Current situation and future trends in force measurement

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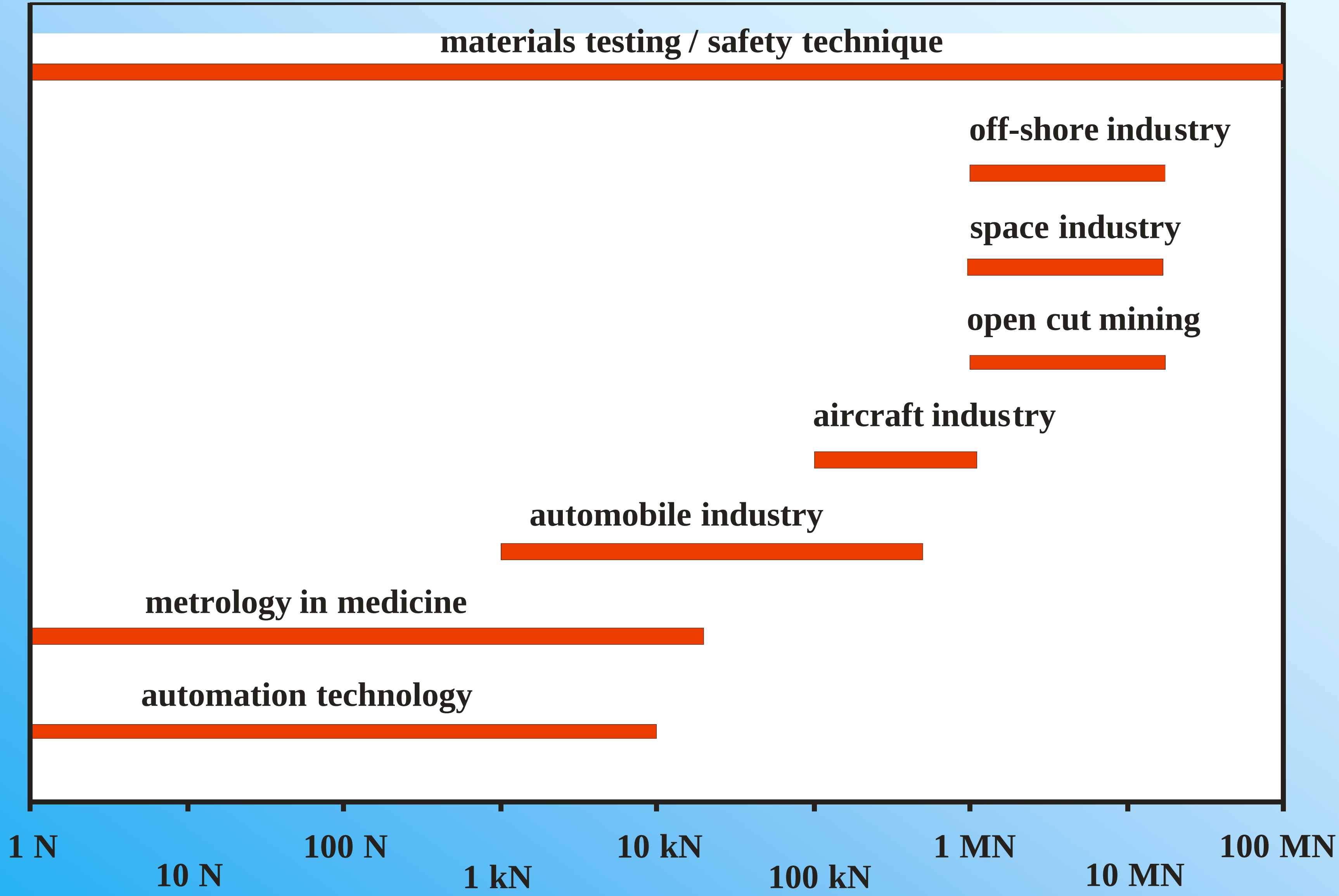
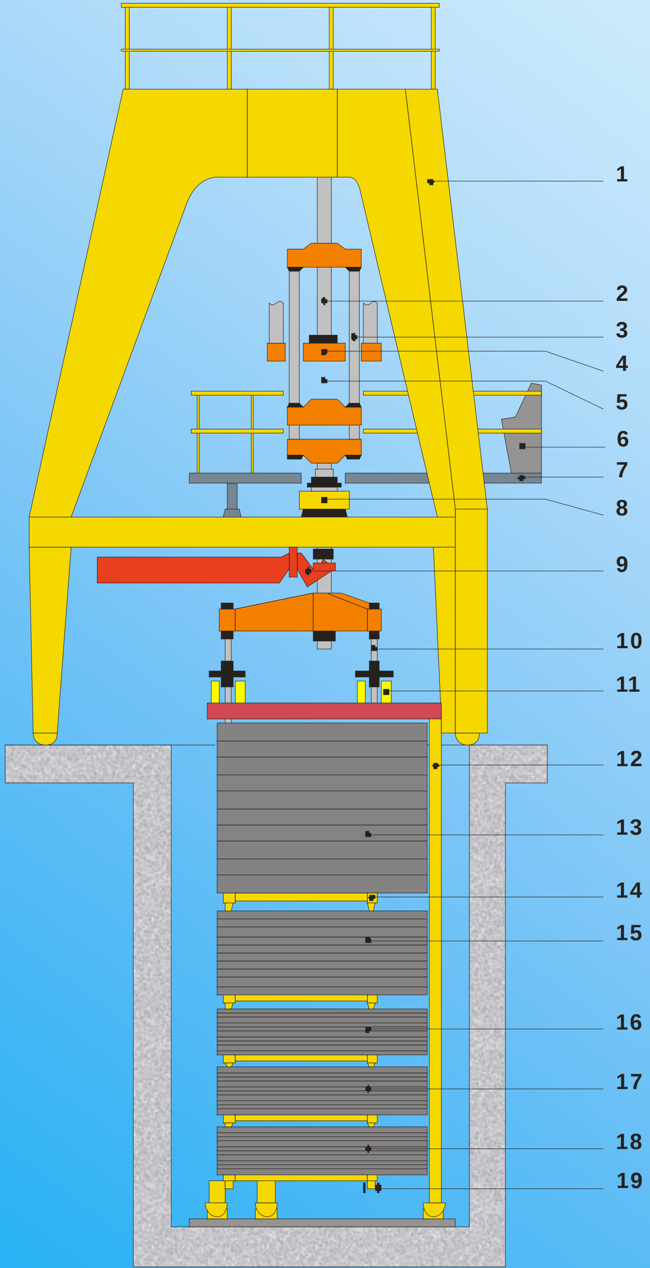
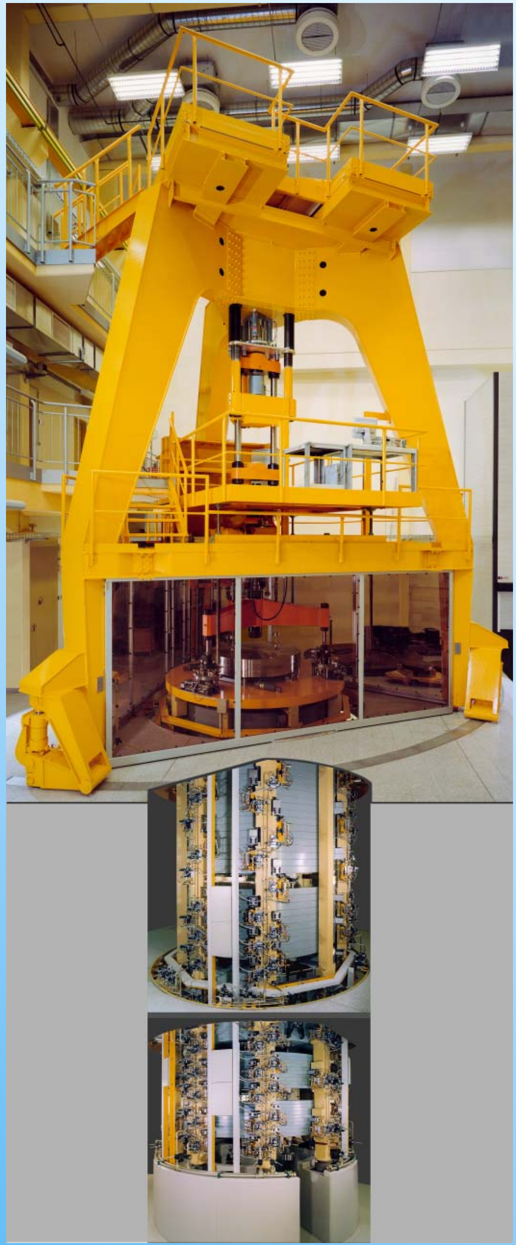
WG 1.21 + WG 1.23

Applications of Force Measurement



PTB‘s 2 MN Deadweight FSM





Measurement Uncertainty of 2 MN Deadweight Force Standard Machine

$$F = m \cdot g_{loc} \cdot \left(1 - \frac{\rho_L}{\rho_m}\right) \cdot \prod_{i=1}^{3} \left(1 - \Delta_i\right)$$

m	mass of deadweights
g_{loc}	local gravity at the position of deadweight
ρ_{m}	density of the deadweights
ρ_{L}	density of air
Δ_1	relative deviation due to magnetic forces
Δ_2	relative deviation due to influences of the compensation lever
Δ_3	relative deviation due to other effects like force introduction (verified by ideal force transducers)

$$w(F) = \sqrt{w^2(m) + w^2(g_{loc}) + \left(-\frac{\rho_L}{\rho_m}\right)^2 w^2(\rho_L) + \left(\frac{\rho_L}{\rho_m}\right)^2 w^2(\rho_m) + \sum_{i=1}^{3} w^2(\Delta_i)}$$

=> Rel. Uncertainty: W <= $2 \cdot 10^{-5}$ (*k*=2)

Comparison of stack 5 (10 x 100 kN) with stack combination 4, 3, 2, 1 by using a 2 MN force transducer.

