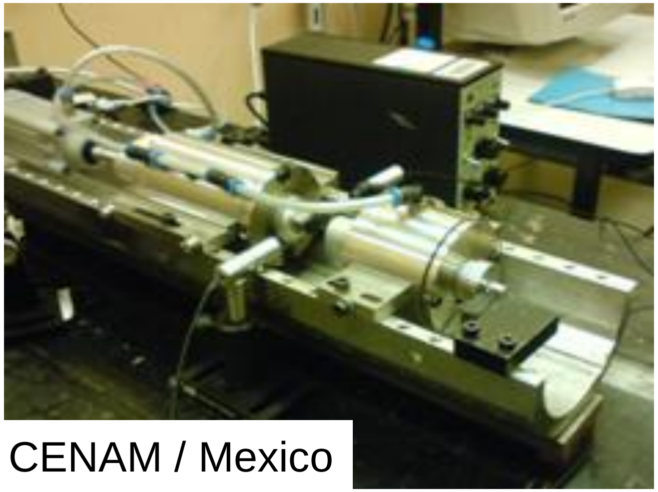
CMS/ITRI
Chinese Taipei

Low intensity acceleration shock

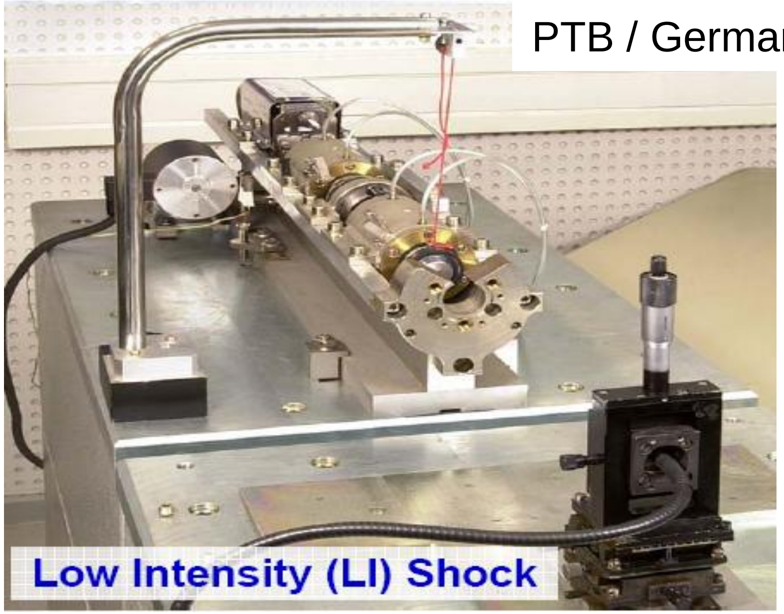
NMIJ / Japan

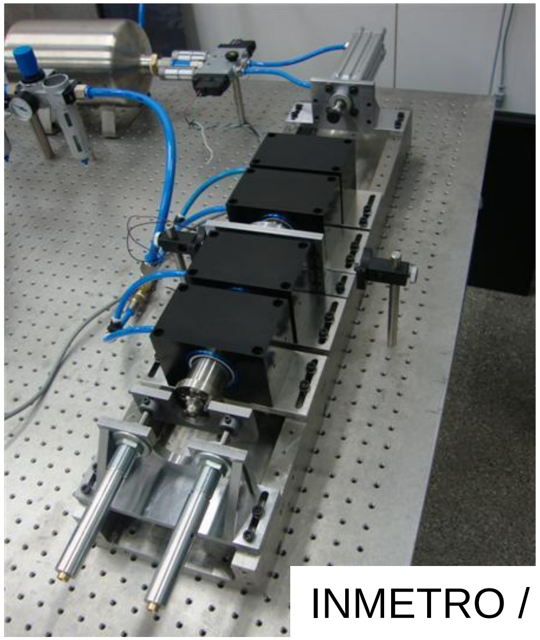


CENAM / Mexico



PTB / Germany

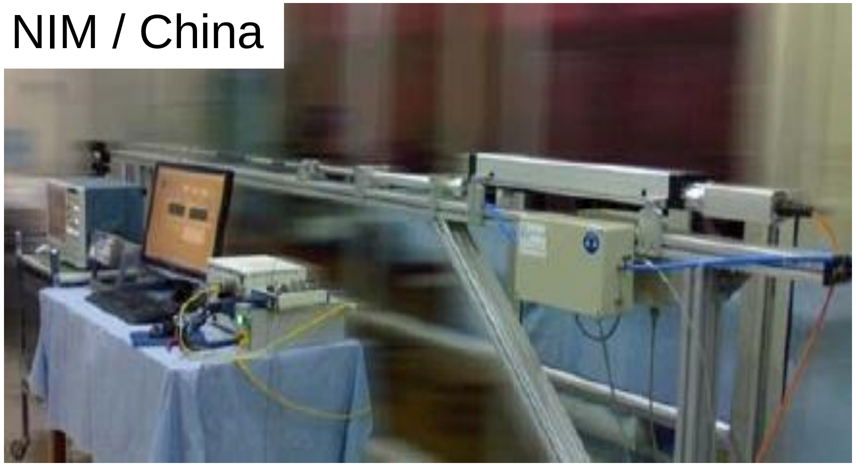




