„RECENT ISSUES IN THE CALIBRATION OF MATERIAL TESTING MACHINES“
(Future Developments from Static to Dynamic Forces, from Single to Multicomponent Forces and from Large to Small Forces in respect to Applications like in the Field of Material Testing, ...)

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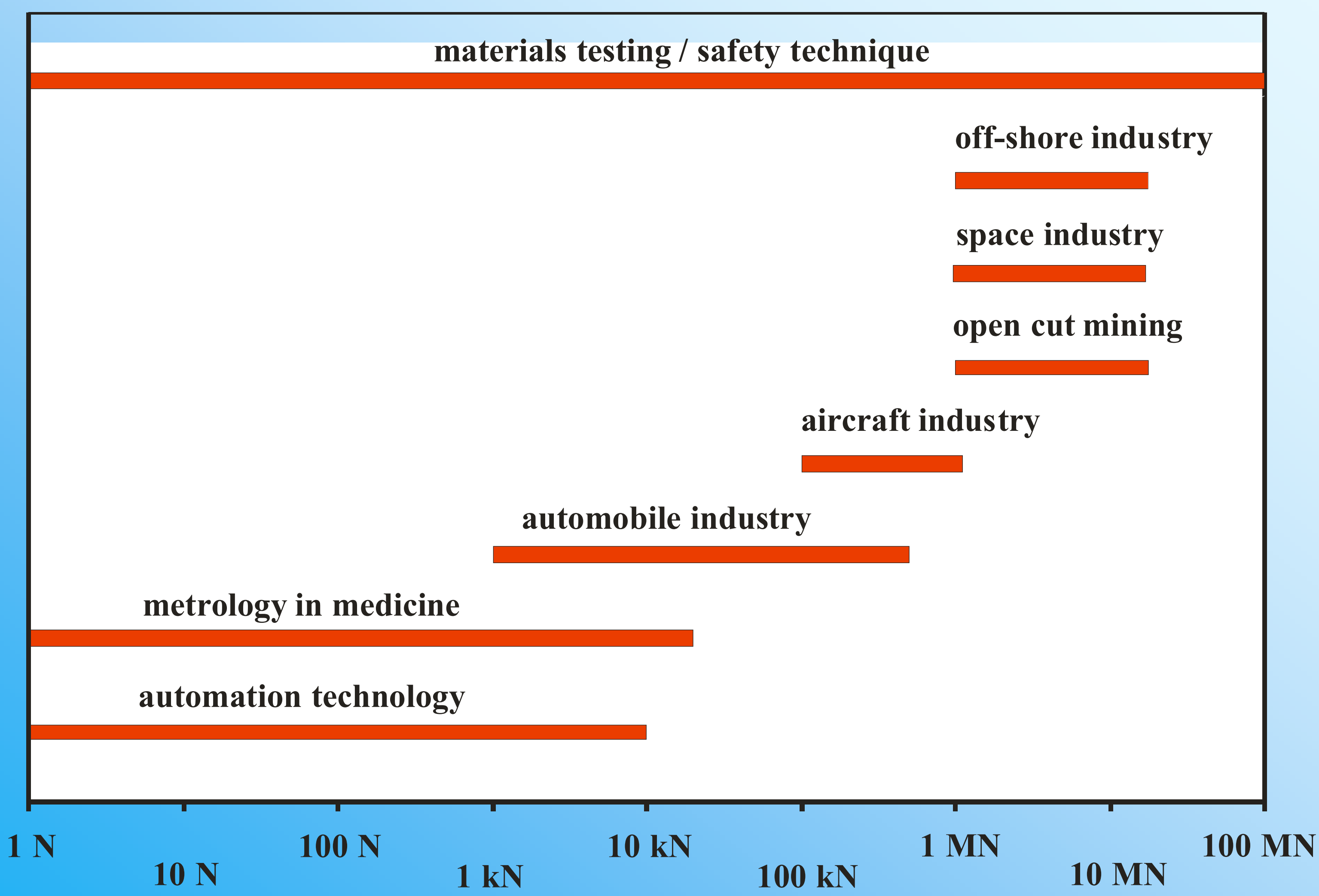
WG 1.21 + WG 1.23