Stack

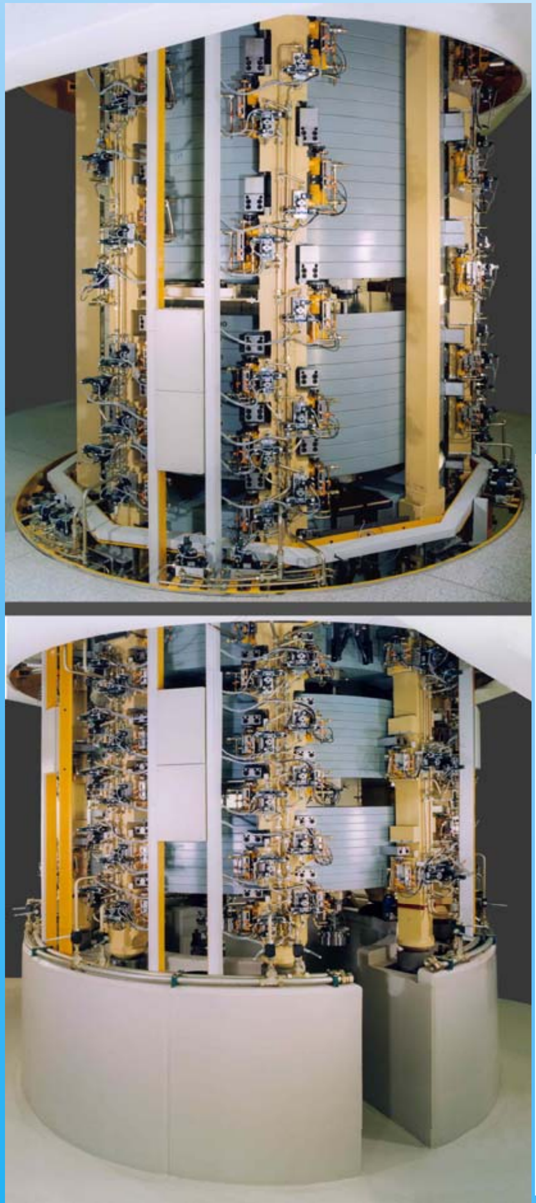
No.5 10x 100kN

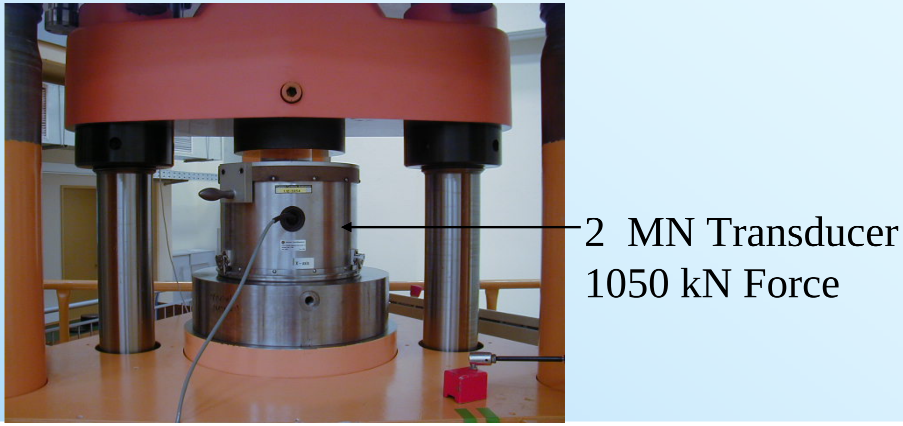
No.4 10x 50kN

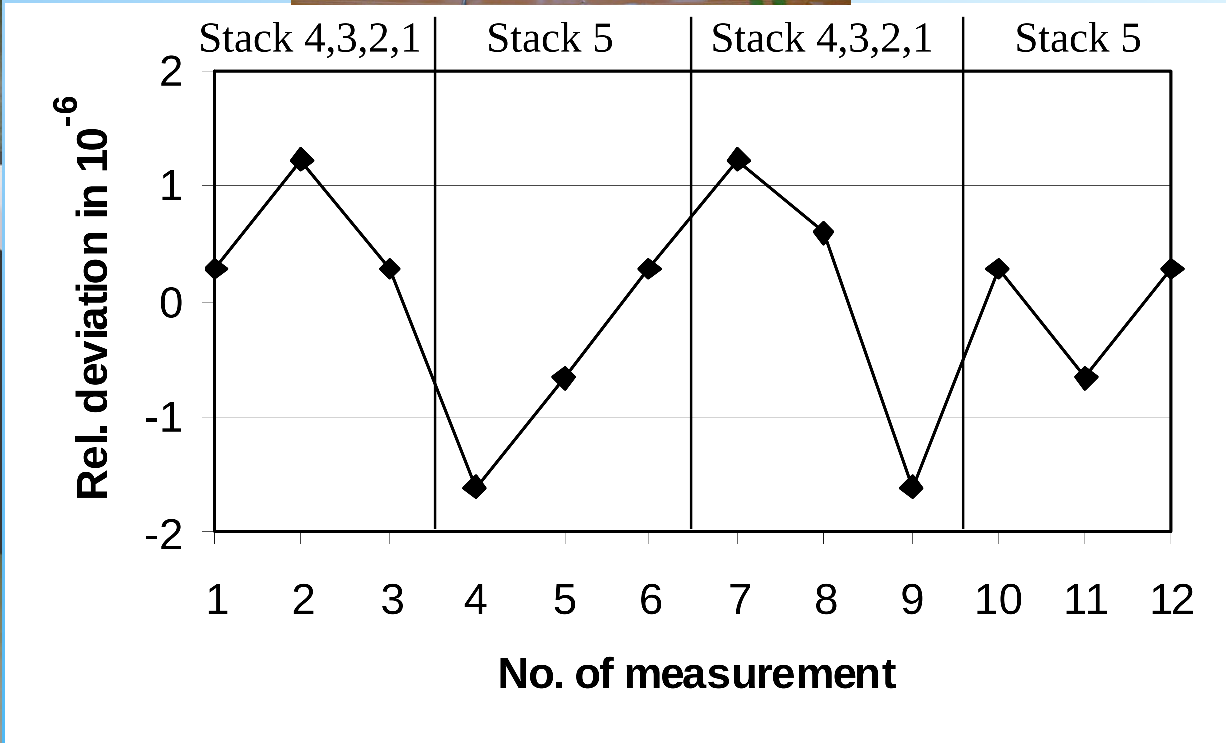
No.3 10x 20kN

No.2 10x 20kN

No.1 10x 10kN

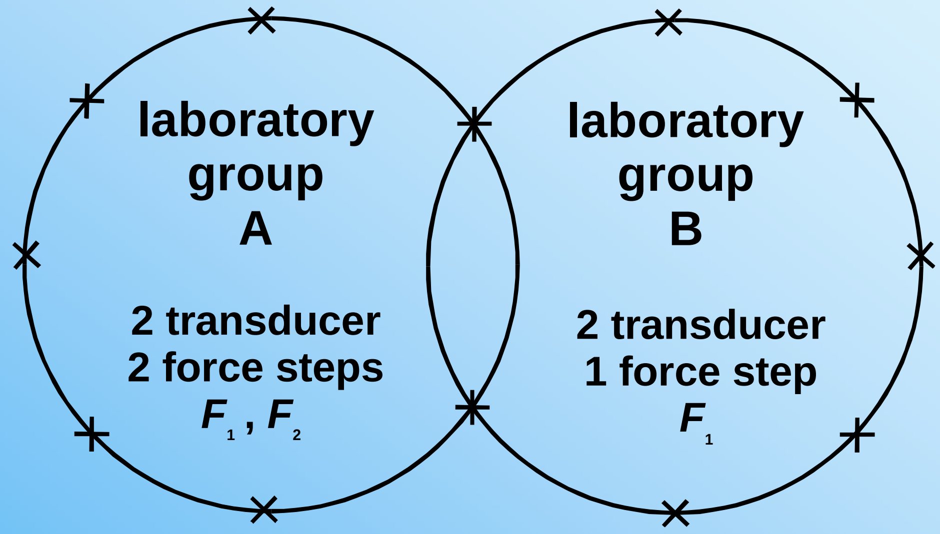






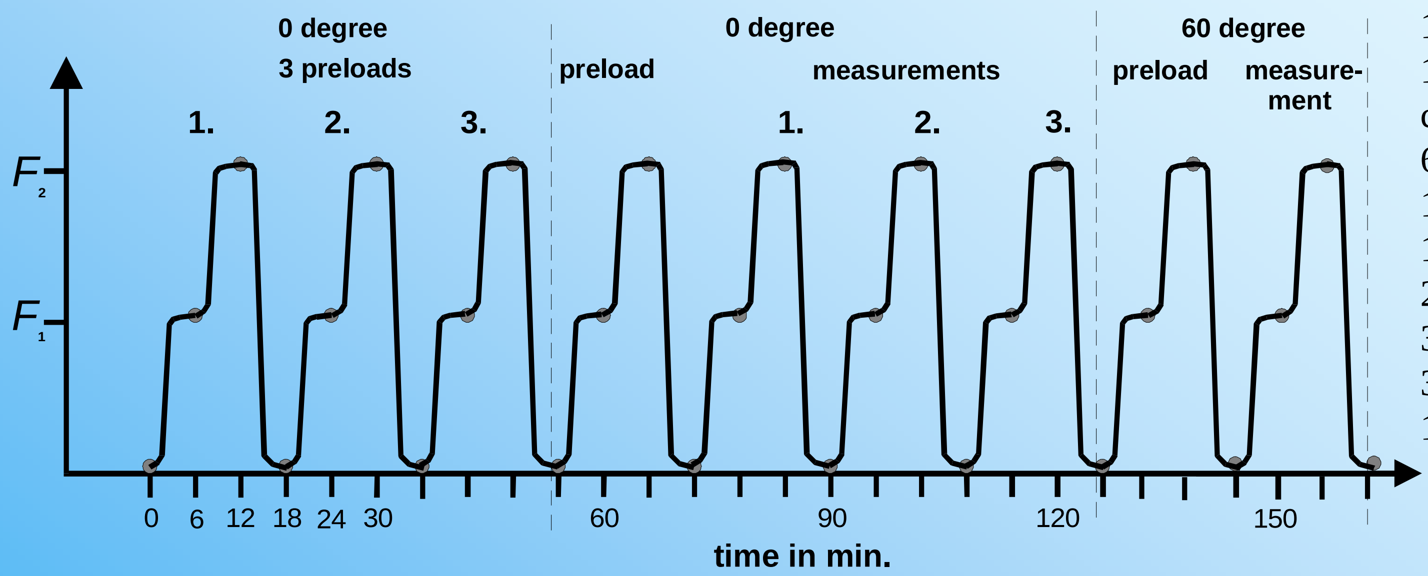
CIPM + EUROMET Force key comparison

Comparison loops for laboratory group A and B



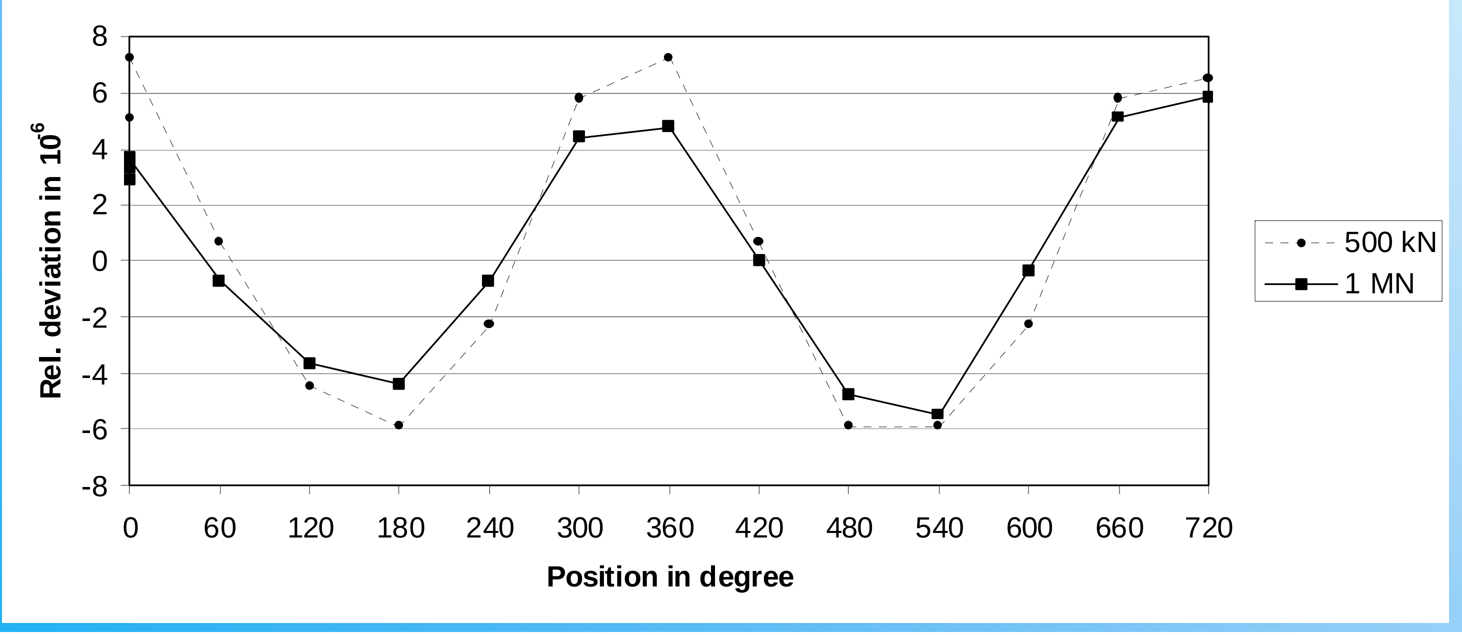
	Pilot laboratory		Force steps	
Force range	CCM	EUROMET	Lab. Group A	Lab. Group B
10 kN	MIKES (FI)	MIKES (FI)	0-5kN-10kN	0-5kN
100 kN	NPL (GB)	NPL (GB)	0-50kN-100kN	0-50kN
1 MN	PTB (DE)	PTB (DE)	0-500kN-1000kN	0-500kN
4 MN	NIST (US)	PTB (DE)	0-2MN-4MN	0-2MN

Rotation effect in the 2 MN force standard machine measured in 2 rotations according key comparison procedure.



1 preload +
1 measurement
cycle in position

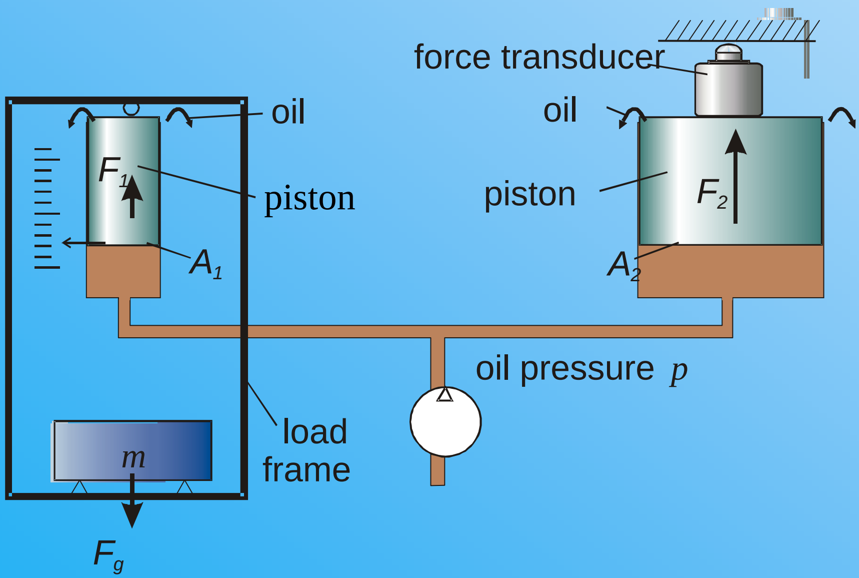
60°	60°
120°	120°
180°	180°
240°	240°
300°	300°
360°/0°	360°
1.rotation	2.rotation



Multicomponent measurments in the 2 MN force standard machine.

PTB

16,5-MN-hydraulic amplification-FSM



3 MN and 9 MN comparison between INRIM and PTB

The results of the calibration made using the PTB dead-weight hydraulic amplification machine (capacity 16.5MN, declared uncertainty $1 \cdot 10^{-4}$) are compared. The calibrations were done in 1984, 1988, 1991, 1995 , 1997 and 2004 for the 9MN cell and in 1984, 1991 1997 and 1999 for the 3MN cell.

The following characteristics of each reference transducer were compared: calibration factor, repeatability with and without rotation, hysteresis, zero variations at zero load.

Fig. 8. Calibration of the INRIM - 3 MN Build-up system on the 16.5 MN PTB hydraulic multiplication machine

PTB

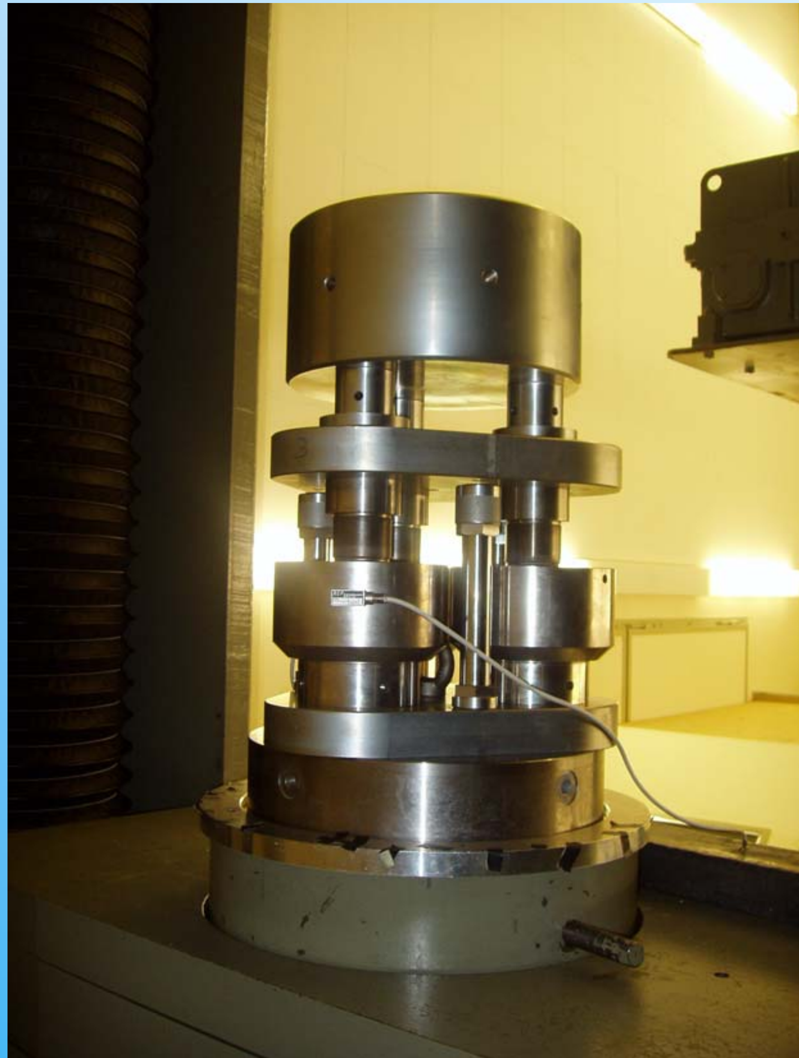


Fig.7: Calibration of the INRIM - 3 MN Build-up system on the INRIM - 1 MN DWM

Fig.1: 3MN force transducer - Calibration factor

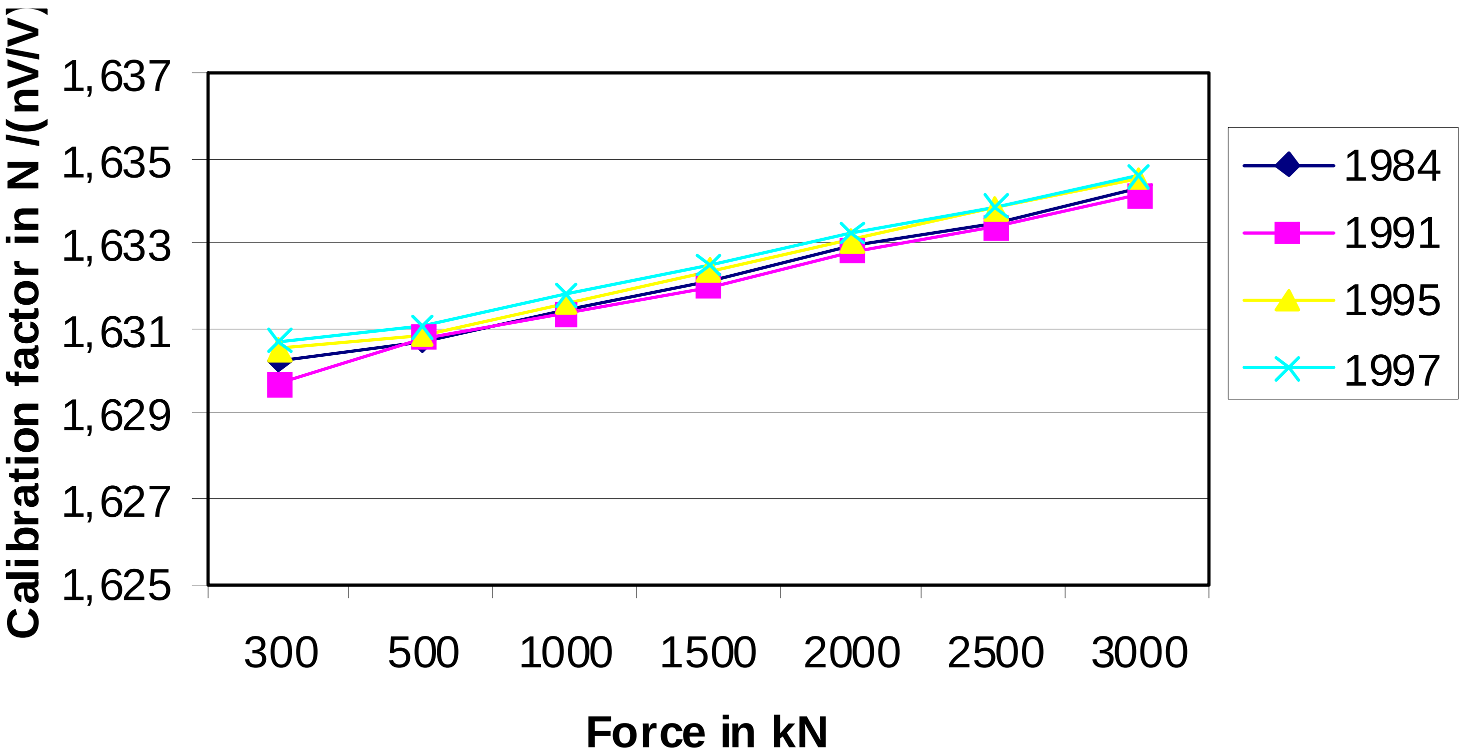


Fig.2: 3 MN force transducer - Relative deviation to the mean calibration factor obtained from Fig. 1.