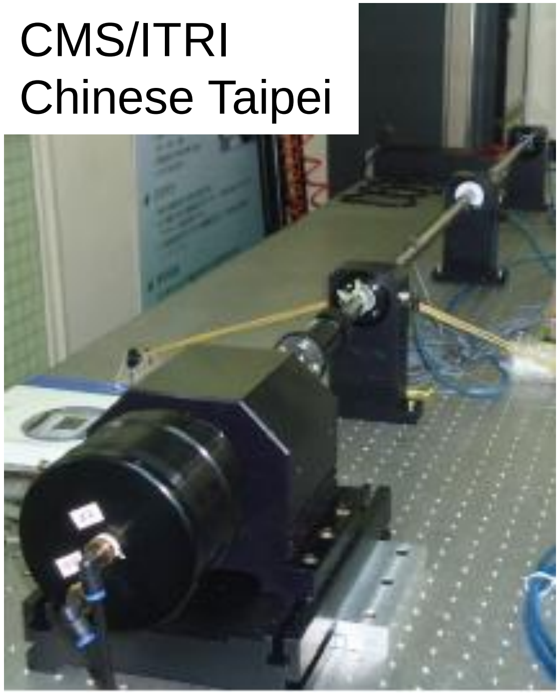
INMETRO / Brazil

High intensity shock

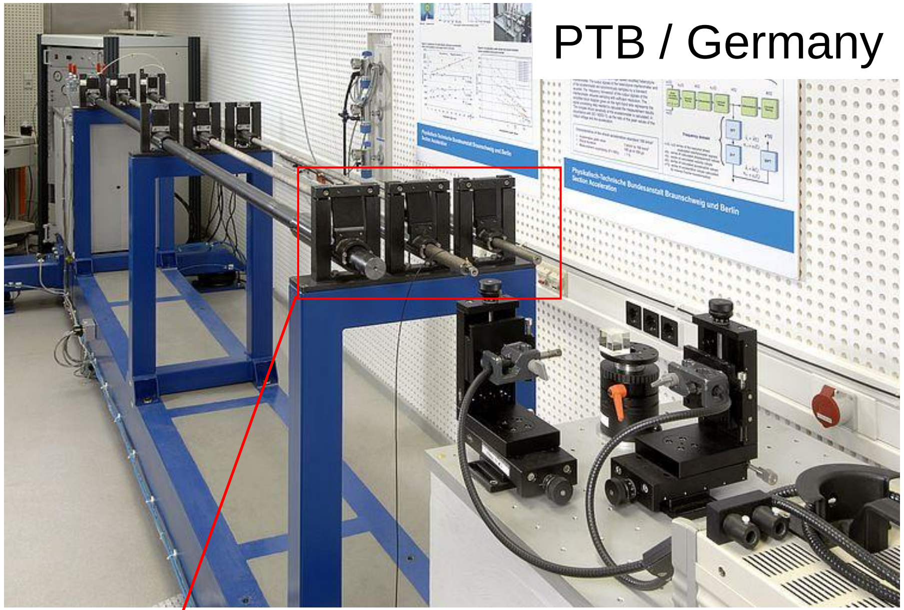
NIM / China



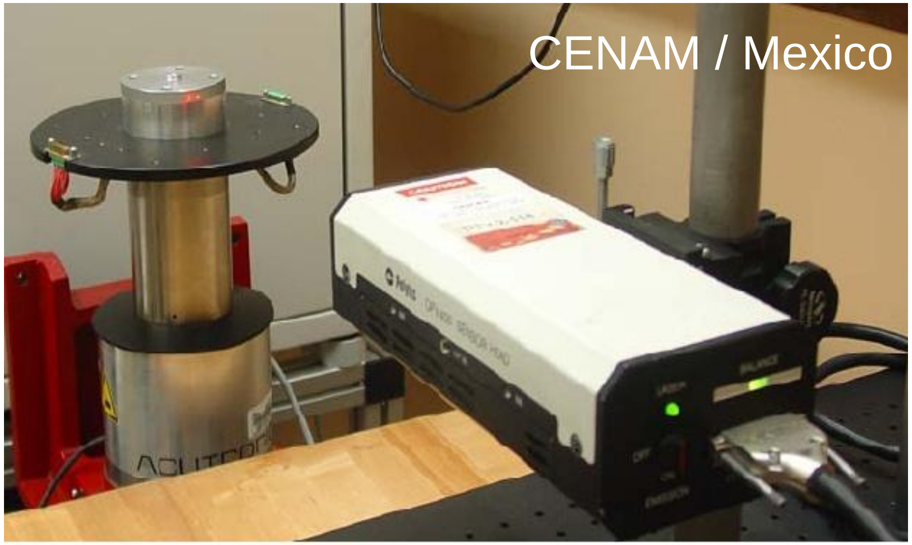
CMS/ITRI
Chinese Taipei

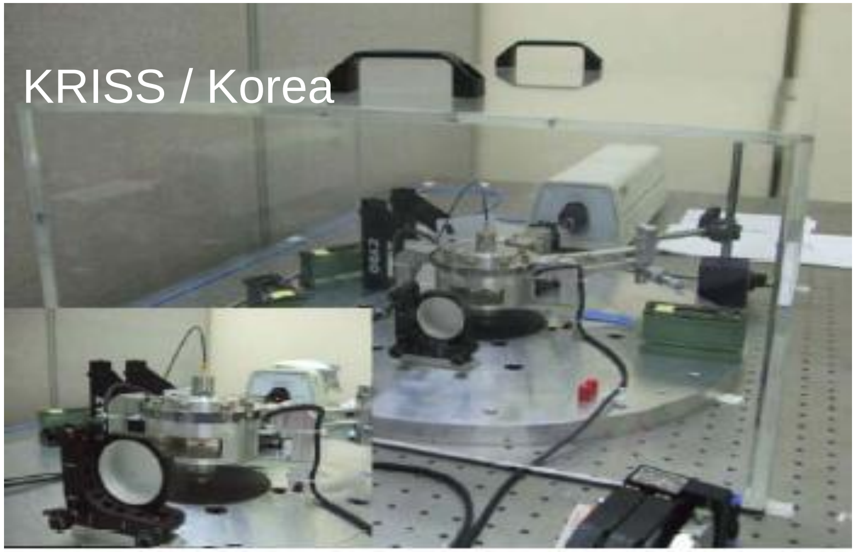


PTB / Germany