Applications of Force Measurement

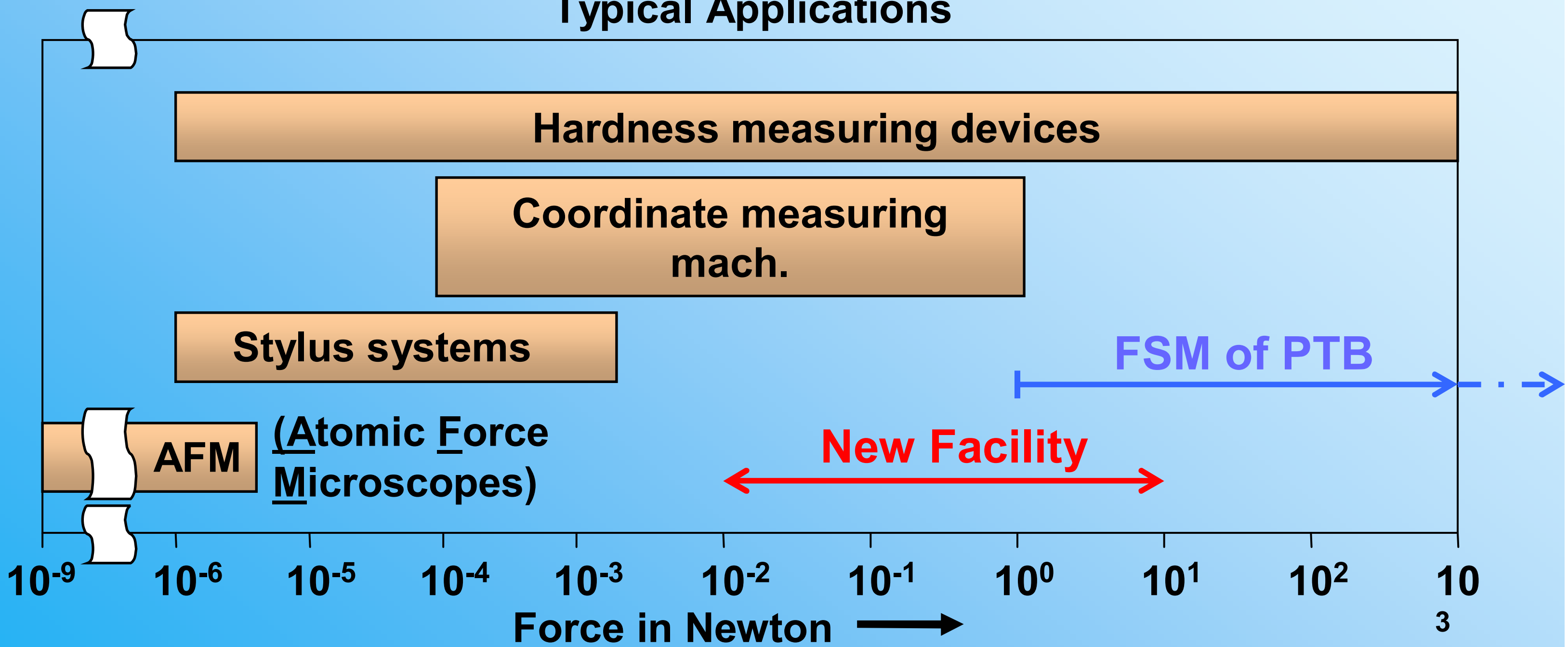


Needs for extension of PTB´s FSM to small forces

PTB

Microsystem and nanotechnology ⇨ demand of traceability of small forces

Typical Applications



Calibration of Material Testing Machines

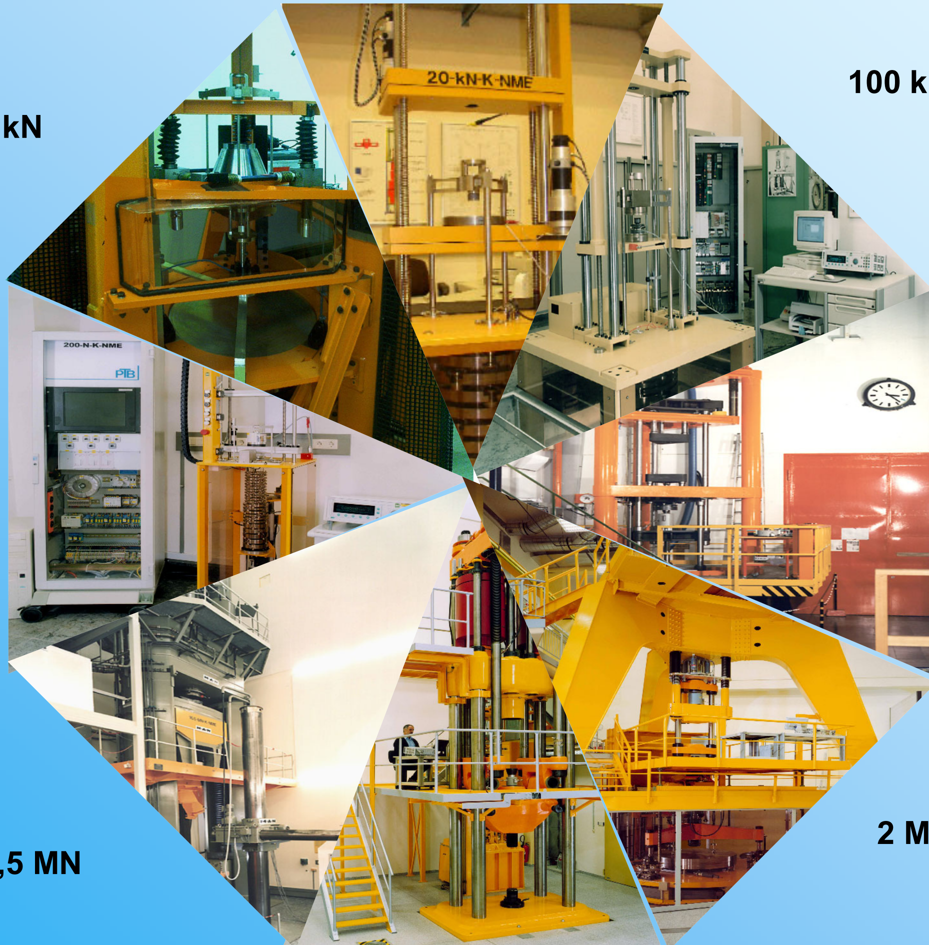
PTB

The verification and calibration of the tension/compression testing machine is in general performed on site at the place of installation of the testing machine,
according to the procedure described in **ISO 7500-1**.
The standard specifies the criteria for the classification of the testing machine by way of the on-site calibration of its force-measuring system.
The class of the transfer standard (force-proving instrument, specified in ISO 376) shall be equal to or better than the class for which the testing machine is to be classified.
Conformity with respect to the classification of a testing machine according to ISO 7500-1 thus implies that the uncertainties of forces associated with the transfer standard have been taken into account.