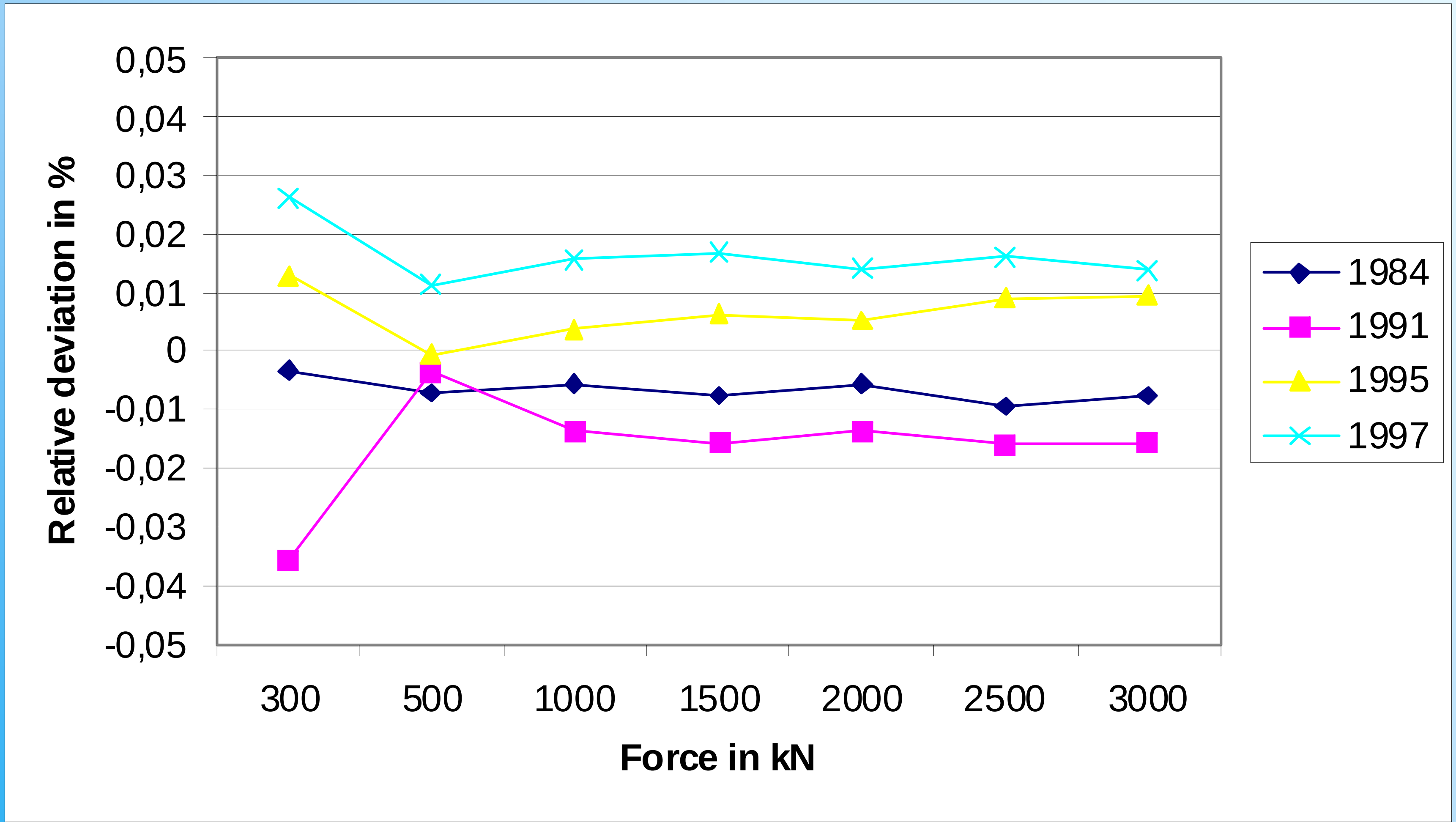


Fig.5: 9MN load cell - Calibration factor

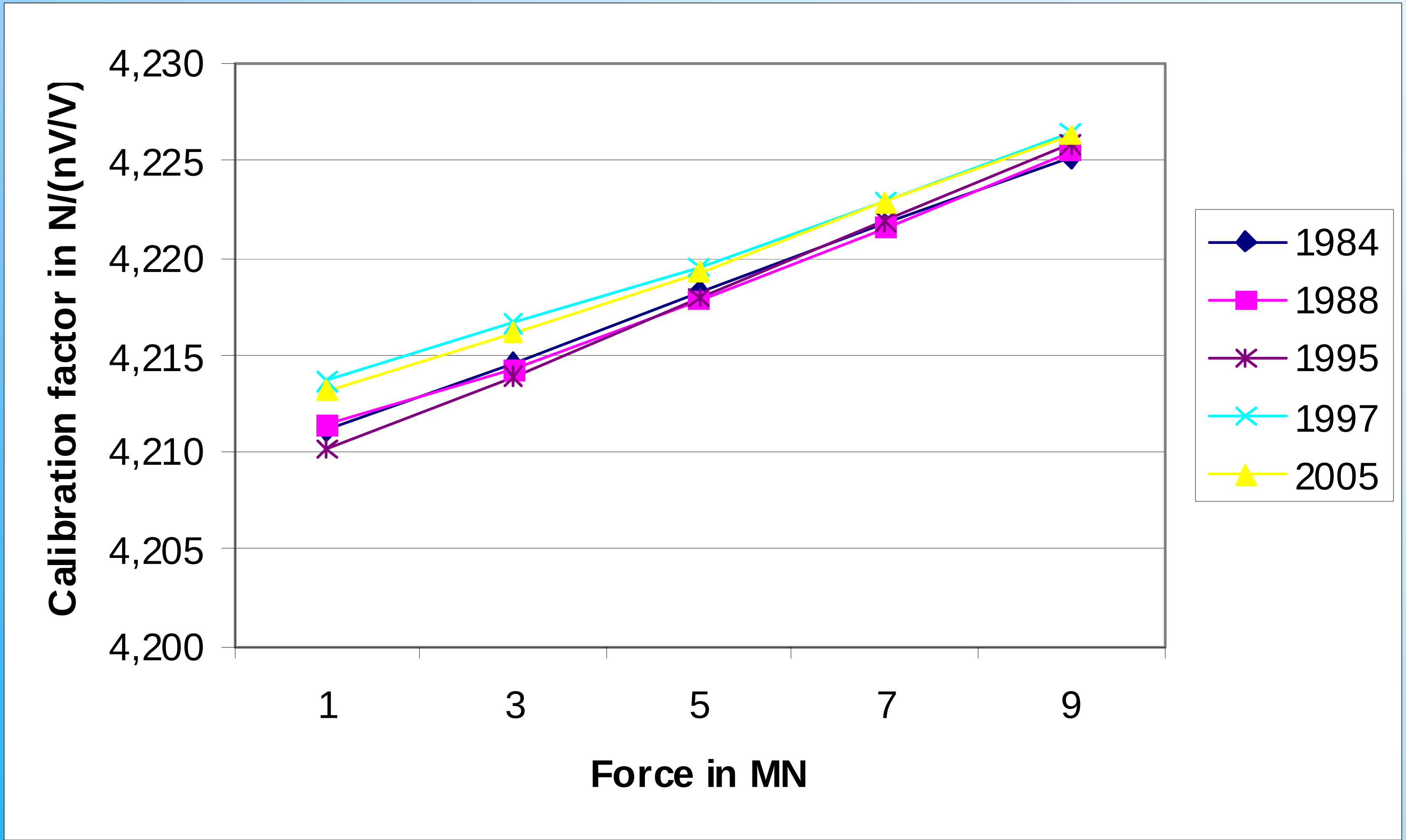


Fig.6: 9 MN force transducer - Rel. deviation to mean calibration factor obtained from Fig. 5.

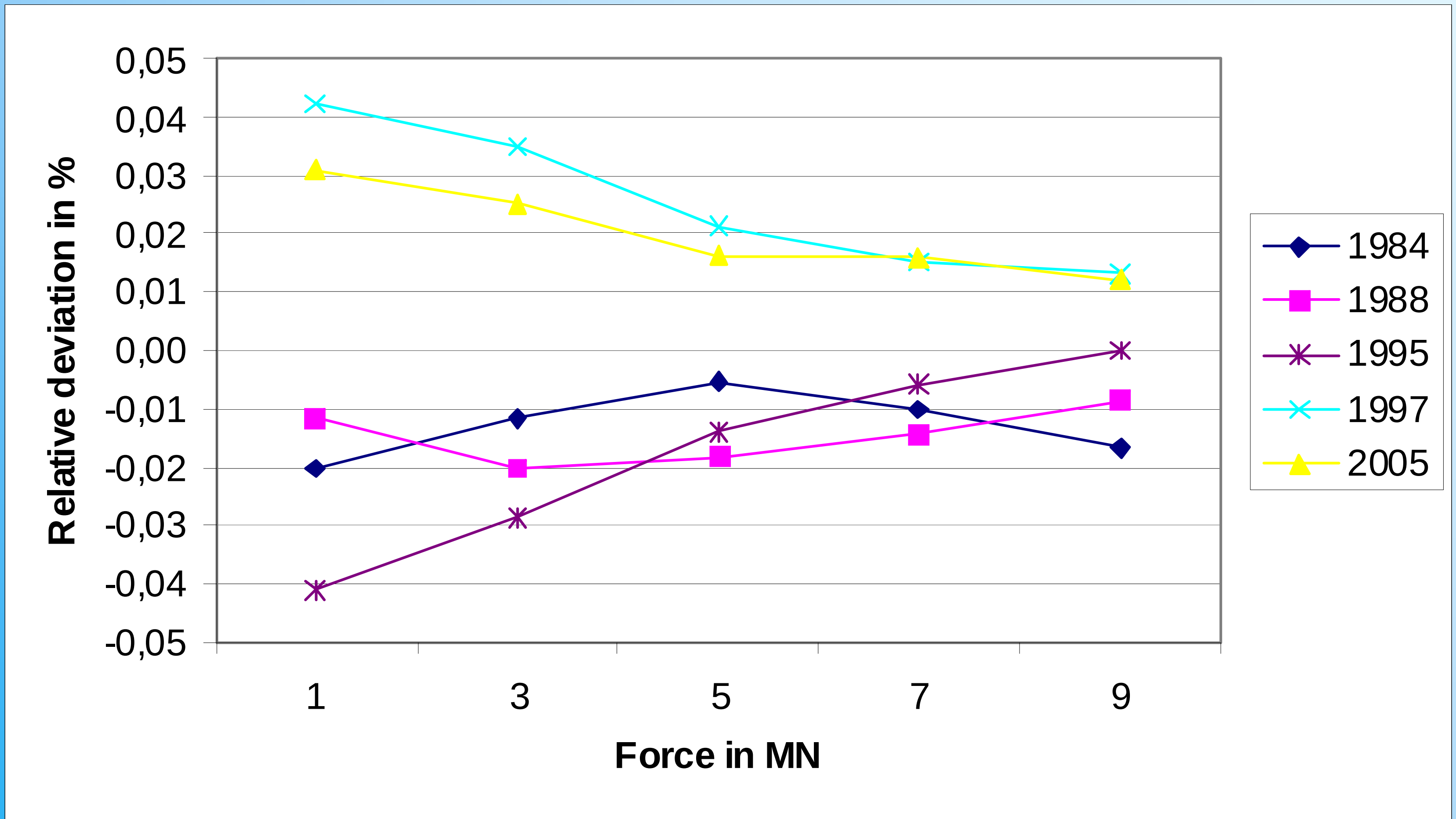


Fig.3: 9 MN force transducer - Repeatability

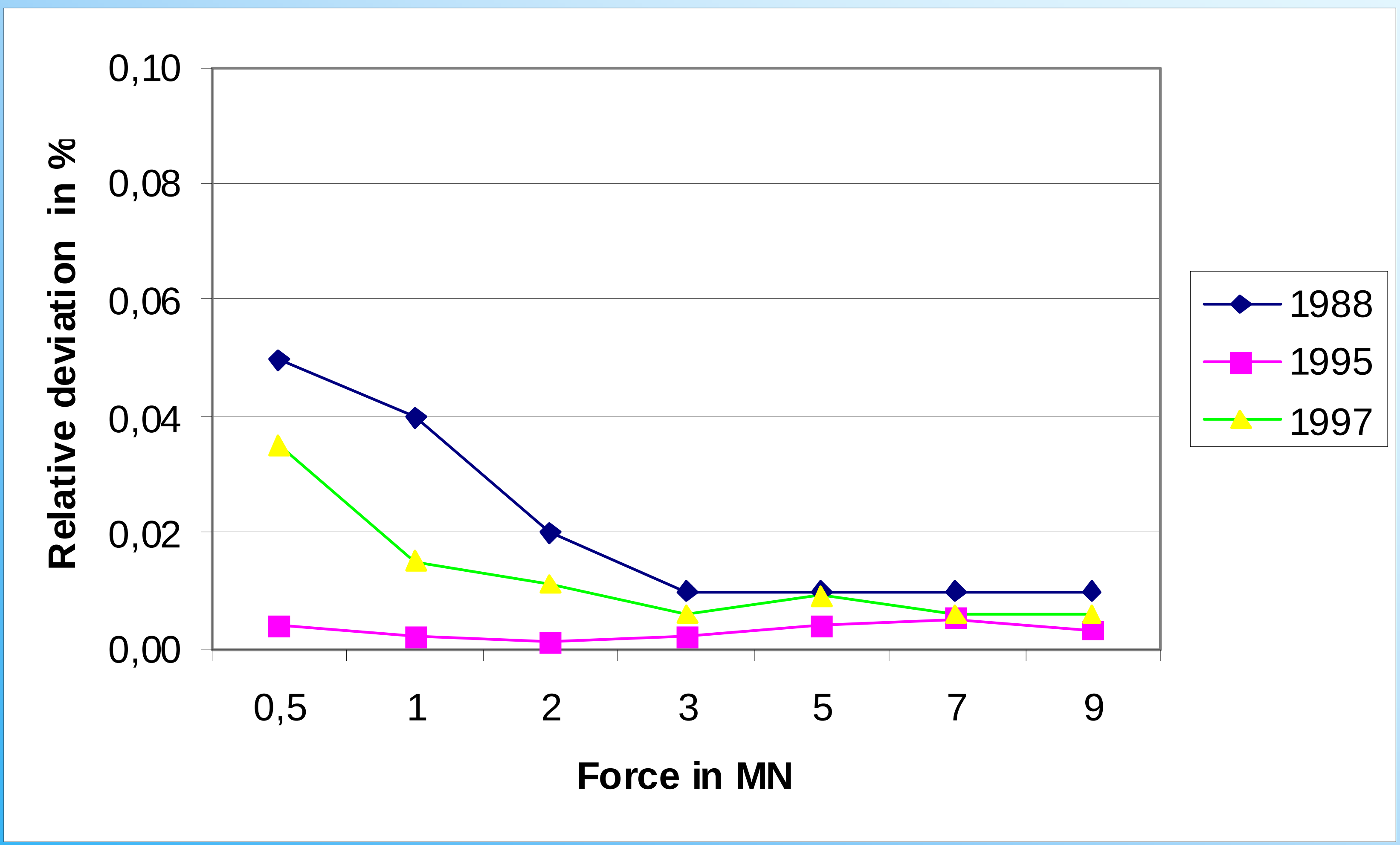


Fig.4: 9 MN force transducer - Rotation effect

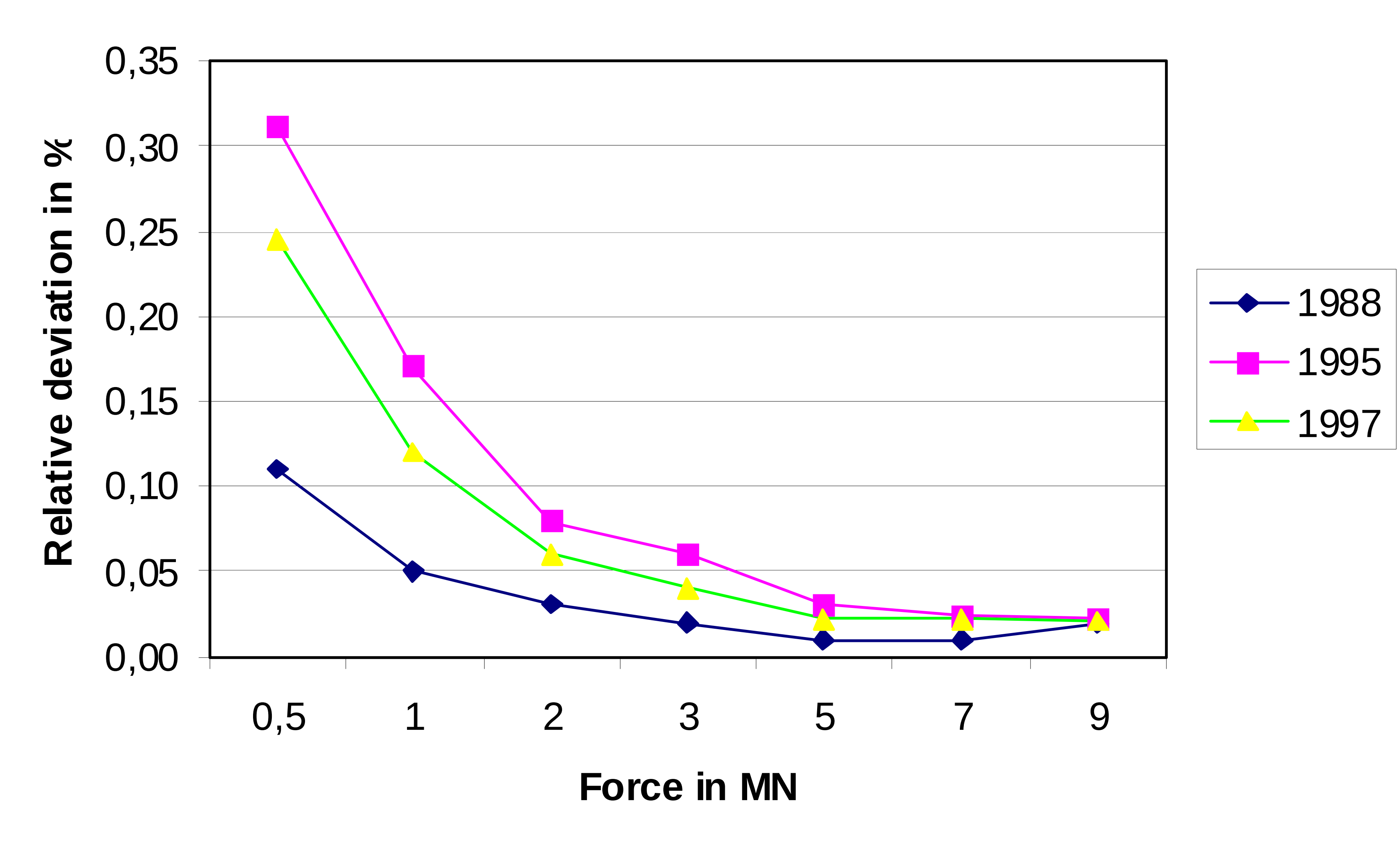


TABLE 1. Expanded Uncertainty Evaluation

	Probability distribution	Standard uncertainty (k=1)
Individual calibration of the 1 MN force standard transducers • Reference force applied • Resolution • Repeatability without rotation • Repeatability with rotation • Reversibility • Zero error • Interpolation error	• Normal • Rectangular • Rectangular • U shaped • Rectangular • Rectangular • Triangular	$1 \cdot 10^{-5}$
• Total calibration uncertainty		$8 \cdot 10^{-5}$ F/3