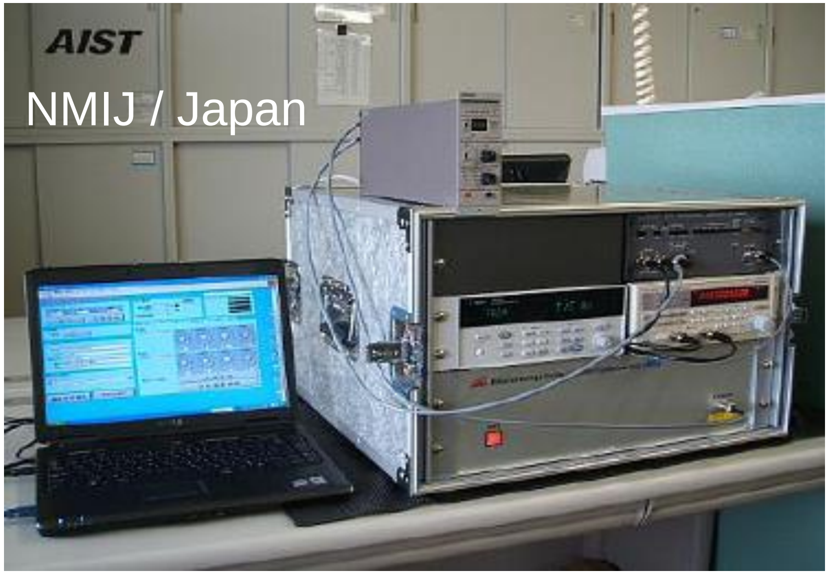


Angular vibration





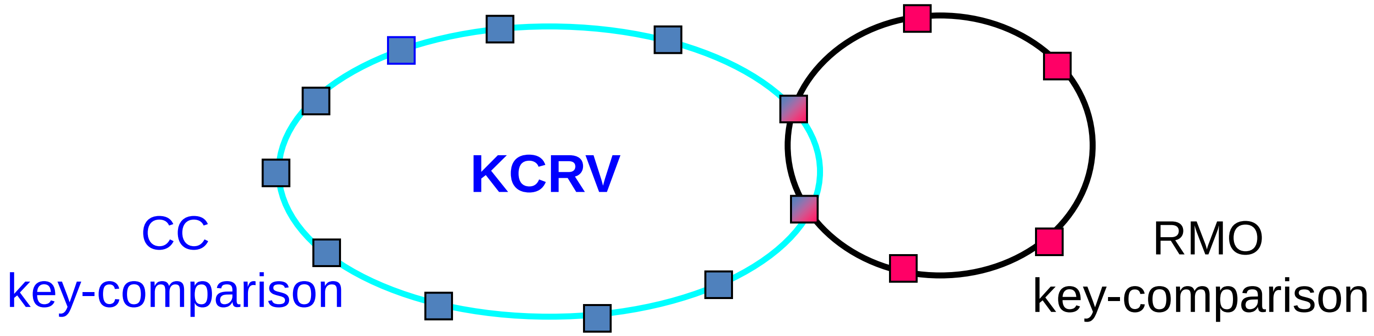
Charge amplifier calibration systems



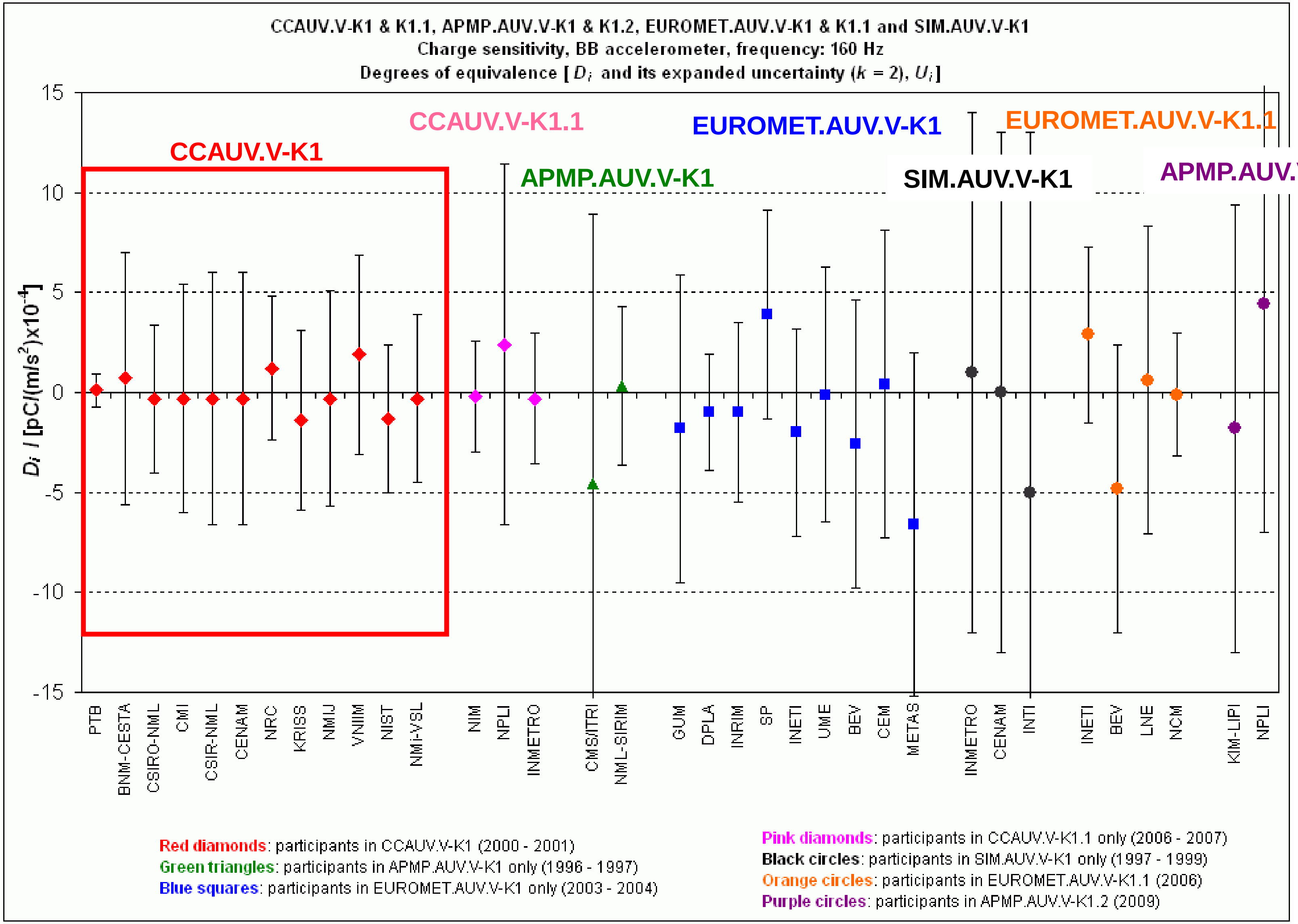
Vibration key-comparisons

- **CCAUV.V-K1** (Final report published on 12 Dec 2002)