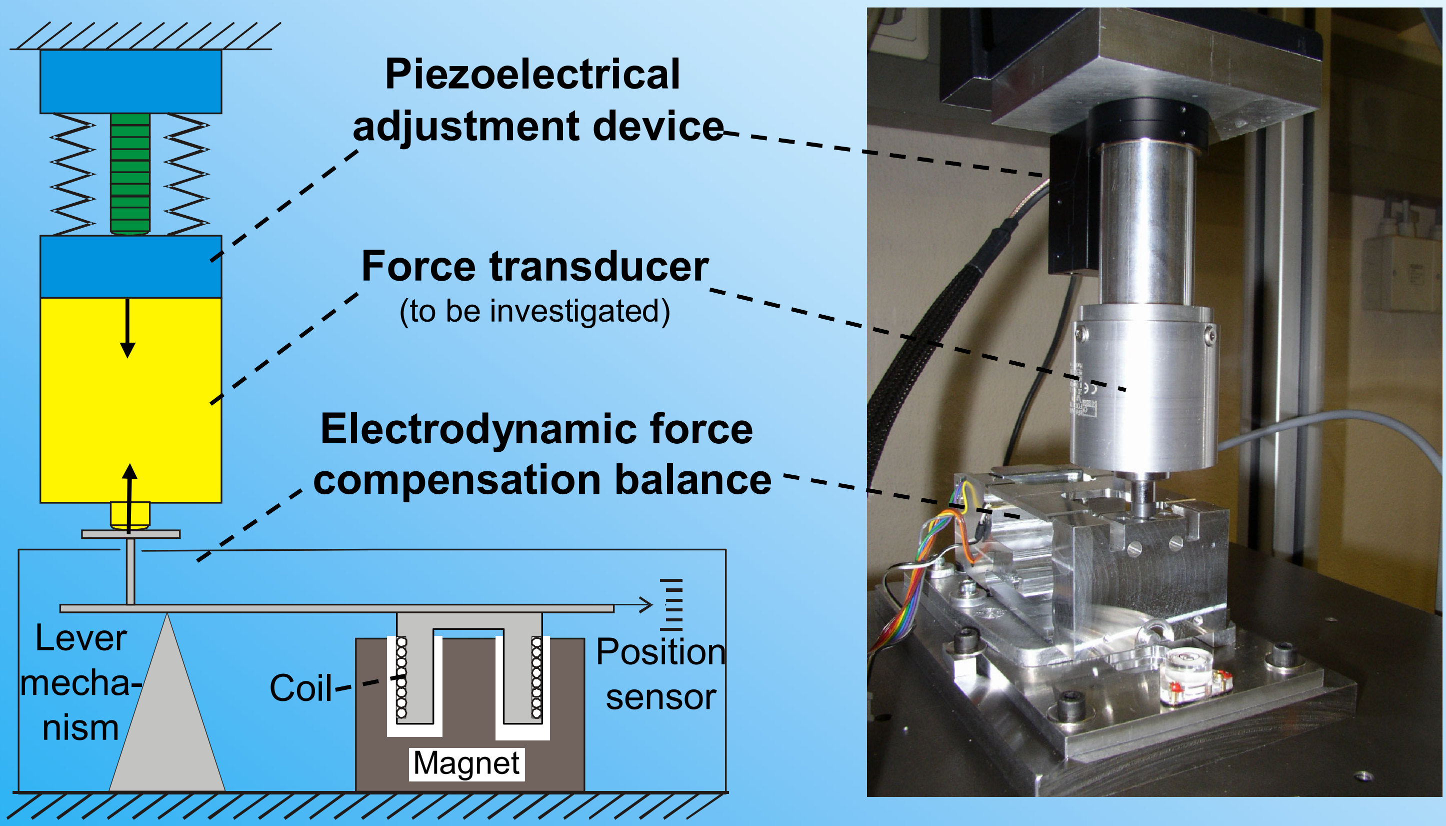
=> „UNCERTAINTY OF MEASUREMENT IN THE VERIFICATION AND CALIBRATION OF THE FORCE-MEASURING SYSTEMS OF TESTING MACHINES“ by Amritlal Sawla, PTB
In: PROCEEDINGS OF THE ASIA-PACIFIC SYMPOSIUM ON MEASUREMENT OF FORCE, MASS AND TORQUE (APMF 2000) TSUKUBA, JAPAN - NOVEMBER, 2000.