TABLE 1. Expanded Uncertainty Evaluation

<table>
<tr><td>Use of the Force Transducers
• Creep (30 min.)
• Long time drift
• Temperature drift (2° C)</td><td>• Normal
• Rectangular
• arcsine</td><td>$0.3 \cdot 10^{-4}$ F/3
$0.8 \cdot 10^{-5}$ F/3
$0.15 \cdot 10^{-4}$ F/3</td></tr>
<tr><td colspan="3">$u_c^2 = (8 \cdot 10^{-5}\ F/3)^2 + (0.3 \cdot 10^{-4}\ F/3)^2 + (0.8 \cdot 10^{-5}\ F/3)^2 + (0.15 \cdot 10^{-4}\ F/3)^2 = (8.4 \cdot 10^{-5}\ F/3)^2$</td></tr>
<tr><td colspan="3">BUILD-UP
$3\ u_c^2 = 3(8.4 \cdot 10^{-5}\ F/3)^2 = 2.3 \cdot 10^{-9}\ F^2$</td></tr>
<tr><td>Force generating system
• internal coherence of the masses
• intercomparison</td><td></td><td>$0.8 \cdot 10^{-4}$ F</td></tr>
<tr><td>Build-up system</td><td colspan="2">$u_c^2 = 2.3 \cdot 10^{-9}\ F^2 + 6.4 \cdot 10^{-9}\ F^2 =$
$= 8.7\ 10^{-9}\ F^2$
$u_c = 0.93 \cdot 10^{-4}$ F
$U = 2\ u_c = 1.87 \cdot 10^{-4}$ F
$U_{bmc} = 2 \cdot 10^{-4}$ F</td></tr>
</table>

Conclusion of the comparison between INRIM and PTB

The results of the calibrations performed at PTB over the last 20 years not only confirm the principal results of the force transducer characteristics expressed after the first decade of use of the INRIM reference standard, they also enable us to make the following evaluations:

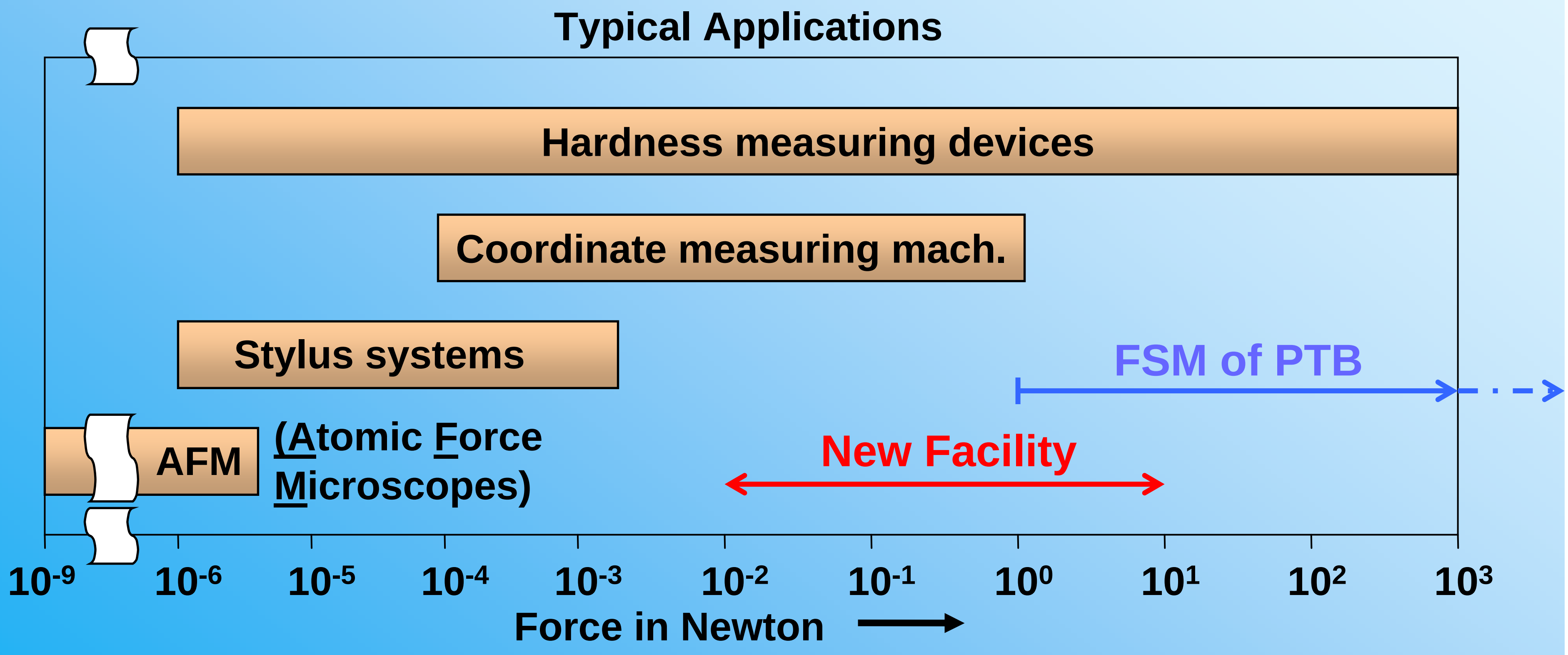
The two reference force standards of 3 MN and 9 MN showed an average stability of the order of $2 \cdot 10^{-4}$ over four years, while the 5 MN shows a reproducibility of $1 \cdot 10^{-4}$ during the measurements carried out with the PTB, and INRIM force standard machines.

The 3 MN build-up system revealed a relative deviation less than $2 \cdot 10^{-4}$ in agreement with preliminary results up to 1000 kN on the INRIM DWM.

In agreement with these measurement results the different load cells could be used in the INRIM Comparator Machine with a declared relative expanded uncertainty of $5 \cdot 10^{-4}$

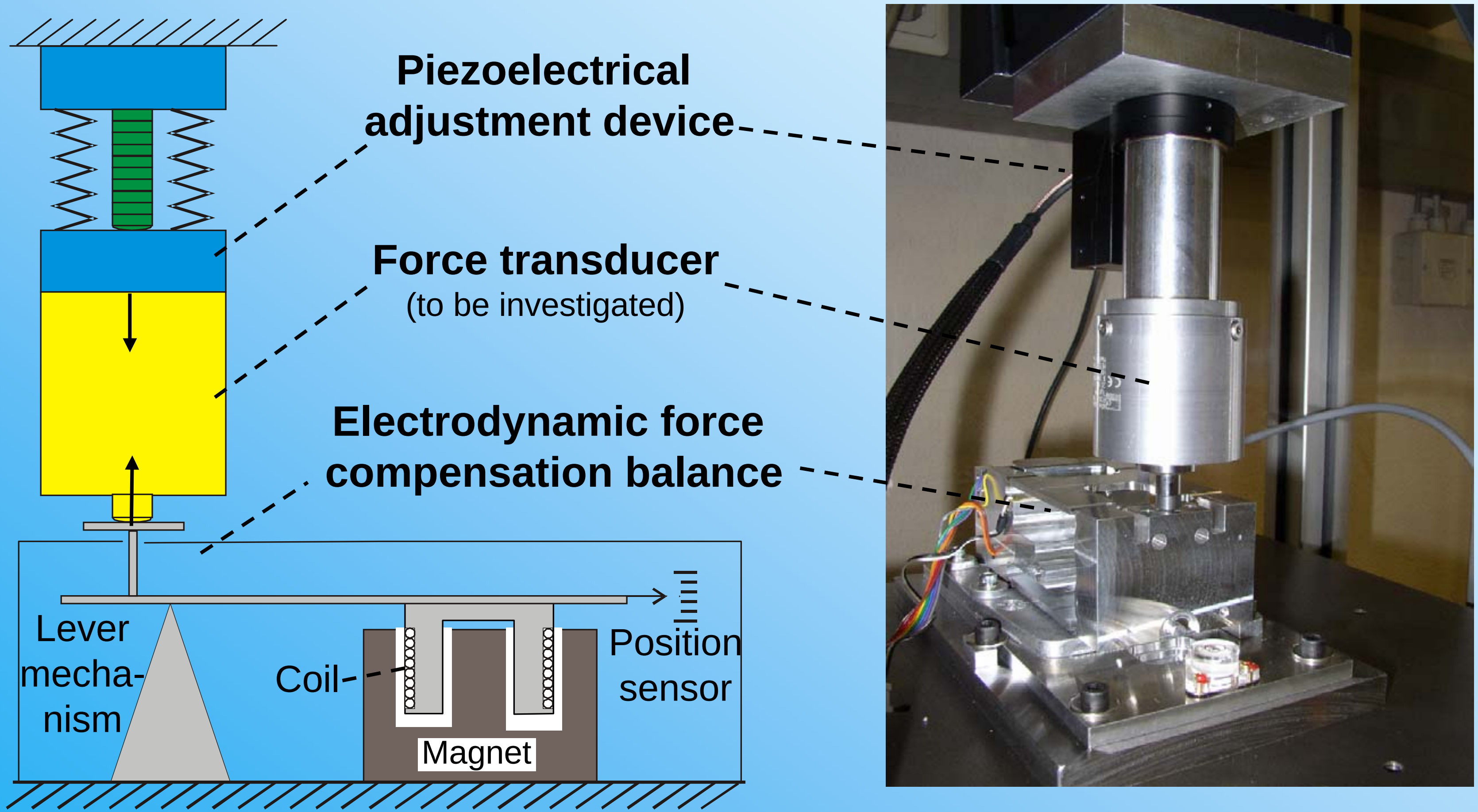
Needs for extension of PTB´s FSM to small forces

Microsystem and nanotechnology ⇨ demand of traceability of small forces

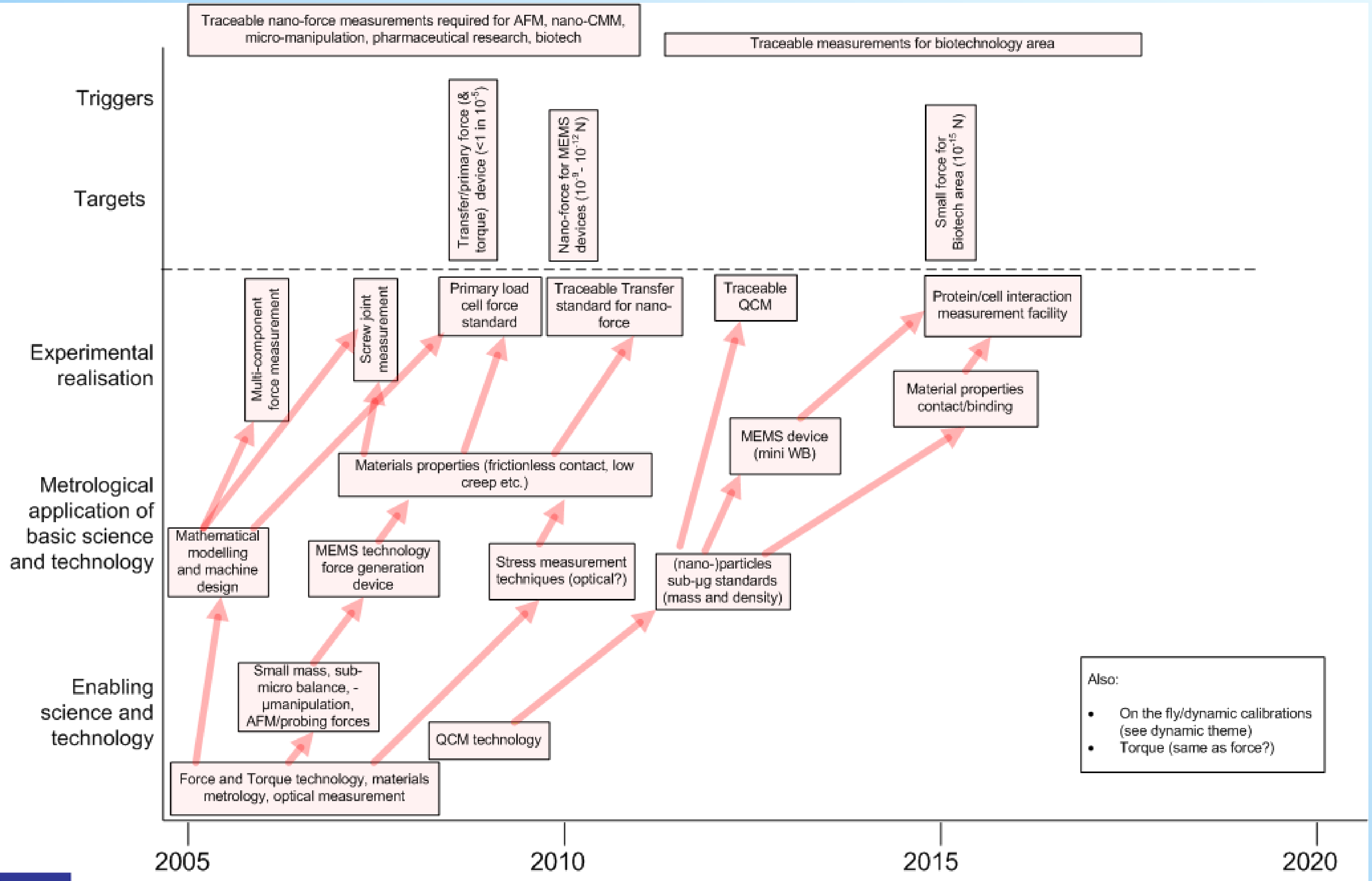


Set-Up based on a compensation balance

PTB



Roadmap Force



Calibration Procedures of Force Measuring Devices

1. Key Comparison
Comparison of Force Standard Machines with rel. Uncertainties of ≤ 0,002% (Deadweight)

2. Traceability of Accreditatied Laboratories for Calibration of Force Measuring Devices

DKD Procedure to verify the Traceability of Force Calibration Machines with rel. Uncertainties down to 0,005% (Deadweight)

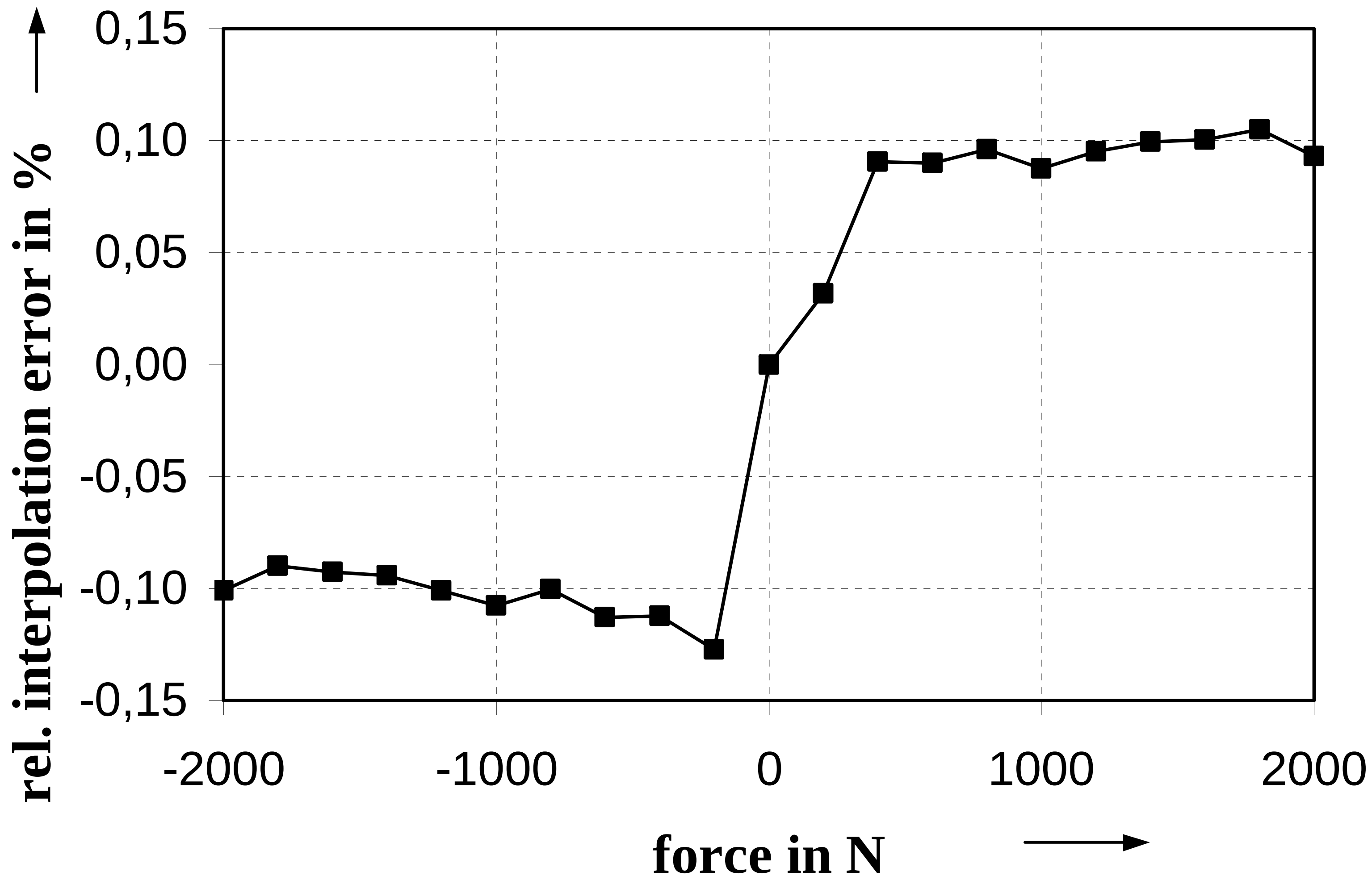
3. Procedure according IS0 376 for Calibration of Material Testing Machines

4. Simplified Procedures according DKD 3-3

5. Continous Procedures according DKD 3-9

6. Special Procedures which have to be evaluated.

Static sensitivity of force transducers.