  - Primary interferometric calibrations
  - Sensitivity magnitude, from 40 Hz to 5 kHz

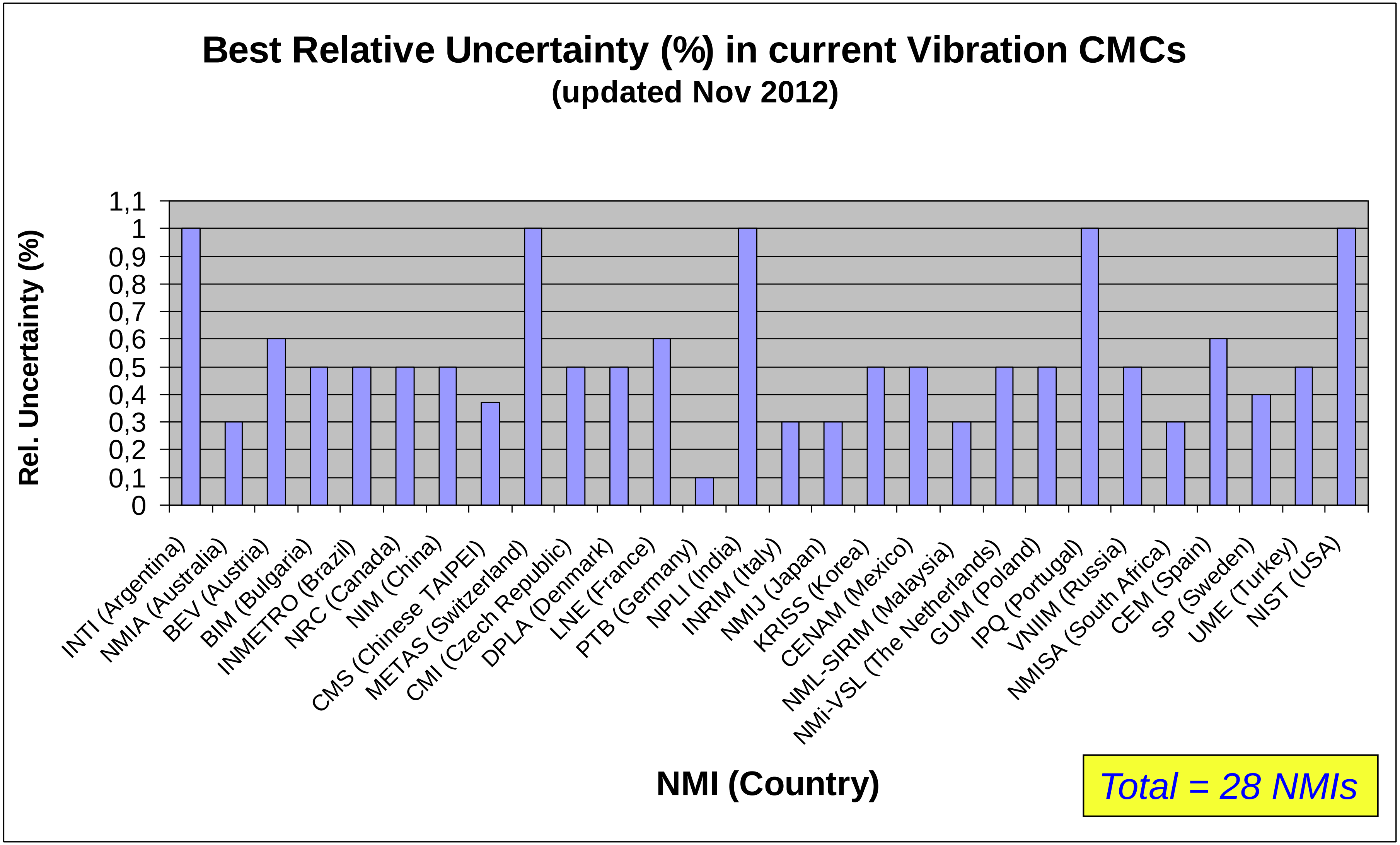
- **CCAUV.V-K2** (Measurements concluded)
  - Primary interferometric calibrations
  - Sensitivity magnitude & phase, from 10 Hz to 10 kHz