Acrobat-Dokument

Force Standard Machines of PTB



Set-Up based on a compensation balance



16,5-MN-hydraulic amplification-FSM

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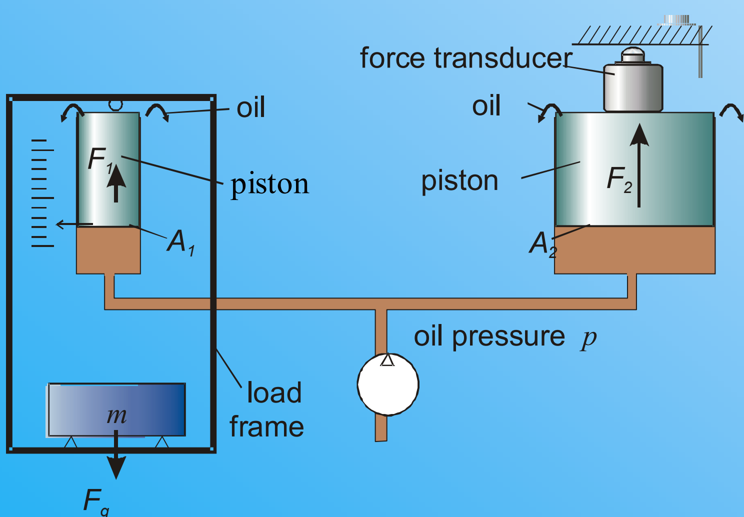
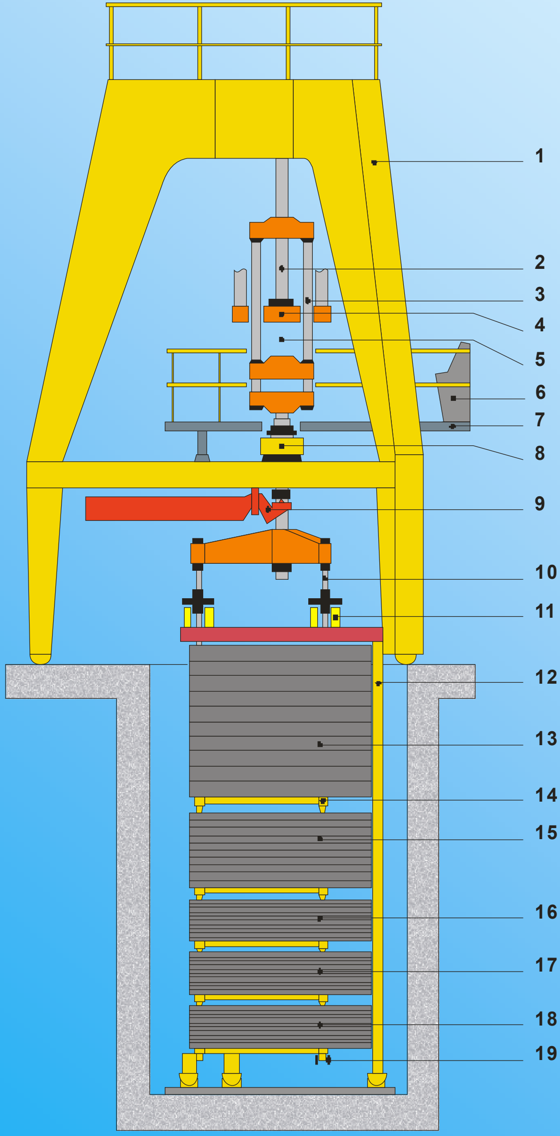
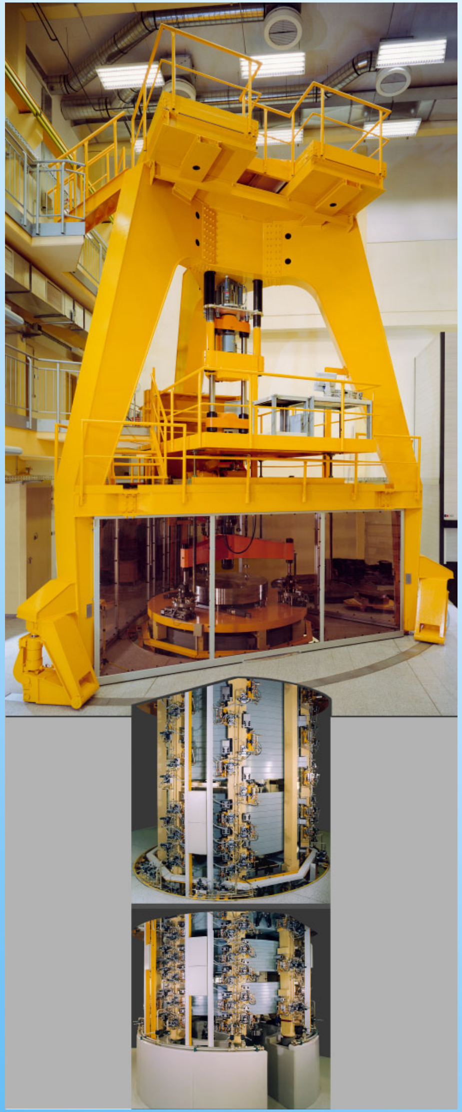