Summary Measurement Uncertainty Force

1. MU is depending on the Procedure.
2. MU is only valid for the calibration result.
3. The user has to take additional contributions into account.

Needs for extension of FSM and methods to dynamic forces

1. Material Testing Machines

- sinusoidal testing

- impact testing

2. Crash tests in automobile industry

- collision forces

- dummy forces

3. Modal analysis

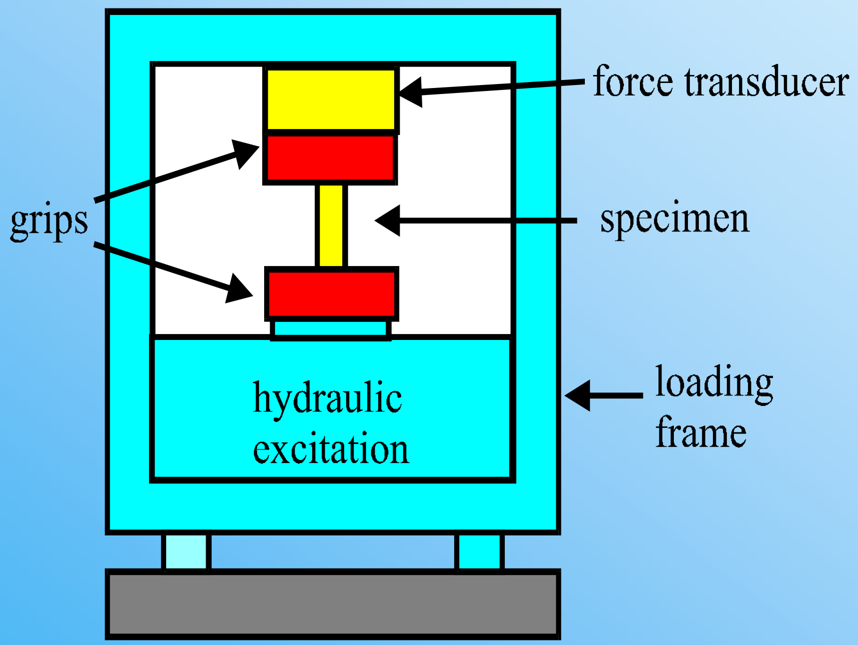
- sinusoidal excitation

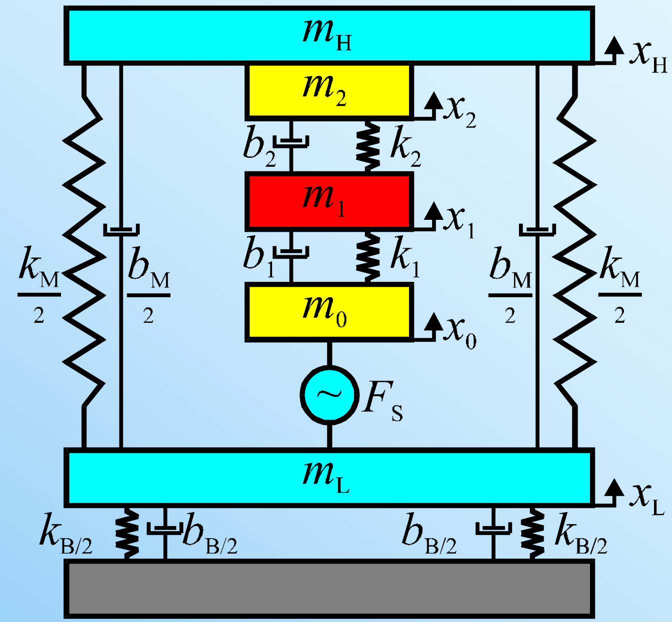
- impact excitation

4. Dynamic weighing

- different loading times and sequences

How can we use dynamic force calibration in materials testing machines ?





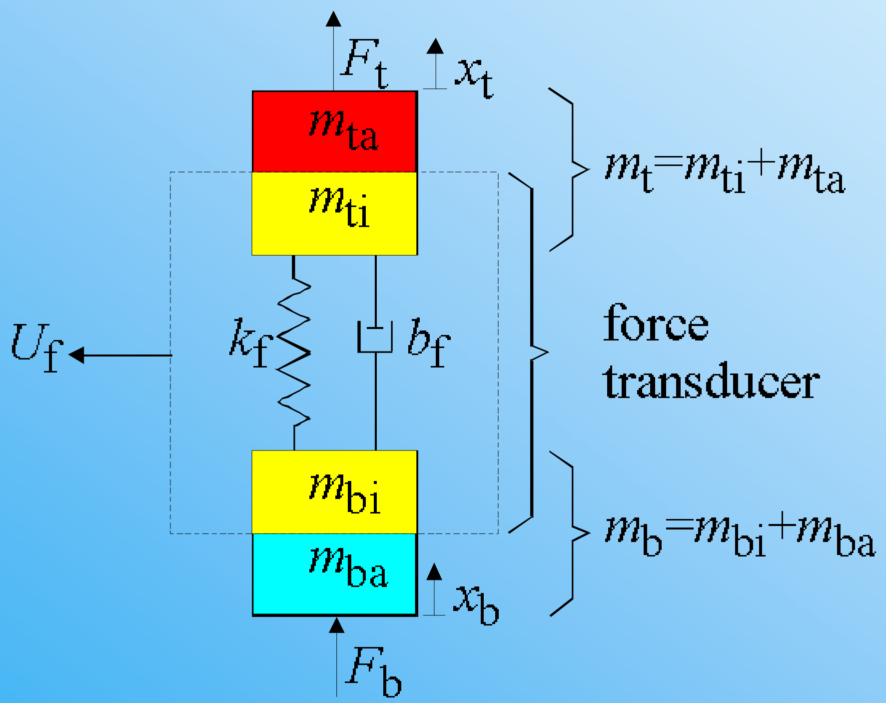
1. force measuring devices of good dynamic properties

2. interaction with materials testing machine

=> analysis of application, resonance effects

3. Compensation of systematic dynamic influences

Force transducer model.



differential equations:

$$m_t \cdot \ddot{x}_t = F_t - k_f \cdot (x_t - x_b) - b_f \cdot (\dot{x}_t - \dot{x}_b)$$

$$m_b \cdot \ddot{x}_b = F_b + k_f \cdot (x_t - x_b) + b_f \cdot (\dot{x}_t - \dot{x}_b)$$

relative deformation:

$$r_f = x_t - x_b$$

$$m_t \cdot \ddot{r}_f + b_f \cdot \dot{r}_f + k_f \cdot r_f = F_t - m_t \cdot \ddot{x}_b$$

$$m_b \cdot \ddot{r}_f + b_f \cdot \dot{r}_f + k_f \cdot r_f = -F_b + m_b \cdot \ddot{x}_t$$

static sensitivity:

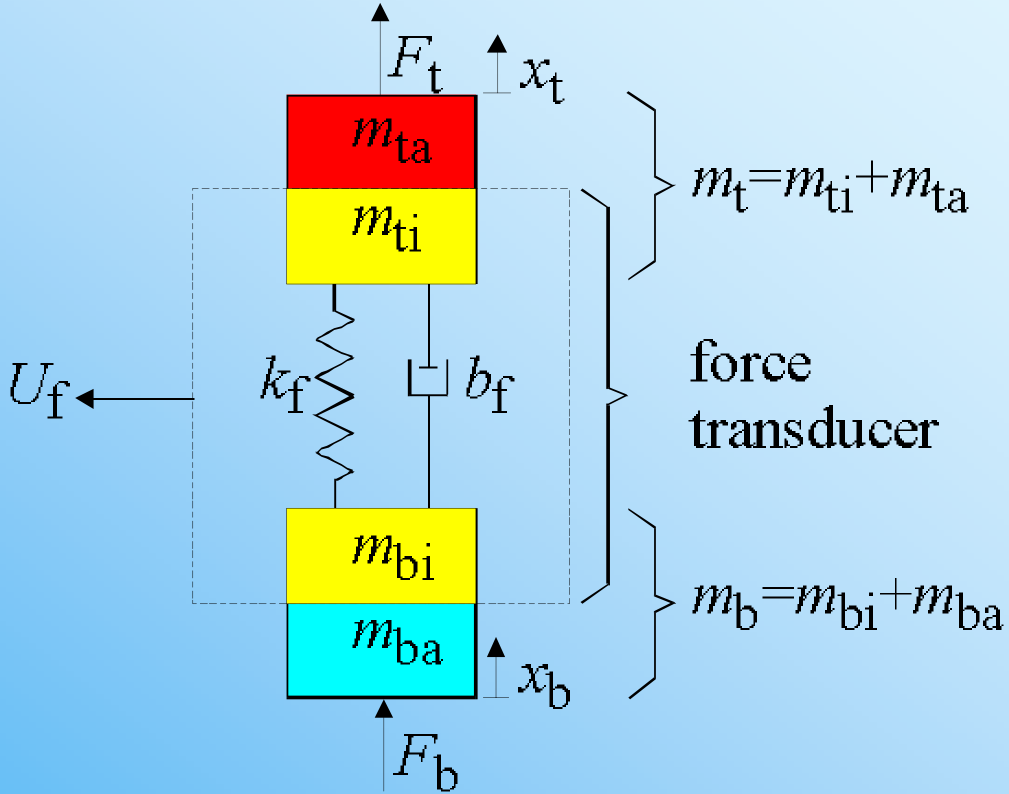
$$S_{f0} = \frac{\Delta U_f}{\Delta F_t}$$

linear characteristic:

$$k_f \cdot r_f = S_{f0}^{-1} \cdot U_f$$

Compensation of mass forces.

PTB



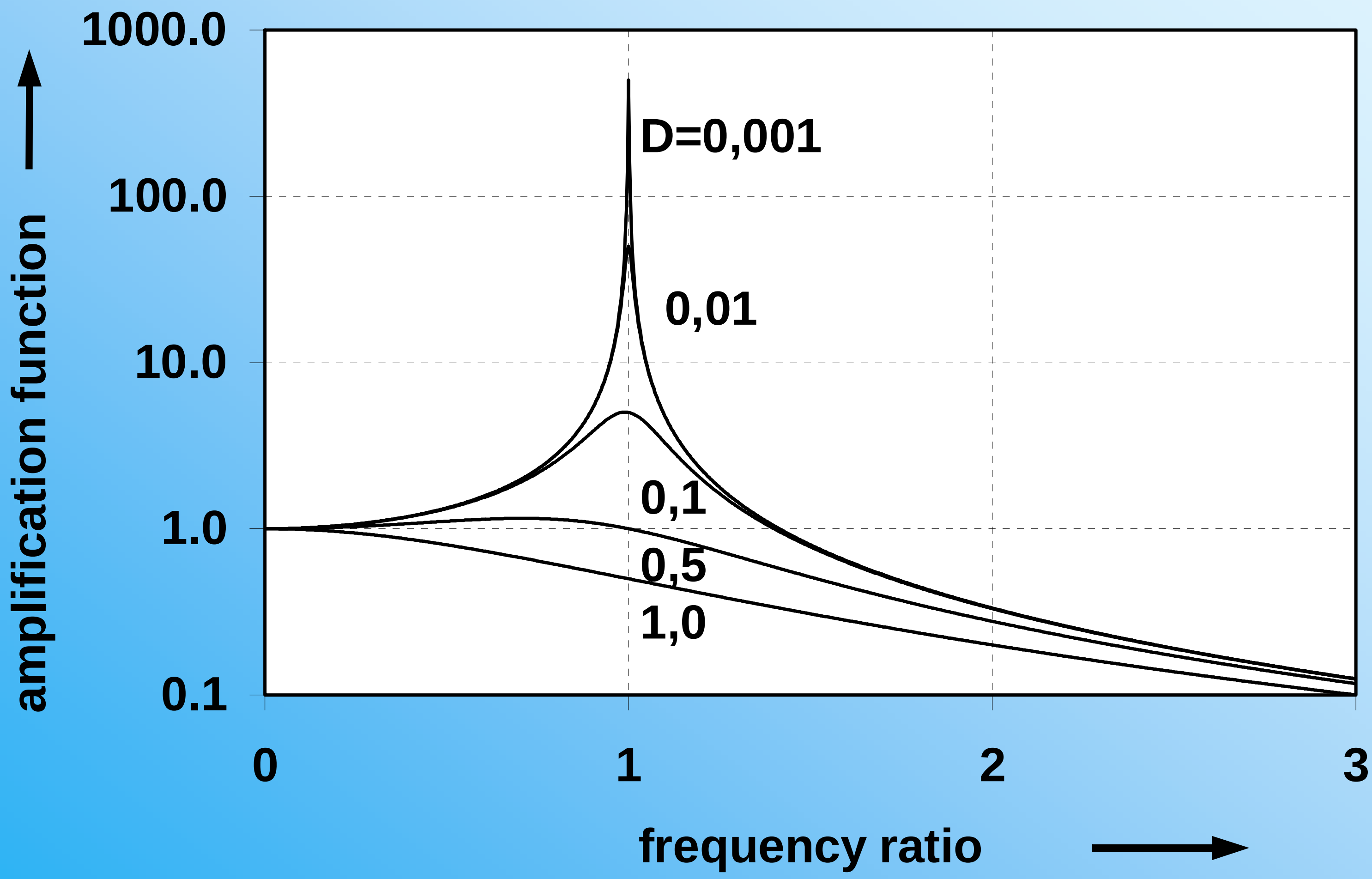
$$m_t \cdot \ddot{r}_f + b_f \cdot \dot{r}_f + k_f \cdot r_f = F_t - m_t \cdot \ddot{x}_b$$

$$F_t = S_{f0}^{-1} \cdot U_f + m_t \cdot \ddot{x}_t + \frac{b_f}{k_f} \cdot S_{f0}^{-1} \cdot \dot{U}_f$$

Amplitude response of the force transducer

$$m_t \cdot \ddot{r}_f + b_f \cdot \dot{r}_f + k_f \cdot r_f = F_t - m_t \cdot \ddot{x}_b$$

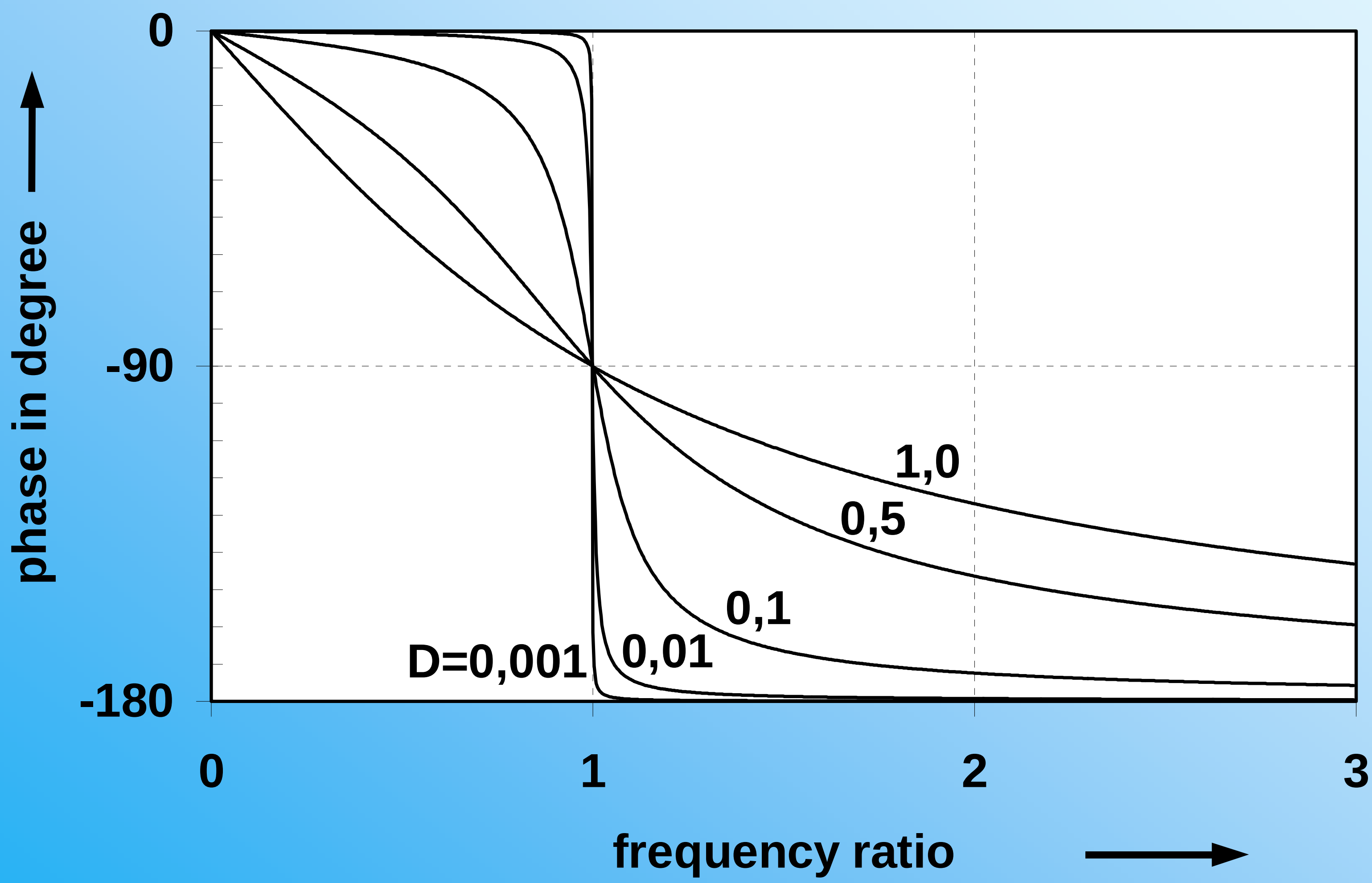
$$m_t \cdot \ddot{r}_f + b_f \cdot \dot{r}_f + k_f \cdot r_f = F_t(t) = \hat{F} \cdot \cos(\omega \cdot t + \varphi_F) = \mathrm{Re}\left\{\underline{\hat{F}} \cdot e^{j\omega \cdot t}\right\}$$