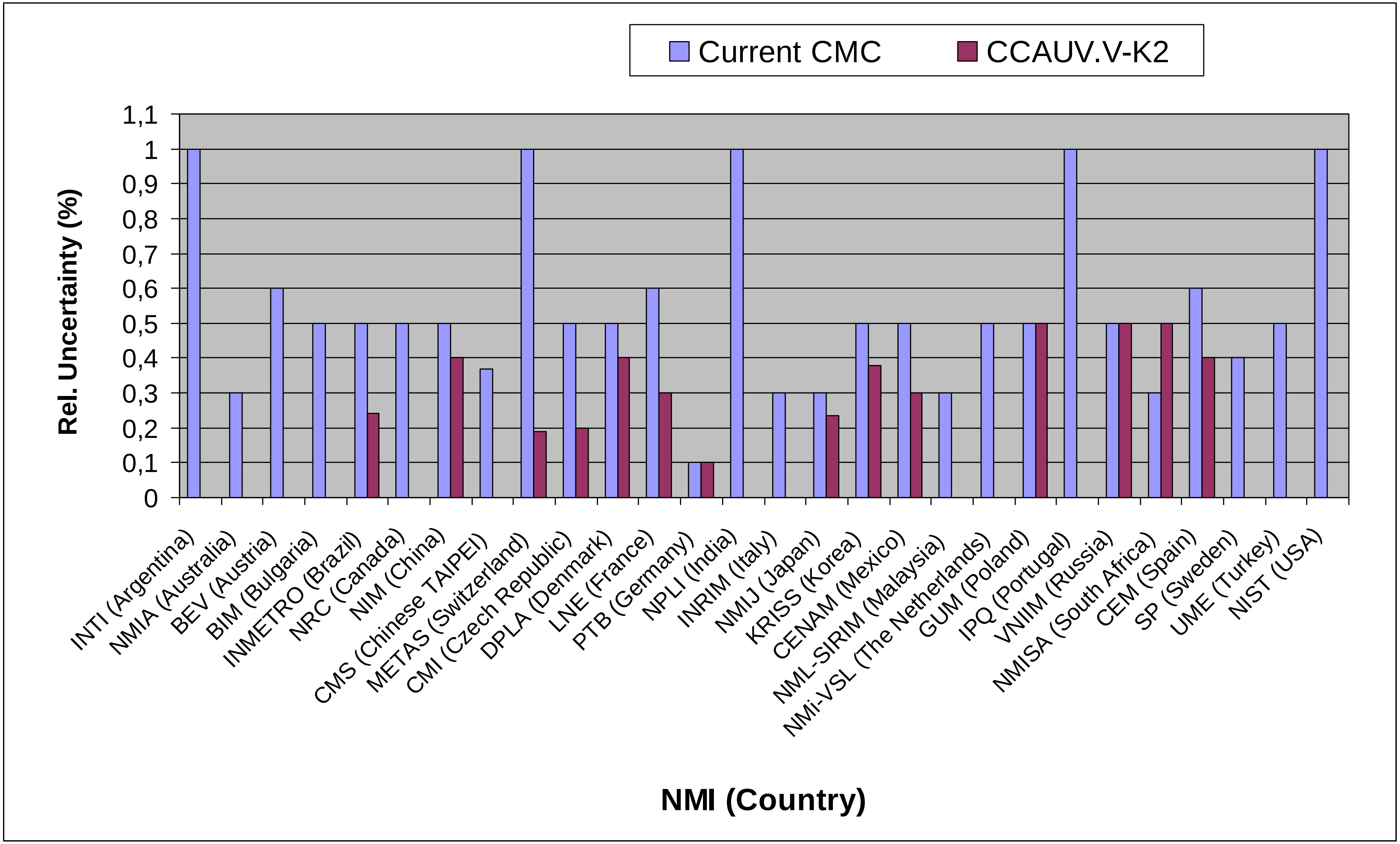
Comparisons linked to CCAUV.V-K1 KCRV



Current CMC uncertainties in Vibrations



Expectation of future improvement



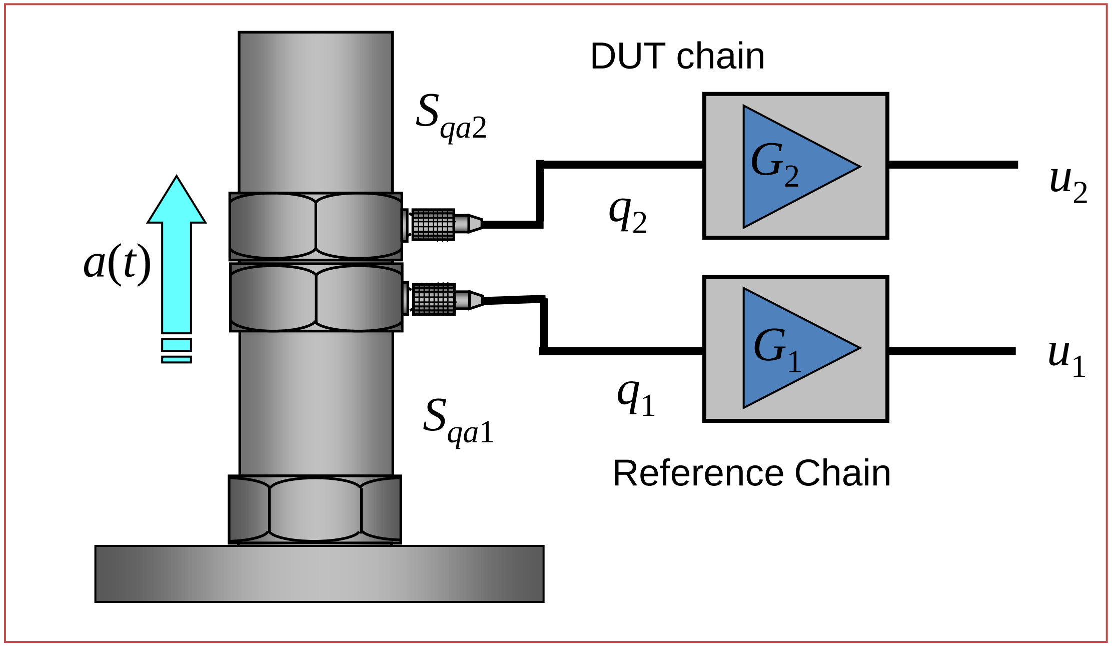
Other primary vibration and shock services