PTB‘s „new“ 2 MN Deadweight FSM





Measurement Uncertainty of 2 MN Deadweight Force Standard Machine

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

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

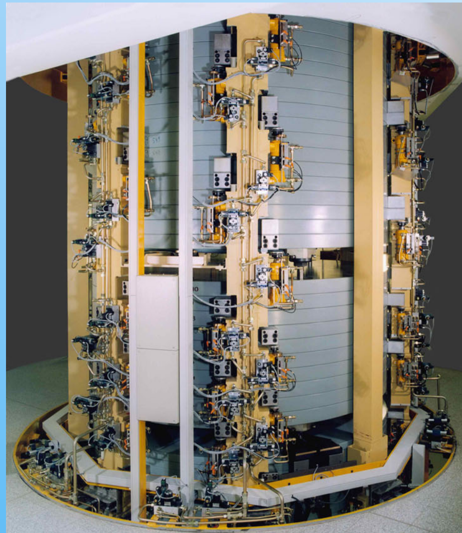
No.5
10x
100kN

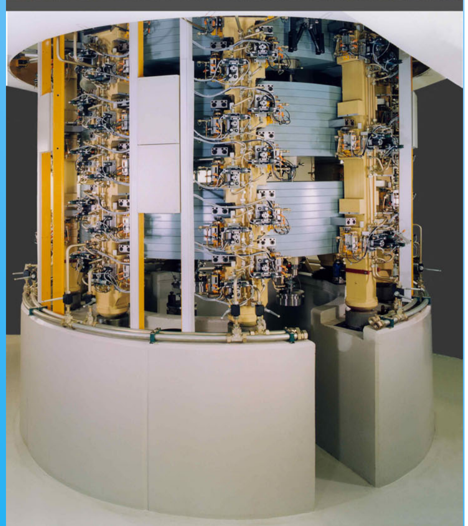
No.4
10x
50kN

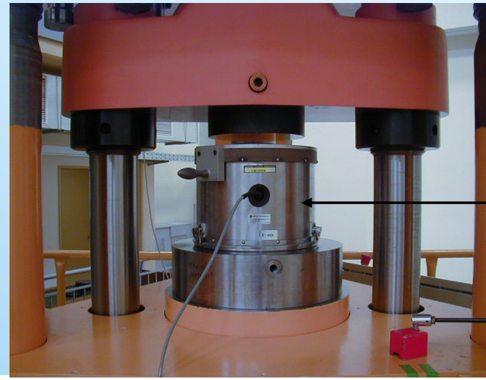
No.3
10x
20kN

No.2
10x
20kN

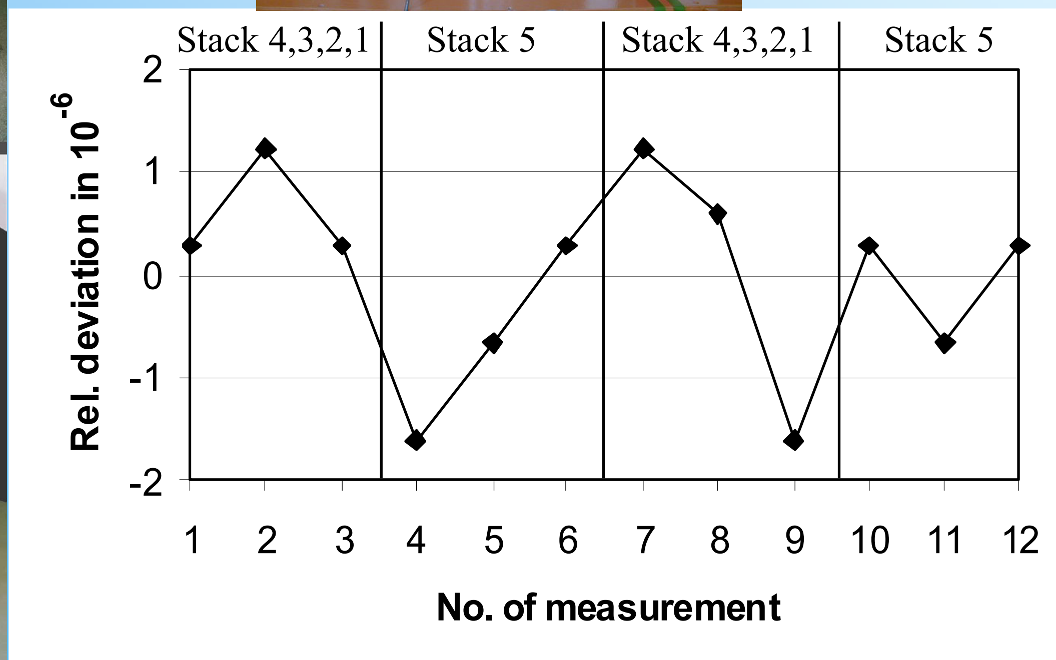
No.1
10x
10kN



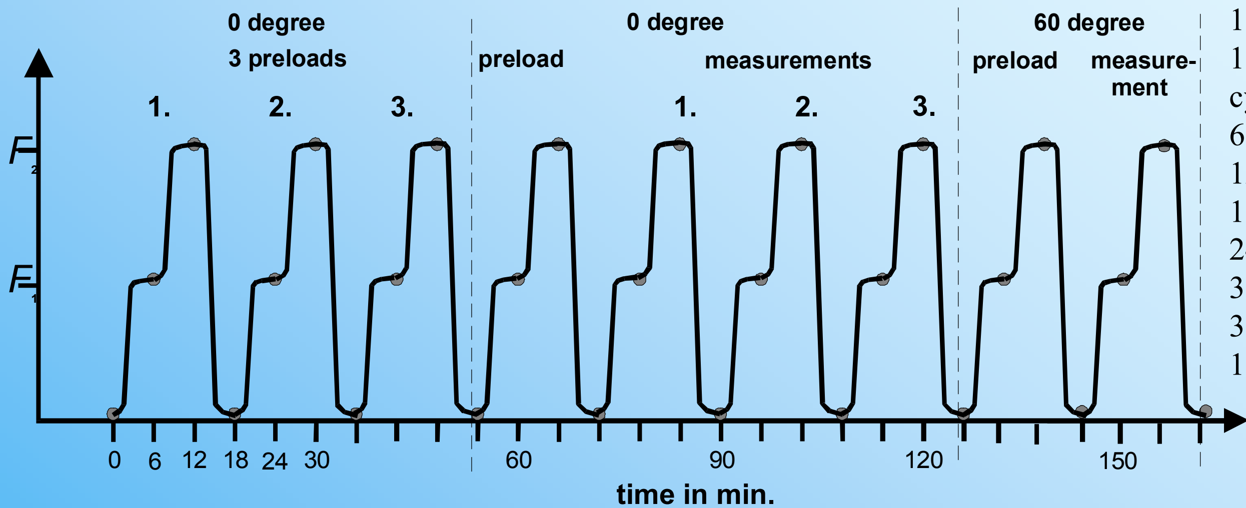




2 MN Transducer
1050 kN Force

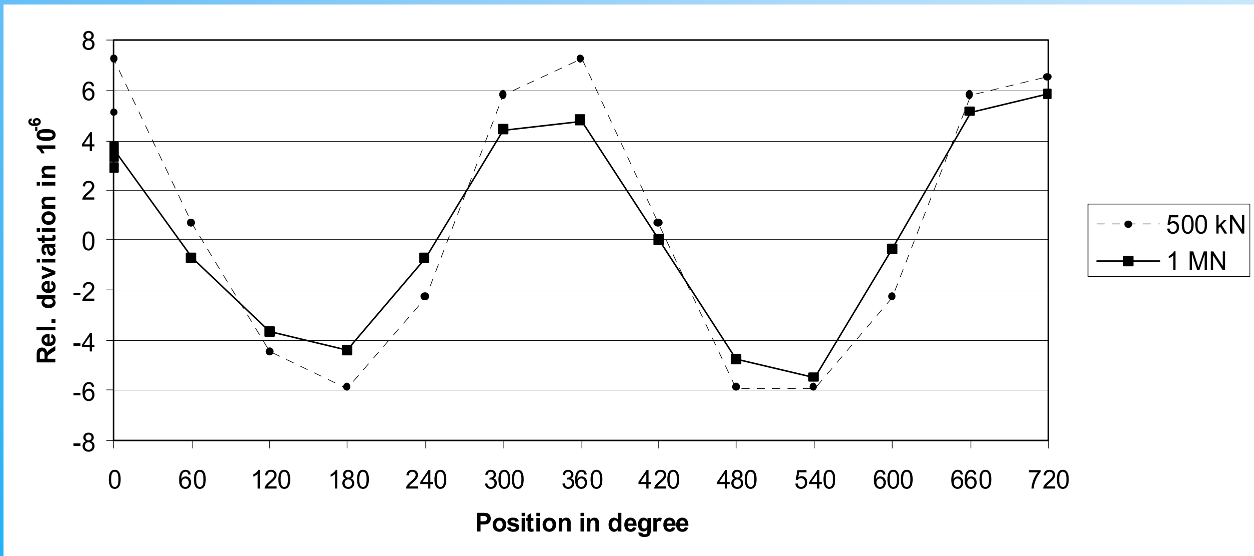


Rotation effect in the 2 MN force standard machine measured in 2 rotations according key comparison procedure.



1 preload + 1 measurement cycle in position

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



Inluences on the Uncertainty of Force Calibration

The Measurement Uncertainty is determinded by:

- **Force Calibration Machine** → W_{bmc}
- **Calibration Procedure** → W_{bmc}, W_{tra}
- **Force Transducer to be calibrated** → W_{tra}

MU is calculated as follows:

The relative expanded uncertainty of calibration *W* will be determined by considering the best measurement capability of the force calibration machine as follows:

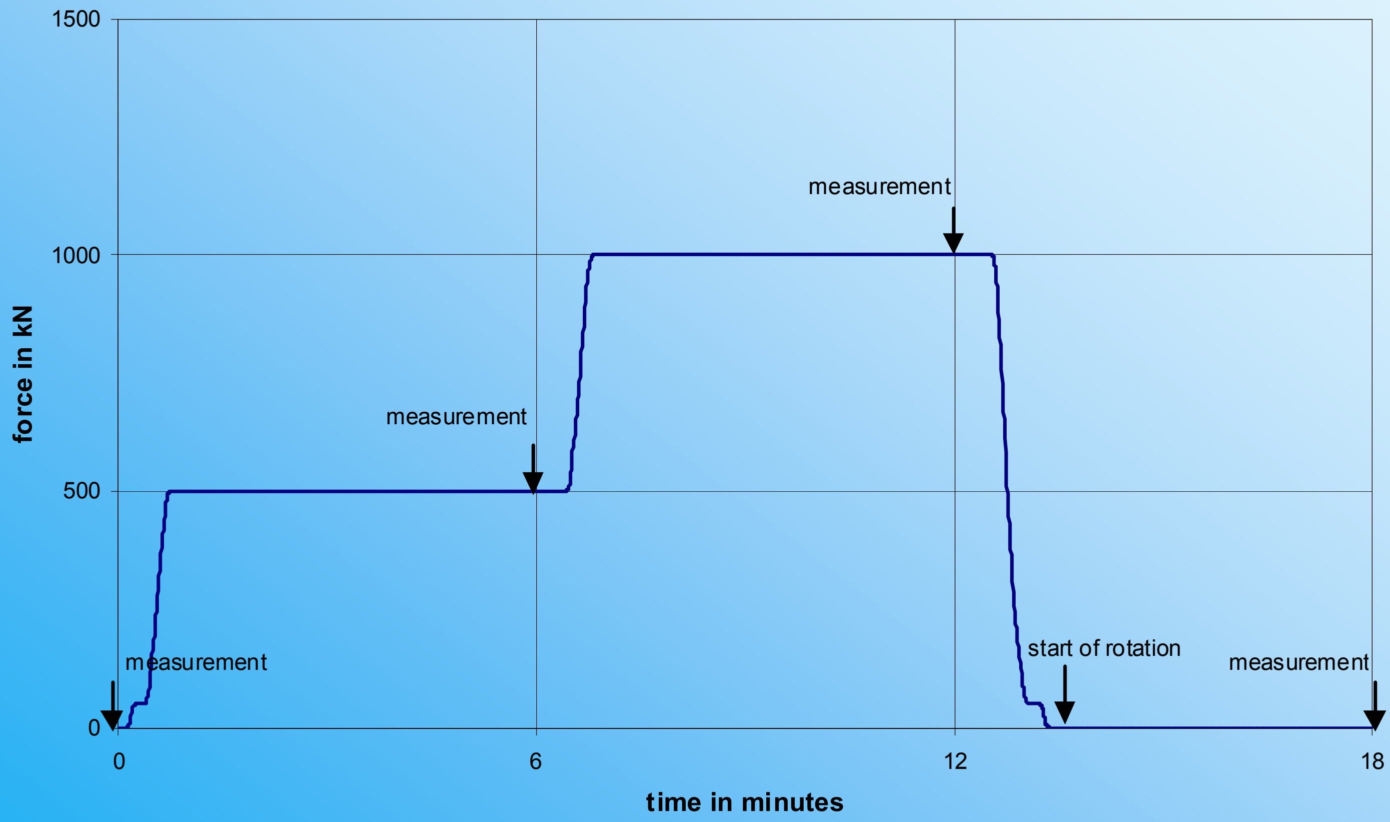
$$W = k \cdot \sqrt{w_{tra}^2 + w_{bmc}^2}$$

EA10/04 describes the calculation only for ISO 376 and for the Force Measuring Device (Transducer+Indicator)

New Uncertainty Annex for ISO 376 under discussion.

Contibution for fixed loading profile (Key Comparison)

$$w_{tra} = \sqrt{\cancel{w_{zer}^2} + \cancel{w_{rep}^2} + w_{rot}^2 + \cancel{w_{inp}^2} + w_{res}^2 + \cancel{w_{rev}^2}}$$



Calibration Procedures of Force Measuring Devices

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1. Key Comparison
Comparison of Force Standard Machines
with rel. Uncertainties of $\leq$ 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.

Influences in the calibration of force transducers

MU according EA10/04 :

$$w_{tra} = \sqrt{w_{zer}^2 + w_{rep}^2 + w_{rot}^2 + w_{inp}^2 + w_{res}^2 + w_{rev}^2}$$

Comments to MU:

- **MU components of indicator has to be taken into account if indicator is changed.**
- **MU according loading procedure is missing.**
- **MU valid only for parts of force introduction used in calibration.**

=> User has to take additional influences into account.

Contibutions according EA10/04

Table 7.1: Probability distributions assumed for the different input quantities (*a*: relative half-width of the maximum deviation of the input quantity)

Uncertainty contributions (input quantities)	Probability distribution	Estimated relative variance
zero deviation	rectangular distribution	$w_{\mathrm{zer}}^2 = \frac{a^2}{3} = \frac{\left(\frac{f_0}{2}\right)^2}{3}$
reproducibility without rotation	rectangular distribution	$w_{\mathrm{rep}}^2 = \frac{a^2}{3} = \frac{\left(\frac{b'}{2}\right)^2}{3}$
reproducibility with rotation	U-shaped distribution	$w_{\mathrm{rot}}^2 = \frac{a^2}{2} = \frac{\left(\frac{b}{2}\right)^2}{2}$
interpolation deviation	triangular distribution	$w_{\mathrm{inp}}^2 = \frac{a^2}{6} = \frac{\left(\frac{f_c}{2}\right)^2}{6}$
resolution	rectangular distribution	$w_{\mathrm{res}}^2 = \frac{a^2}{3} = \frac{\left(\frac{r/F}{2}\right)^2}{3}$
reversibility (hysteresis)	rectangular distribution	$w_{\mathrm{rev}}^2 = \frac{a^2}{3} = \frac{\left(\frac{\nu}{2}\right)^2}{3}$