Phase response of the force transducer.

$$m_{\mathrm{t}} \cdot \ddot{r}_{\mathrm{f}} + b_{\mathrm{f}} \cdot \dot{r}_{\mathrm{f}} + k_{\mathrm{f}} \cdot r_{\mathrm{f}} = F_{\mathrm{t}} - m_{\mathrm{t}} \cdot \ddot{x}_{\mathrm{b}}$$

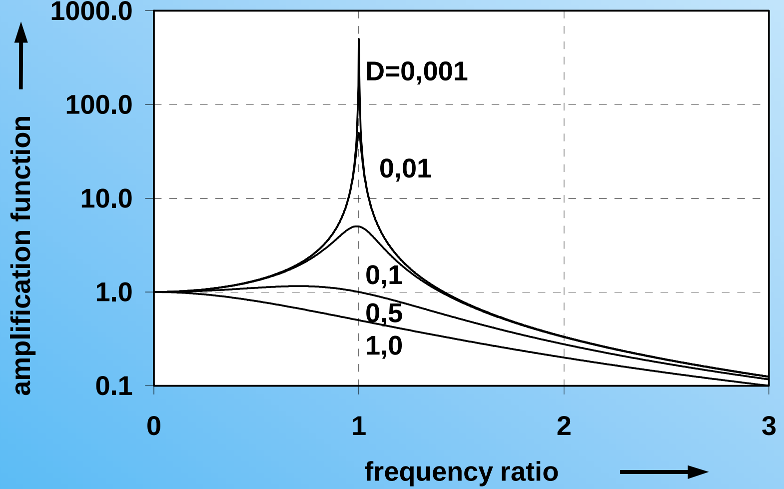
$$m_{\mathrm{t}} \cdot \ddot{r}_{\mathrm{f}} + b_{\mathrm{f}} \cdot \dot{r}_{\mathrm{f}} + k_{\mathrm{f}} \cdot r_{\mathrm{f}} = F_{\mathrm{t}}(t) = \hat{F} \cdot \cos(\omega \cdot t + \varphi_{\mathrm{F}}) = \mathrm{Re}\left\{\underline{\hat{F}} \cdot e^{j\omega \cdot t}\right\}$$



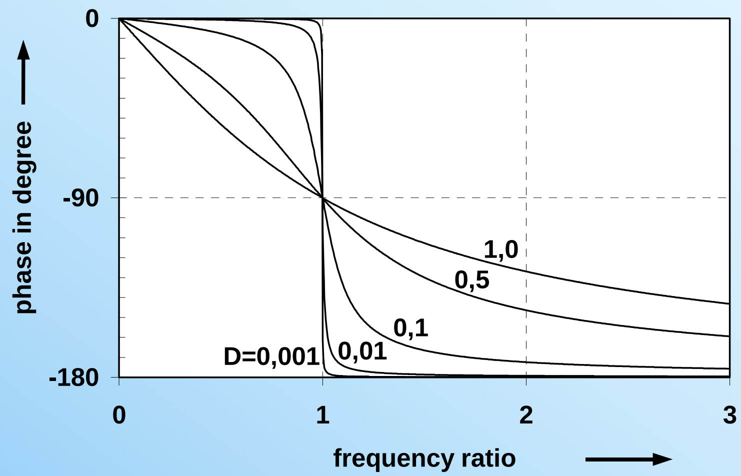
Resonance behaviour of a force transducer.

PTB

amplification function



matching phase curve



$$V\left(\frac{\omega}{\omega_0}, D\right) = \frac{k_f \cdot \hat{r}}{\hat{F}} = \frac{1}{\sqrt{\left(1-\left(\frac{\omega}{\omega_0}\right)^2\right)^2 + 4D^2\left(\frac{\omega}{\omega_0}\right)^2}}$$

$$\varphi_{rF} = \varphi_r - \varphi_F = -\arctan\left(\frac{2D\frac{\omega}{\omega_0}}{1-\left(\frac{\omega}{\omega_0}\right)^2}\right)$$

resonance frequency f_r , eigenfrequency f_d , characteristic frequency f_0

$$f_r = f_0\sqrt{1-2D^2}$$

small damping factor $0<D<0{,}01$ =>

$$f_r = f_d = f_0 = \frac{1}{2\pi}\cdot\sqrt{\frac{k_f}{m_{ti}+m_{ta}}}$$

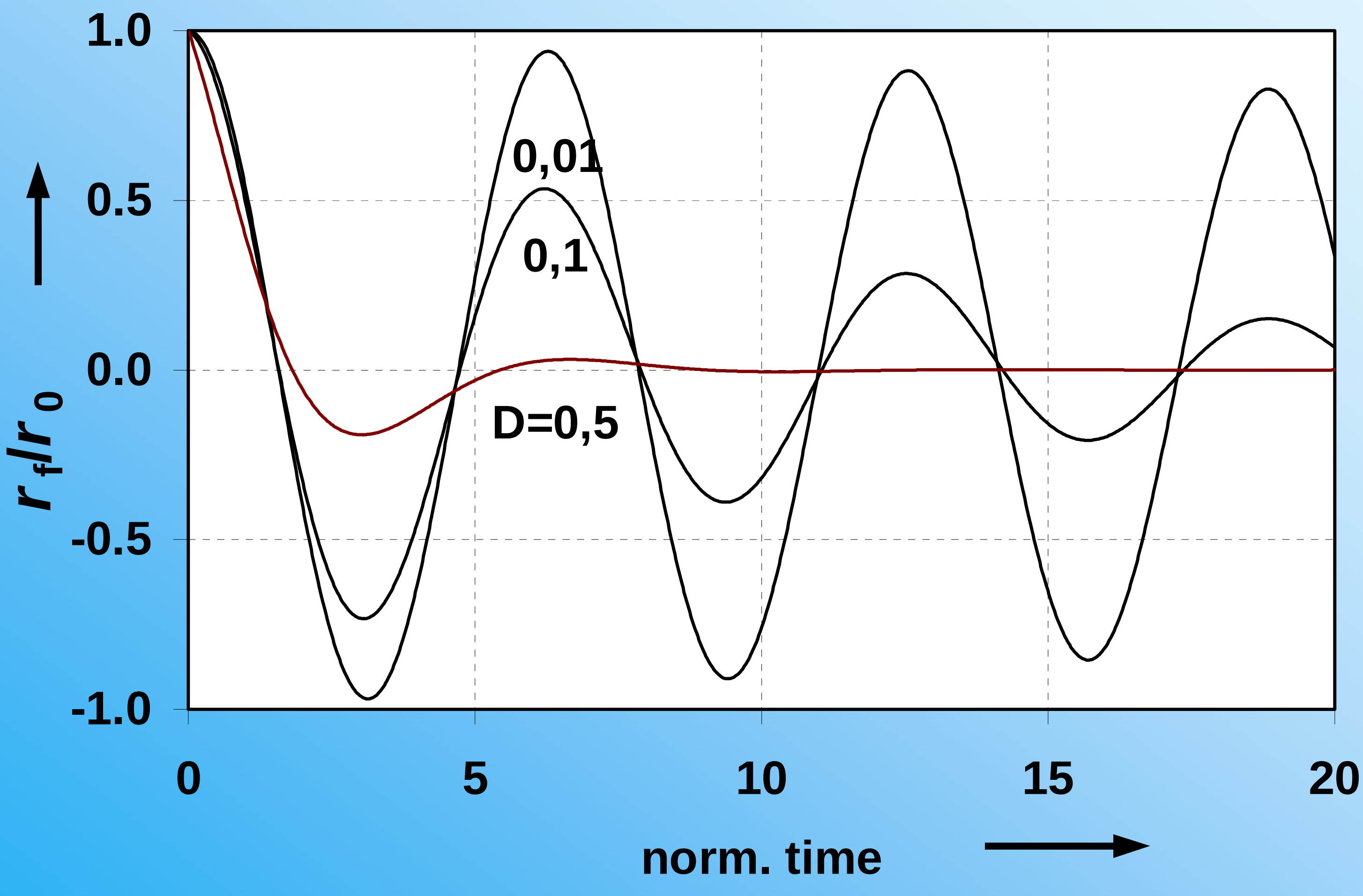
fundamental eigenfrequency f_{0g}

$$f_{0g} = \frac{1}{2\pi}\cdot\sqrt{\frac{k_f}{m_{ti}}}$$

Abrupt unloading of a force transducer.

$$m_t \cdot \ddot{r}_f + b_f \cdot \dot{r}_f + k_f \cdot r_f = F_t - m_t \cdot \ddot{x}_b$$

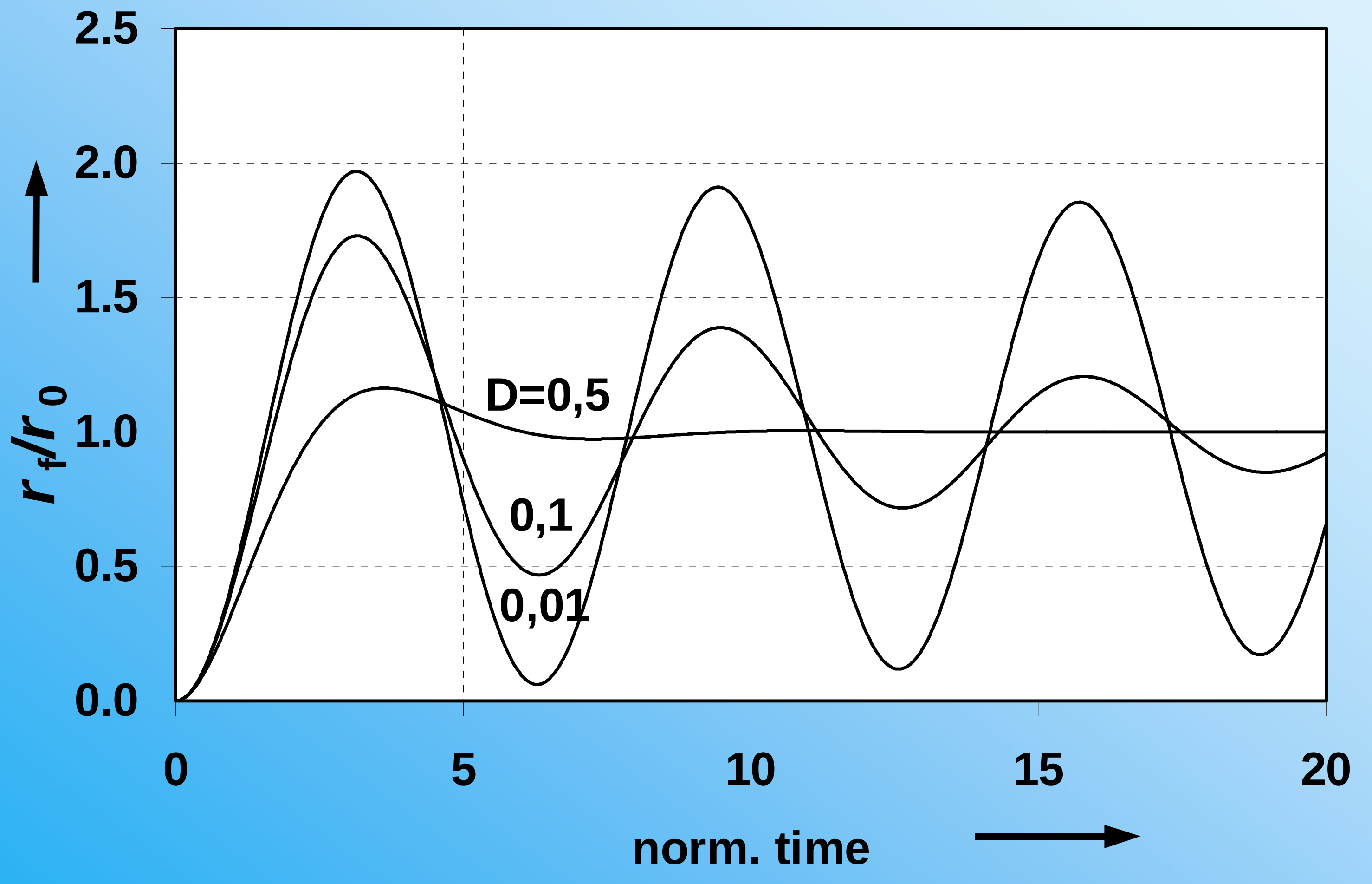
$$\frac{1}{\omega_0^2} \cdot \ddot{r}_f + \frac{2D}{\omega_0} \cdot \dot{r}_f + r_f = \frac{F_0}{k_f}\left(= r_0\right) = 0$$



Abrupt loading of a force transducer.

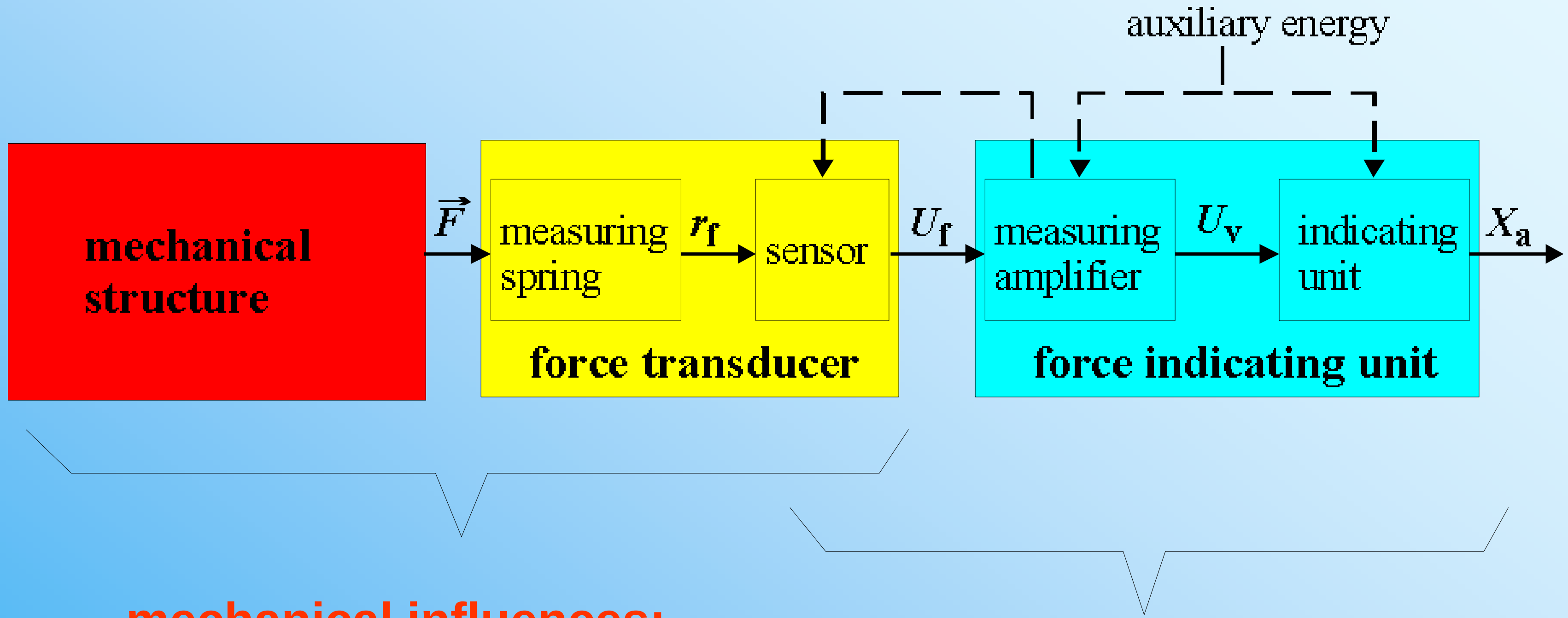
$$m_\mathrm{t} \cdot \ddot{r}_\mathrm{f} + b_\mathrm{f} \cdot \dot{r}_\mathrm{f} + k_\mathrm{f} \cdot r_\mathrm{f} = F_\mathrm{t} - m_\mathrm{t} \cdot \ddot{x}_\mathrm{b}$$

$$\frac{1}{\omega_0^2} \cdot \ddot{r}_\mathrm{f} + \frac{2D}{\omega_0} \cdot \dot{r}_\mathrm{f} + r_\mathrm{f} = \frac{F_0}{k_\mathrm{f}} (= r_0)$$



Dynamic properties of force measuring devices.