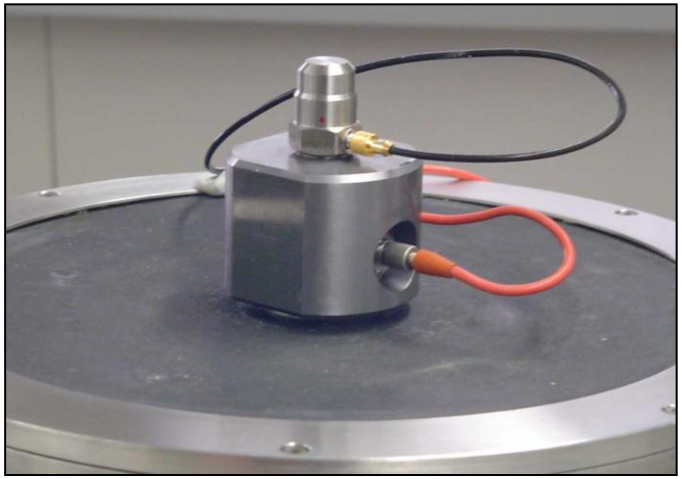
- Low frequency primary vibration (< 10 Hz)
  - Current CMCs: *U* = 0.2 % to 3.2 % (9 NMIs: PTB, NIM, NMISA, NMIA, BIM, CMS, INRIM, VNIIM, NIST)
  - Near future: several NMIs

- Primary shock
  - Current CMCs: *U* = 0.5 % to 1 % (PTB and NIM only)
  - Near future: CENAM, NMIJ, CMS/ITRI, INMETRO

- Primary angular acceleration
  - Current CMCs: *U* = 0.3 % to 0.5 %, freq. 0.4 Hz to 1 kHz (PTB only)
  - Near future: KRISS, NIM, CENAM, NMIJ

Comparison calibration of accelerometers





Chain
Voltage sensitivity:

$$S_{ua2} = S_{ua1} \frac{u_2}{u_1}$$

Accelerometer
Charge sensitivity:

$$S_{qa_2} = S_{qa_1} \frac{G_1}{G_2} \frac{u_2}{u_1}$$

Calibration solutions available

- Brüel & Kjaer
- Endevco
- PCB / The Modal Shop
- SPEKTRA Dresden
- MB Dynamics
- etc.

Primary calibration systems

Comparison calibration systems

Calibration grade components

Home-built systems
- Time consuming
- Longer development & learning process
- Cooperation
- Higher Flexibility
- Independence

3rd party systems
- Higher cost x Fast implementation
- Contracted supplier support
- Lower Flexibility (software & hardware)
- External dependence

Documentary standards for dynamic calibration of mechanical quantities

- Are important for the realization and dissemination of the units in an harmonized and internationaly agreed way

1. Realization of the units **in compliance with the definition agreed on the international level**.
2. Maintenance of the units by a material measure or measuring device referred to as standard.
3. Dissemination of the units to the users using reference and working standards.

- *ISO 16063-1 Basic concepts*

Basic Concepts

- *ISO 16063-11 Primary vibration calibration by laser interferometry*
- *ISO 16063-12 Primary vibration calibration by the reciprocity method*
- *ISO 16063-13 Primary shock calibration by laser interferometry*
- *ISO 16063-15 Primary angular vibration calibration by laser interferometry*
- *ISO 16063-16 Calibration by Earth's gravity*

Primary Calibrations

- *ISO 16063-21 Vibration calibration by comparison to a reference transducer*
- *ISO 16063-22 Shock calibration by comparison to a reference transducer*
- *ISO 16063-23 Angular vibration calibration by comparison to reference transducers*

Secondary Calibrations

- *ISO 16063-31 Testing of transverse vibration sensitivity*
- *ISO 16063-32 Resonance testing*
- *ISO 16063-33 Testing of magnetic field sensitivity*

Calibration in severe environment

- *ISO 16063-41: Calibration of laser vibrometers*
- *ISO 16063-42 Calibration of seismometers*
- *ISO 16063-43 Calibration of accelerometers by model based parameter identification*
- *ISO 16063-4X Calibration of hand held accelerometer calibrators*
- *ISO 16063-4Y (PWI 2169) Dynamic force transducer calibration*
  - Preliminary work item in the programme of work, confirmed in 2010

Other Calibration Methods

Preliminary Work Item (zero-stage project)

Vibration standards in support of dynamic mechanical quantities

Vibration

- ***ISO 16063-11*** *Primary vibration interferometry*
- ***ISO 16063-21*** *Vibration calibration comparison*

→ **Force and Pressure** (sinusoidal calibration)

Shock

- ***ISO 16063-13*** *Primary shock interferometry*
- ***ISO 16063-22*** *Shock calibration comparison*

→ **Force and Pressure** (shock calibration)

Angular vibration

- ***ISO 16063-15*** *Primary angular vibration interferometry*
- ***ISO 16063-23*** *Angular vibration comparison*

→ **Torque** (sinusoidal calibration)

Standard ISO 7626-1:2011

- **ISO 7626-1:2011** - Mechanical Vibration and Shock – Experimental Determination of Mechanical Mobility Part 1: Basic Terms, definitions and transducer specifications

Calibration:

- Accelerometers – refers to ISO 16063 and ISO 5347
- Force transducer – refers to the mass loading technique

Voltage output

$$S_F = \frac{U_m - U_0}{(m + m_1 + m_2 + m_3)a - (m_1 + m_2 + m_3)a_0}$$

Single loading mass

Acceleration input

m_1 - mass of reference accelerometer

m_2 - effective mass of the bolt

m_3 - effective mass of force transducer

Traceability in the CIPM MRA

CIPM 2009-24
Revised 13 October 2009

Established Policy:

- A NMI or DI publishing CMCs in the KCDB has two choices for establishing its traceability route to the SI:

1. Via a primary realization...

2. Via another NMI or DI having relevant CMCs ... or through calibration and measurement services offered by the BIPM...

Classification of services in mass and related quantities (21 October 2003)

BRANCH: PRESSURE

Dynamic pressure !