PTB



mechanical influences:

design of force transducer

material properies

force introduction

interaction with surrounding mechanical structure

electrical influences:

sensor type

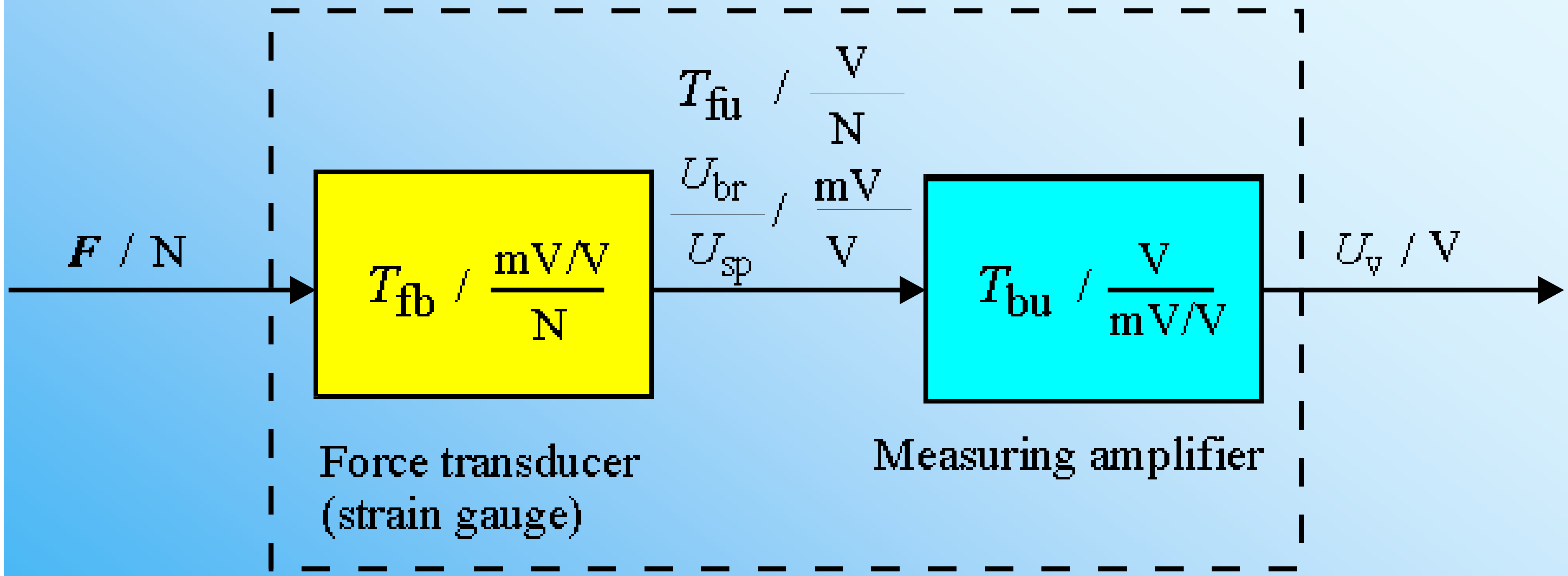
amplifier principle

filter characteristic

dynamics of indicating unit

=> Model description of the force measuring device.

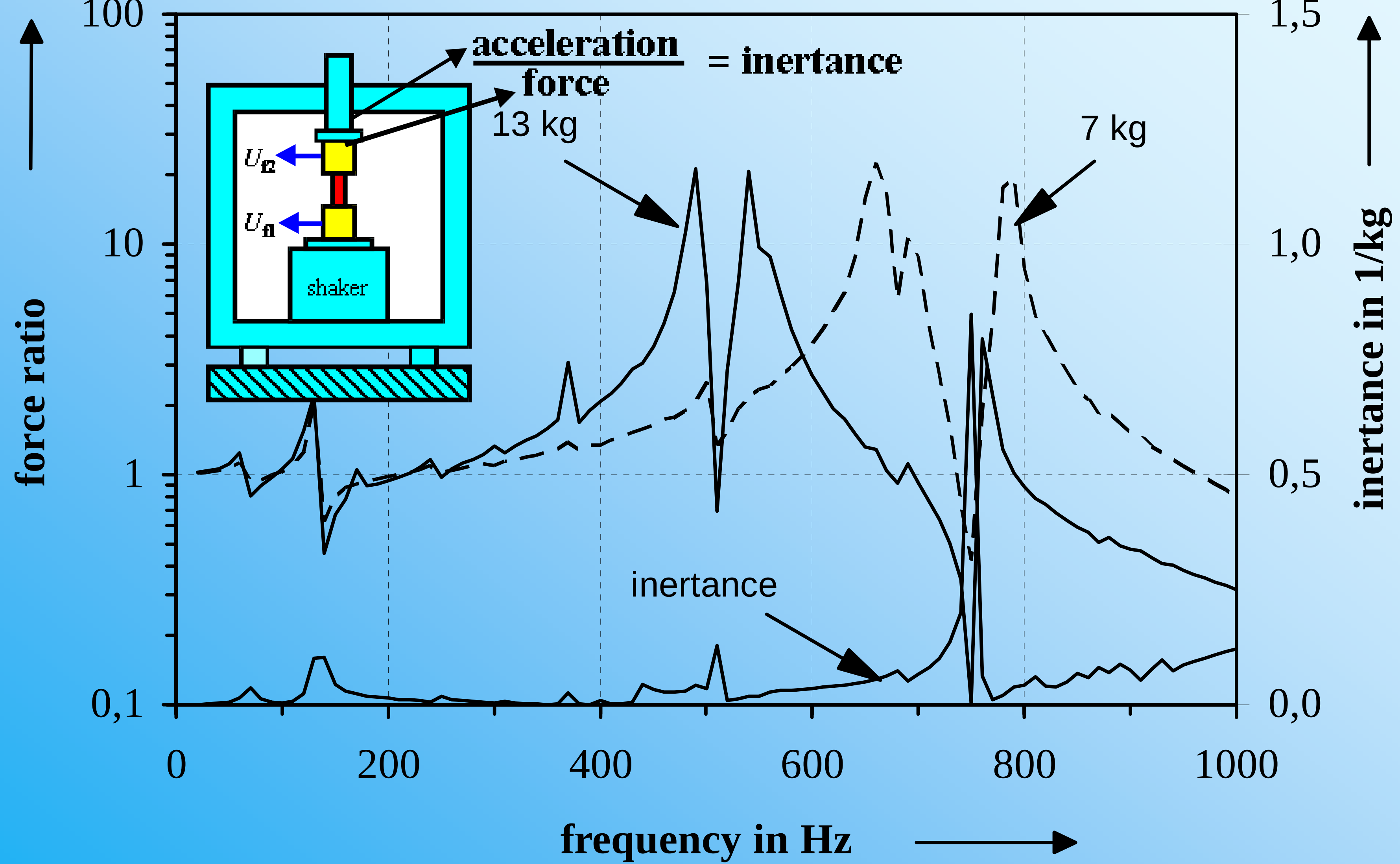
Stain gauge force measuring devices.



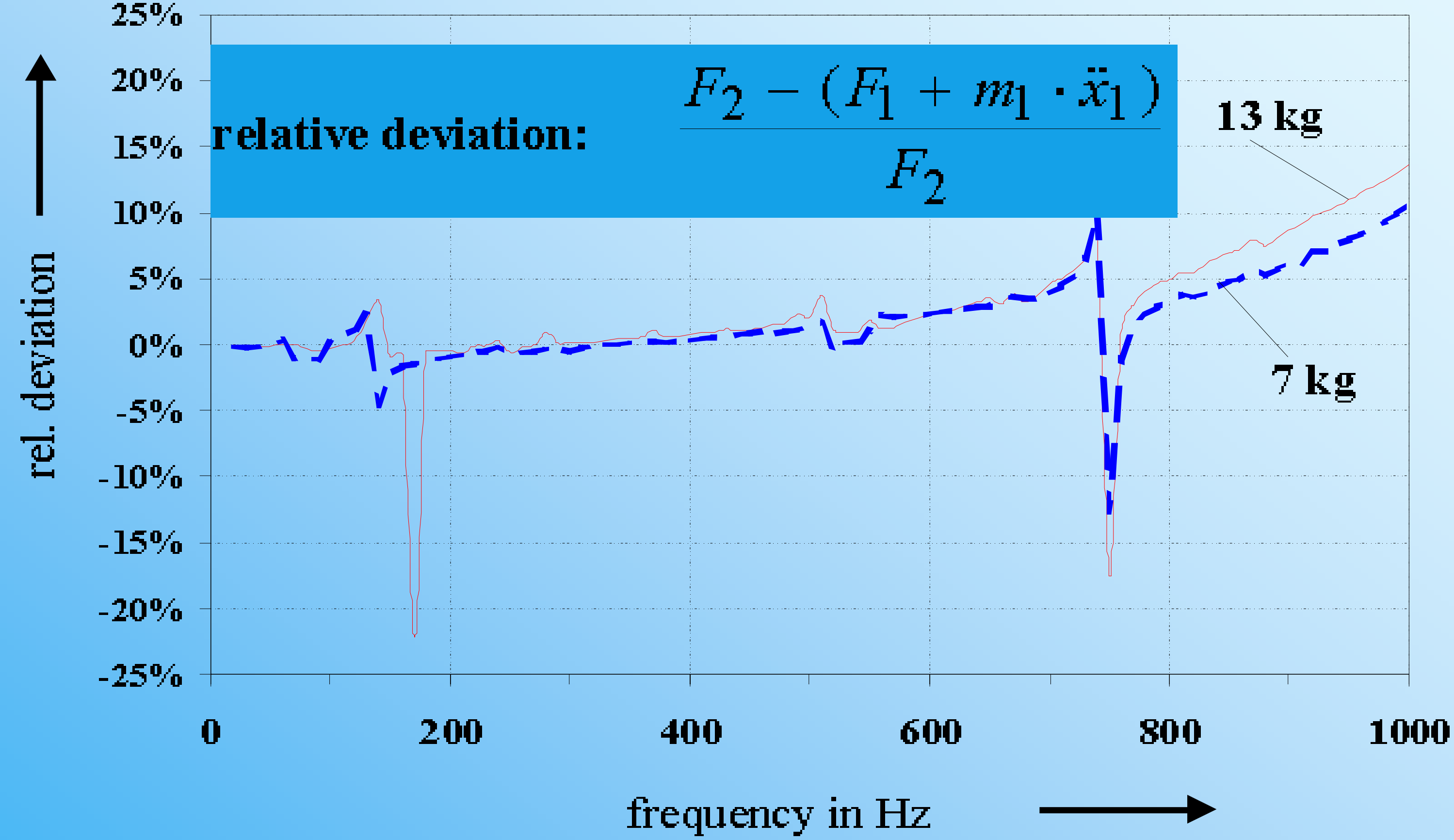
=> Multiplication of frequency responses:

$$T_{fu} = T_{fb} \cdot T_{bu}$$

Force ratio of upper to lower transducer and inertance measurement.



Compensation of inertia forces.



Reasons for the deviations:

deviations static and dynamic sensitivity

coupling between force transducers and connecting mass

no rigid mass

no axial motion (transverse resonances)

Practical techniques to improve dynamic force measurement in applications.

$$m_t \cdot \ddot{r}_f + b_f \cdot \dot{r}_f + k_f \cdot r_f = F_t - m_t \cdot \ddot{x}_b$$

$$F_t = S_{f0}{}^{-1} \cdot U_f + m_t \cdot \ddot{x}_t + \frac{b_f}{k_f} \cdot S_{f0}{}^{-1} \cdot \dot{U}_f$$

1. <u>Rotation effect</u> in dynamic measurements.

2. <u>Multicomponent</u> acceleration measurements.

3. Methods for <u>error compensation</u>:

- electronic circuits for error compensation

- different software techniques

offline, online, realtime depending on the application

Conclusion for dynamic force measurement in practical applications.

- Method is depending on the practical application:

- Compensation of mass forces
  => force measurement

  + acceleration measurement

- Consideration of resonance behaviour

  => force measurement

  + transducer resonance

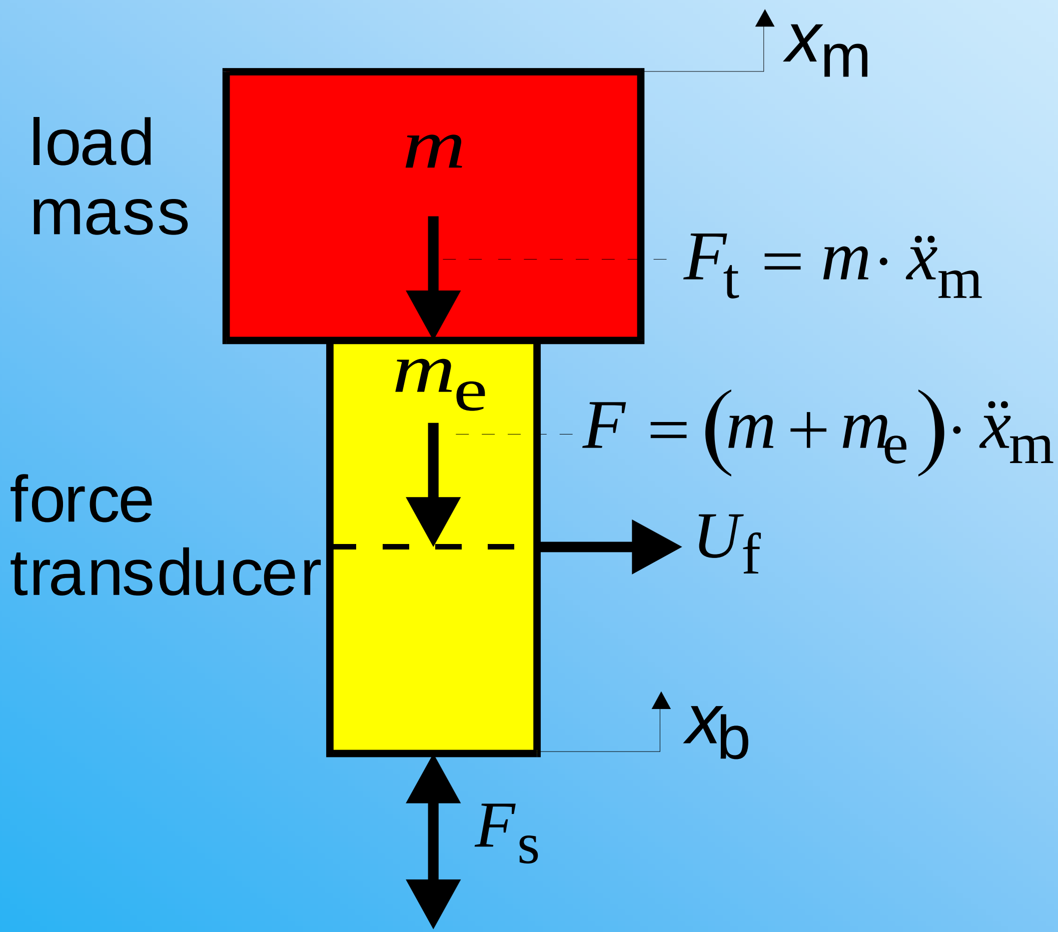
  (+ acceleration measurement)

Dynamic force measurement in future.

1. Extension of the force range to the needs of practical applications.
2. Development of dynamic force transfer standards for material testing machines.
3. Development of force measuring devices

   with compensation techniques for special applications.
4. Reduction of the measurement uncertainty by interferometric measurement techniques.

Principle of dynamic force calibration.



dynamic sensitivity:

$$S_f = \frac{U_f}{F}$$

end mass known:

$$S_f = \frac{U_f}{(m + m_e) \cdot \ddot{x}_m}$$

end mass unknown:

$$\frac{U_f}{\ddot{x}_m} = S_f \cdot (m + m_e)$$

Principle of the facility for dynamic forces up to 10 kN.

Necessary is:

1. Theory for determination of dynamic force: $\vec{F} = m \cdot \vec{a}$

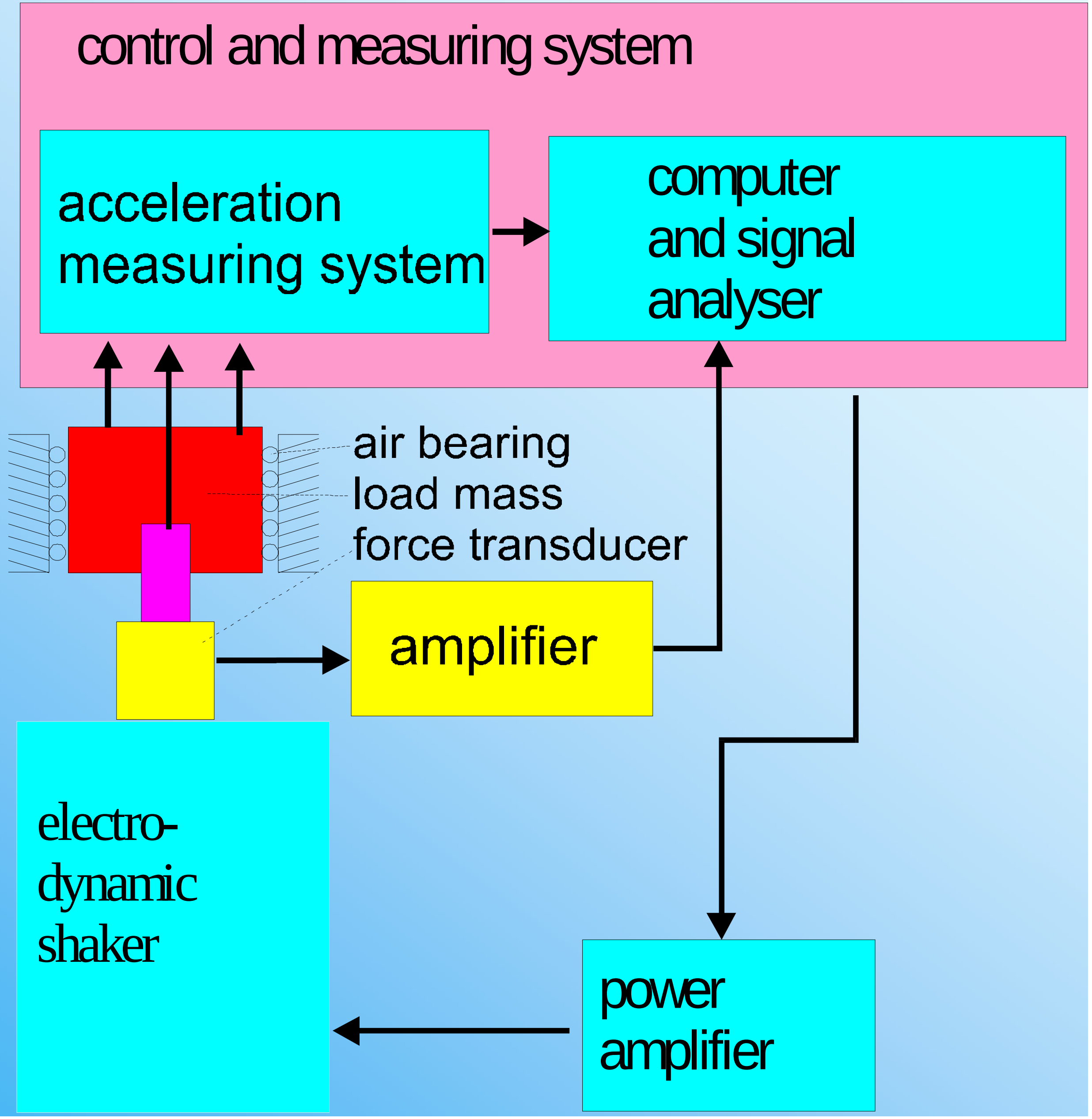
$$F = \int_V \rho \cdot \ddot{u}(x,t) \cdot dV$$

2. Acceleration measuring system
=> acceleration transducers or laser interferometer

3. Axial force generation

=> air bearings
or other methods for the generation of axial forces.

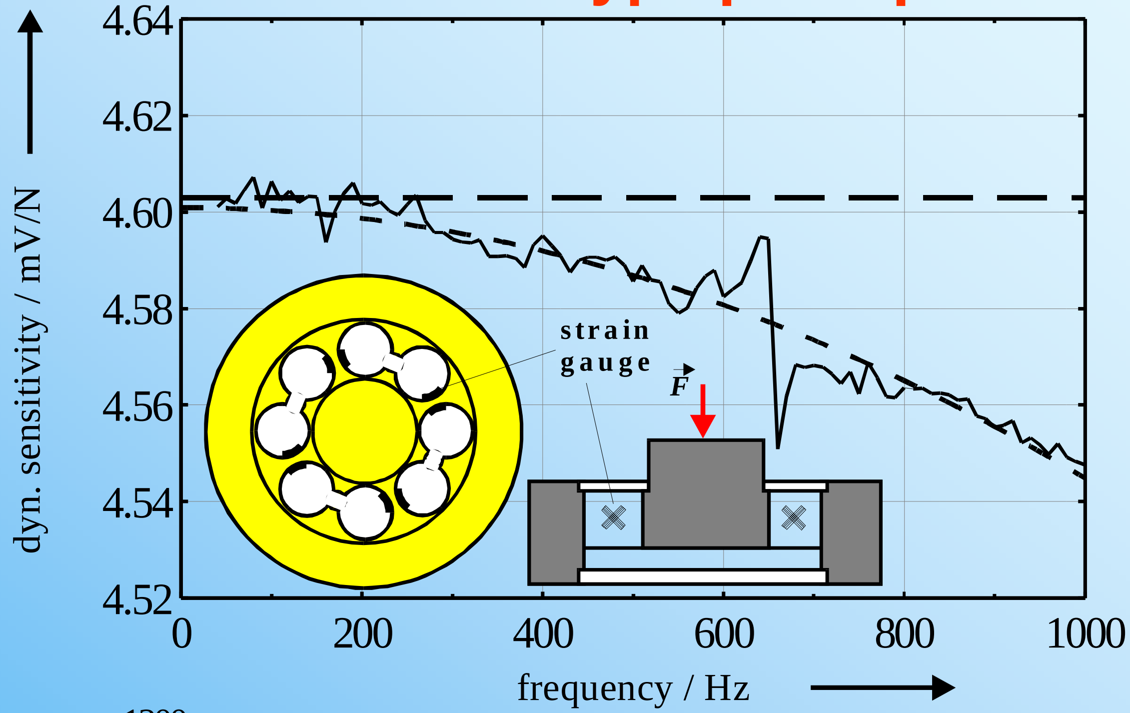
4. Force excition for large dynamic forces
sine: 17,8 kN
half sine: 40 kN

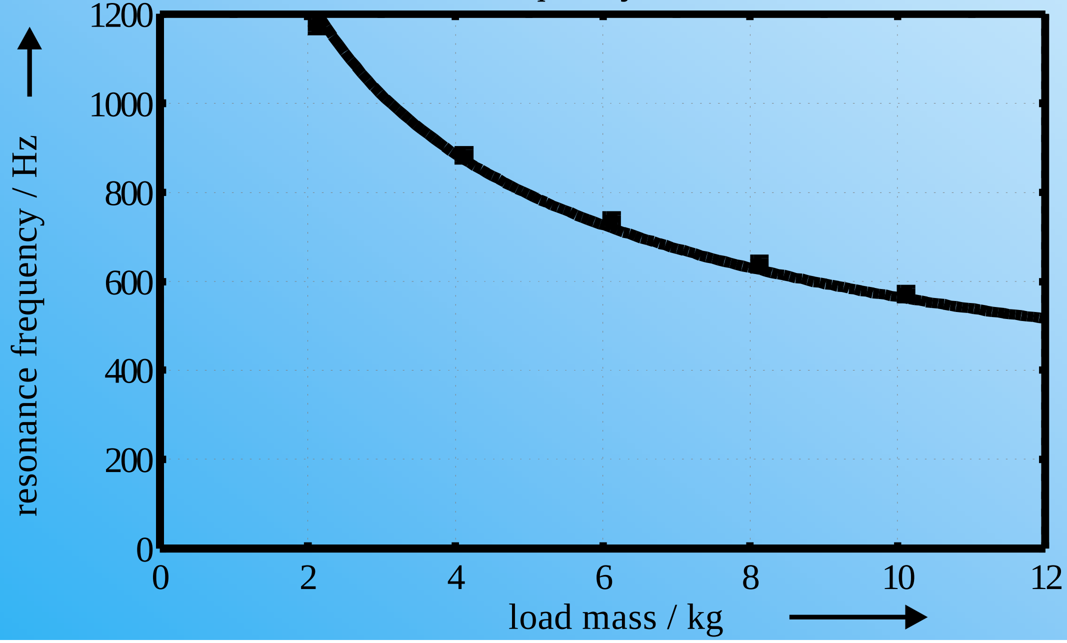


Combination of the 17,8 kN shaker system with laser vibrometer.

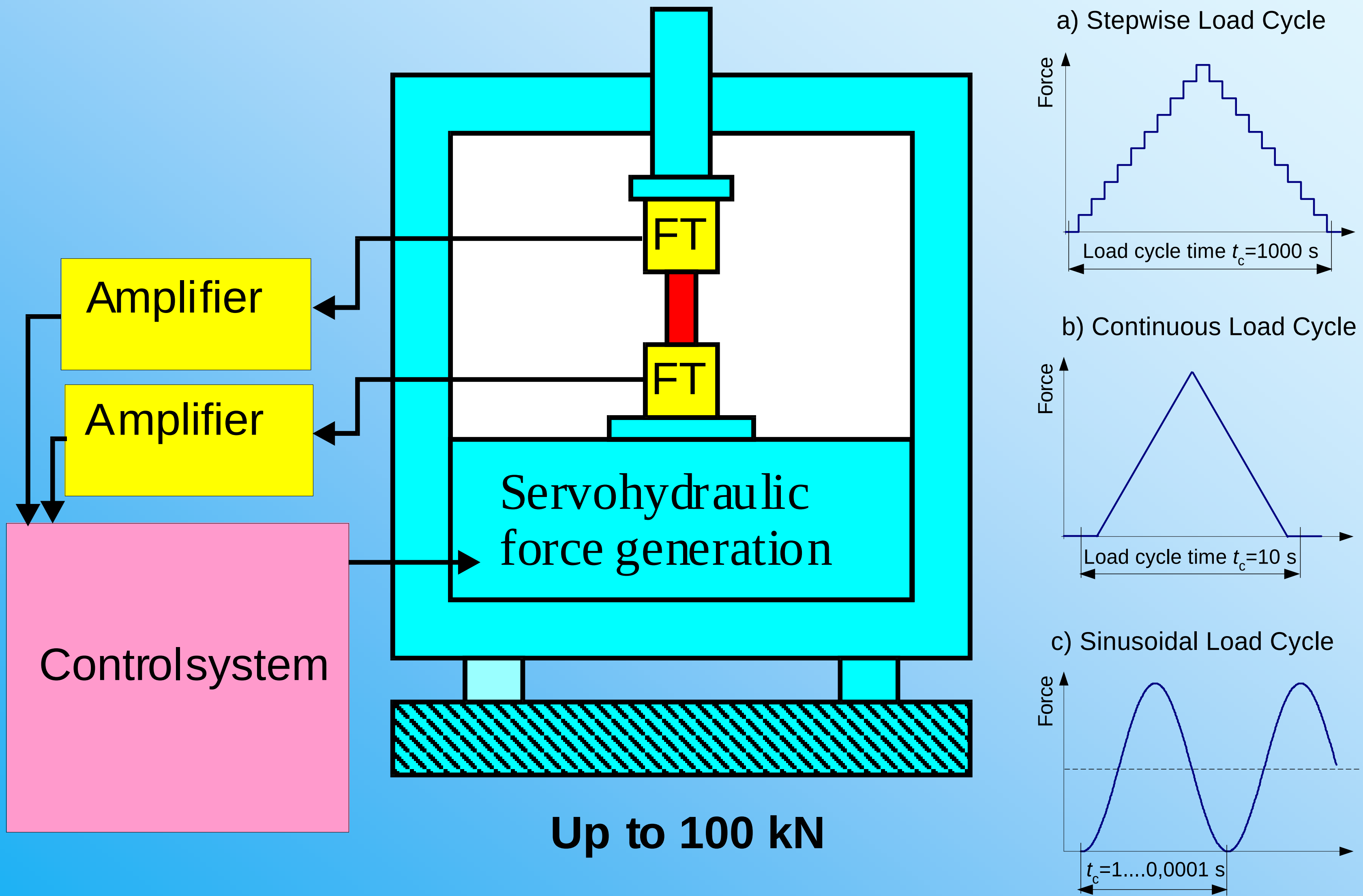
PTB

Force transducer of shear type principle.



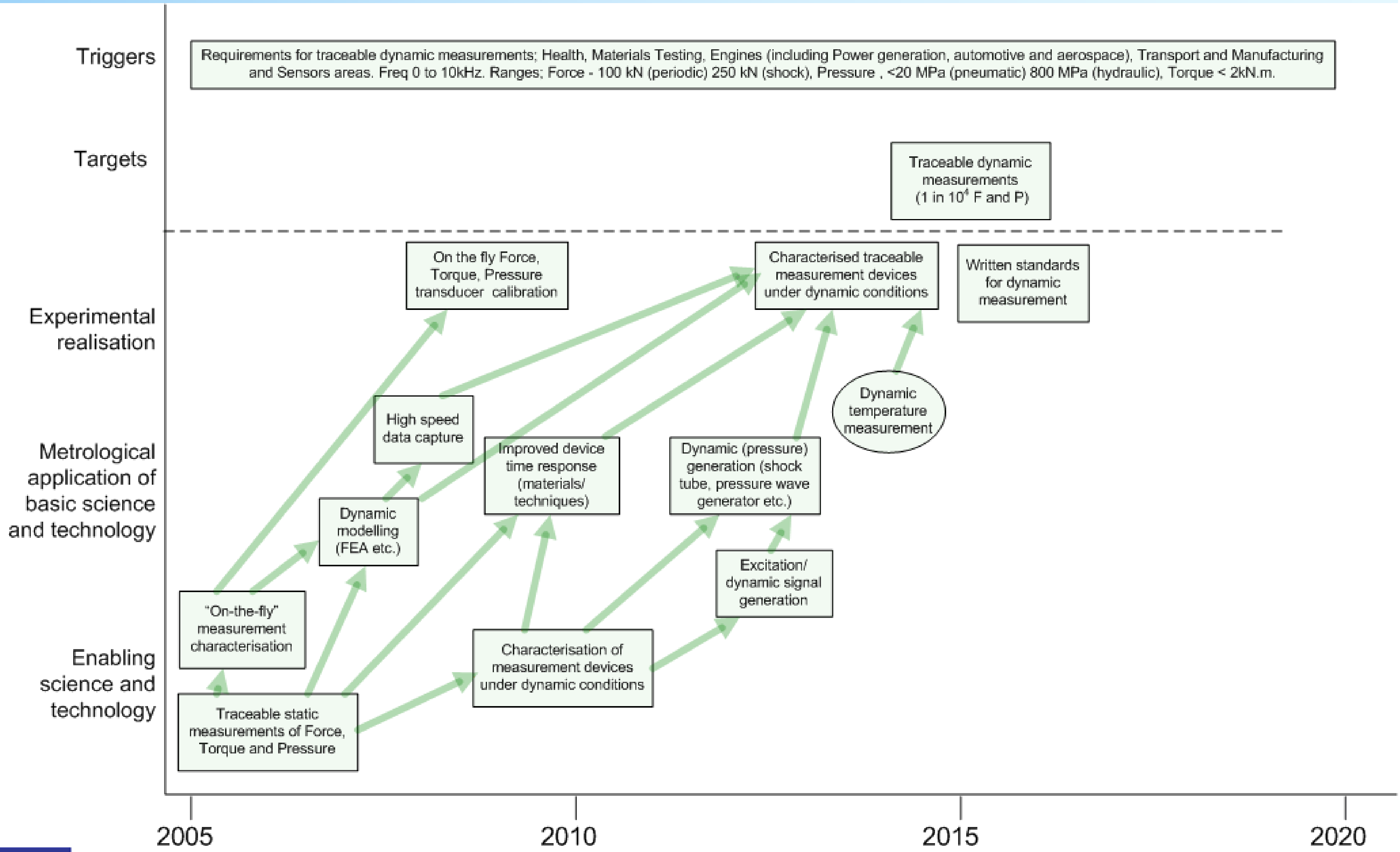


Extension of the calibration to large dynamic forces with the comparison method.



Up to 100 kN

Roadmap Dynamic Force



Conclusion: Calibration of force transducers.

- Different calibration procedures are possible:

static (continous or stepwise)

dynamic (sinusoidal, impact, ...)

- Different influences have to be taken into account:

static and quasistatic influences:

nonlinearity, hysteresis, creep...

=> sensitivity

dynamic influences:

frequency response of amplifier, force transducer, coupling of load mass to transducer

=> dynamic sensitivity

Conclusion for dynamic applications.

PTB

1. Static and dynamic calibration of the force sensor

Deviations between the static sensitivity determined by stepwise calibration methods and the dynamic sensitivity indicate the limits of the use of static sensitivity.

2. Analysis of the mechanical application

Analysis of the vibration behaviour

3. Compensation of systematic influences

Compensation of inertia forces and consideration of the resonance behaviour.

Future developments in force measurement in respect to applications and material testing.

1. Investigation and calibration of force measuring devices with static, quasistatic, coninuous, periodical and impact forces.

2. Extension of the range of force standards according the needs in industry like in the field of material testing machines.

3. Development and investigation of transfer standards for dynamic forces, multicomponent measurements and small forces.

=> Additional Procedures for Calibration of Material Testing Machines.

=> Uncertainty Analysis depending on Application.