3. Pressure

3.4 Dynamic pressure

3.4.1 Gas medium: *pressure measuring device, standard pressure generator, pressure gauge*
3.4.2 Liquid medium: *pressure measuring device, standard pressure generator, pressure gauge*

BRANCH: FORCE

No dynamic force ?

4. Force

4.1 Tension

4.1.1 Tension: *force measuring device*

4.2 Compression

4.2.1 Compression: *force measuring device*

4.3 Tension and compression

4.3.1 Tension and compression: *force measuring device*

BRANCH: TORQUE, VISCOSITY, HARDNESS AND GRAVITY

5. Torque

5.1 Torque

5.1.1 Torque: *torque measuring device*

No dynamic torque ?

Classification of services in Acoustics, Ultrasound and Vibration

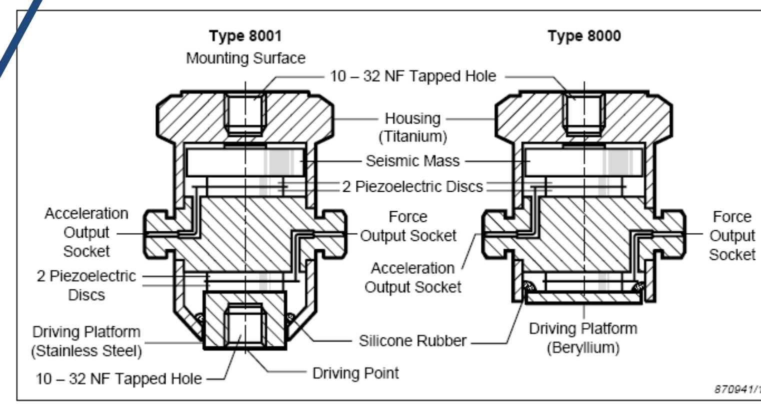
Last update: October 2010

Metrology Area: Acoustics, Ultrasound and Vibration

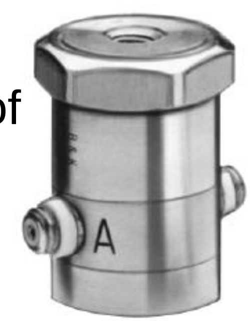
Branch: Sound in Air

1. Measurement microphones
    - 1.1 Pressure sensitivity level
        - 1.1.1. Modulus[1]: *frequency*
        - 1.1.2. Phase: *frequency*
    - 1.2 Free-field sensitivity level
        - 1.2.1. Modulus: *frequency*
        - 1.2.2. Phase: *frequency*
        - 1.2.3. Directivity: *frequency*
    - 1.3 Diffuse field sensitivity level
        - 1.3.1. Modulus: *frequency*
        - 1.3.2. Phase: *frequency*
2. Sound calibrators
    - 2.1 Single frequency
        - 2.1.1. Sound pressure level: *microphone type*
    - 2.2 Multi-frequency
        - 2.2.1. Sound pressure level: *microphone type, frequency*
3. Sound Measuring Instruments
    - 3.1 Response
        - 3.1.1. Sound pressure response level: *frequency*
        - 3.1.2. Free-field response level: *frequency*
        - 3.1.3. Diffuse field response level: *frequency*
        - 3.1.4. Sound intensity response level: *frequency*
4. Ear simulators
    - 4.1 Reference couplers or artificial ears
        - 4.1.1. System response level: *frequency*
        - 4.1.2. Acoustic impedance: *frequency*
    - 4.2 Mechanical couplers
        - 4.2.1. Force response level: *frequency*
        - 4.2.2. Mechanical impedance: *frequency*
    - 4.3 Impedance head force transducer
        - 4.3.1. Modulus of charge sensitivity: *frequency*
        - 4.3.2. Phase shift of charge sensitivity: *frequency*
    - 4.4 Impedance head force measuring chain
        - 4.4.1. Modulus of voltage sensitivity: *frequency*
        - 4.4.2. Phase shift of voltage sensitivity: *frequency*

4.3 Impedance head force transducer
4.3.1. Modulus of charge sensitivity: *frequency*
4.3.2. Phase shift of charge sensitivity: *frequency*
4.4 Impedance head force measuring chain
4.4.1. Modulus of voltage sensitivity: *frequency*
4.4.2. Phase shift of voltage sensitivity: *frequency*



Used for calibration of Artificial Mastoid B&K 4930



8000

Problems

- Current lists of services do not allow inclusion of CMCs for dynamic calibrations of mechanical quantities

Lack of mutual recognition!

- Accredited laboratories need formal traceability!

- Currently, accreditation relies on the personal judgement of the technical assessor

No harmonized criteria!

Dissemination of units of dynamic mechanical quantities

Accreditation of Secondary calibration laboratories will need:

- International documentary standards
- Procedural guides from accreditation bodies
- Stable measuring standards (reference & working standards)
- Traceable calibrations & measurements from NMIs
- Support of the MRA (published CMCs)
- Qualified technical assessors for dynamic measurements.
  - What skills and expertise is required?
- ...

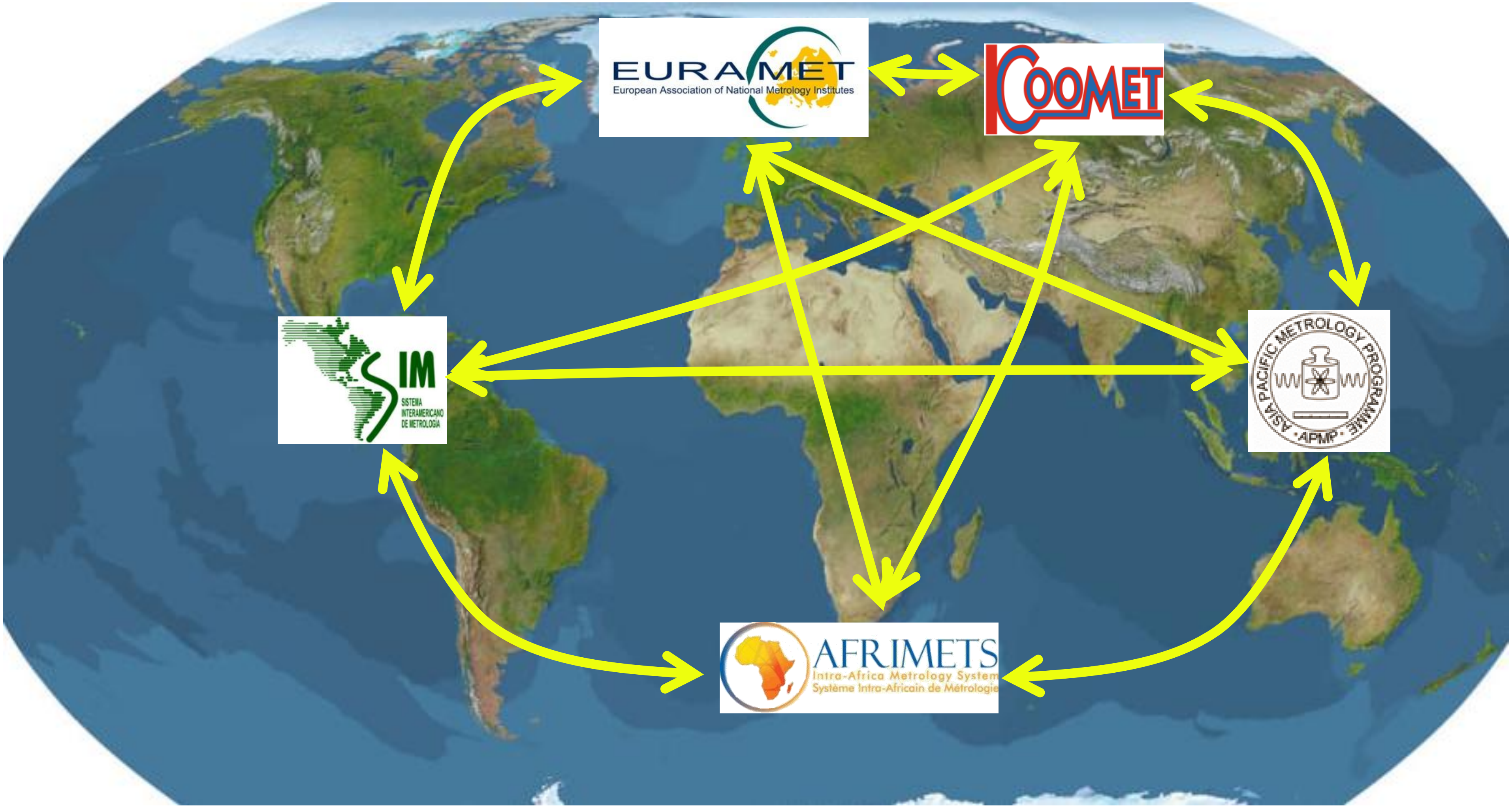
Is the international metrology fit for dynamics?

- Many challenges in the field of making dynamic measurements traceable to the SI;
- Harmonization of terms and methods;
- Consistent approach to
  - the estimation of measurement results,
  - their uncertainties,
  - and comprehensive calibration certificate formats;
- Best practice guides and/or documents which could be adopted as the basis for the measurement aspects of international standardization, regulation and/or legislation.

A lot of work to be done!

Cooperation between NMIs & RMOs

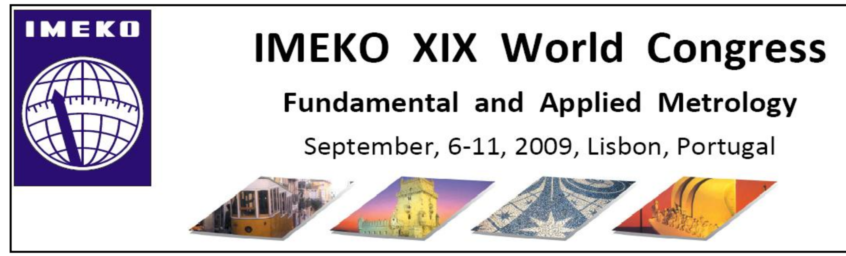
Colaborative work between NMIs and Regional Metrology Organizations



Cooperation in a broader sense

Colaborative work including other important partners with common interests

IMEKO WC and joint conferences



Force, Mass, Torque, Density,
Pressure, Vacuum and Vibrations

TC3, TC5 and TC22 joint conference
2010, November 21-24

Force, Mass, Torque,
Hardness and Vibrations

Workshops

- 7th International Workshop on Analysis of Dynamic Measurements
  - was held at LNE on October 15-16, 2012, Paris, France

- 6th International Workshop on Analysis of Dynamic Measurements
  - was held at Chalmers University of Technology on June 22-23, 2011, Göteborg, Sweden

Summary

- acceleration is directly related to dynamic measurement of other mechanical quantities
- new fields of metrology will require traceability
- new options for co-operation,
- promising field for R&D
- new challenges, too
- borderline work between
  - CCs: CCAUV and CCM (WGs)
  - RMO TCs: TC-AUV and TC-M (WGs)

Thank you for your attention!

Gustavo Ripper