Probable changes in ISO 376

New ISO 376 Annex prepared by ISO/TC 164/SC 1 WG3:

1. The Annex will be independent off EA10/04.

2. The uncertainty should be independent of the classification.

Table 9.2: Limits for the expanded relative uncertainty for different classes of (EN 10002-3) ISO 376

	min.	**max.**
Class 00	Wbmc	0,06 %
Class 0.5	0,06 %	0,12 %
Class 1	0,12 %	0,24 %
Class 2	0,20 %	0,45 %

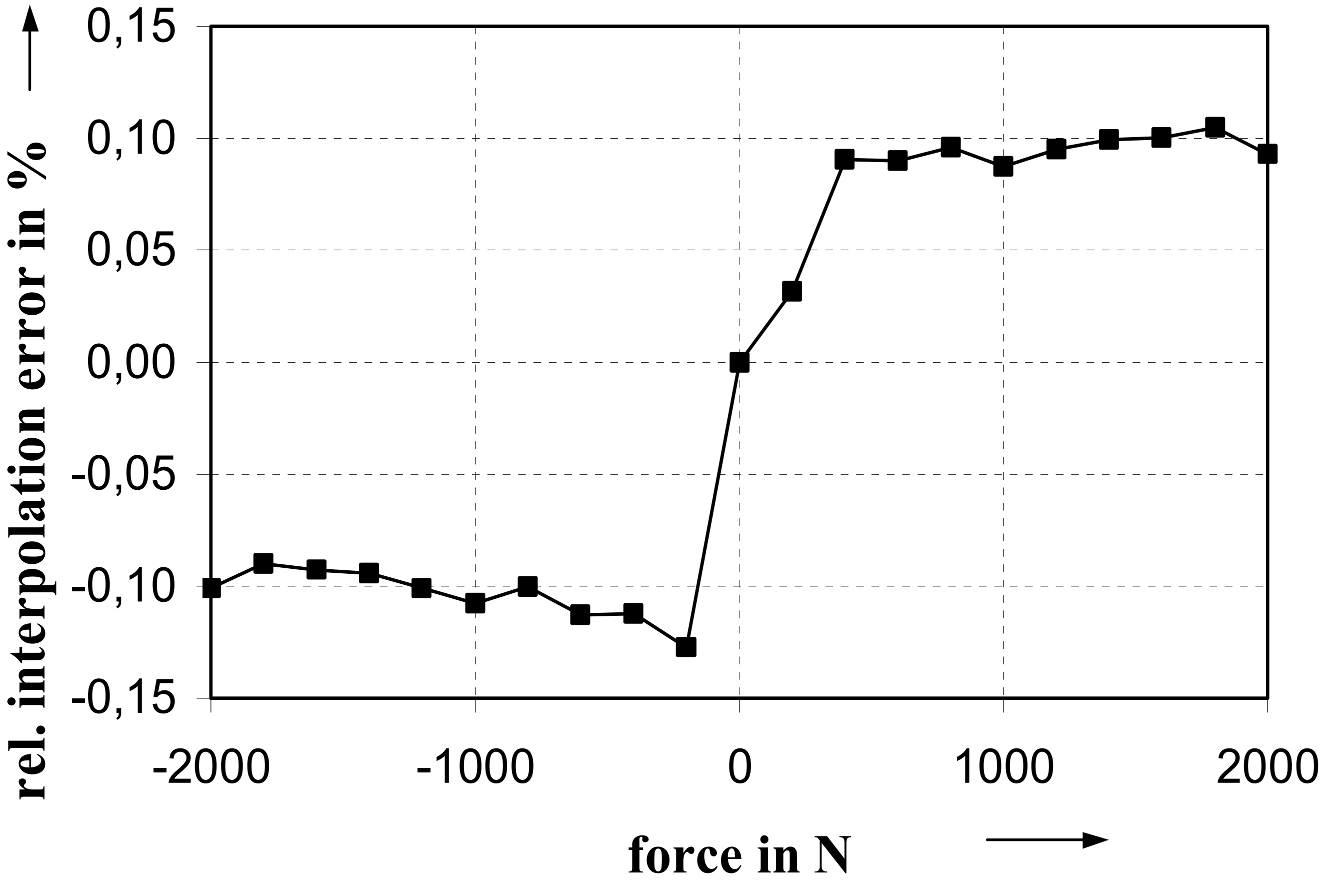
3. The uncertainty for increasing and decreasing forces should be calculated seperately.

For example:

Case 1 $$w_{tra} = \sqrt{w_{zer}^2 + w_{rep}^2 + w_{rot}^2 + w_{inp}^2 + w_{res}^2 + w_{rev}^2}$$

Case 2 $$w_{tra} = \sqrt{w_{zer}^2 + w_{rep}^2 + w_{rot}^2 + w_{inp}^2 + w_{res}^2}$$

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 PTB´s FSM and methods to dynamic forces

PTB

1. Material Testing Machines

- sinusoidal testing
- impact testing

2. Crash tests in automobile industry

- collision forces
- dummy forces

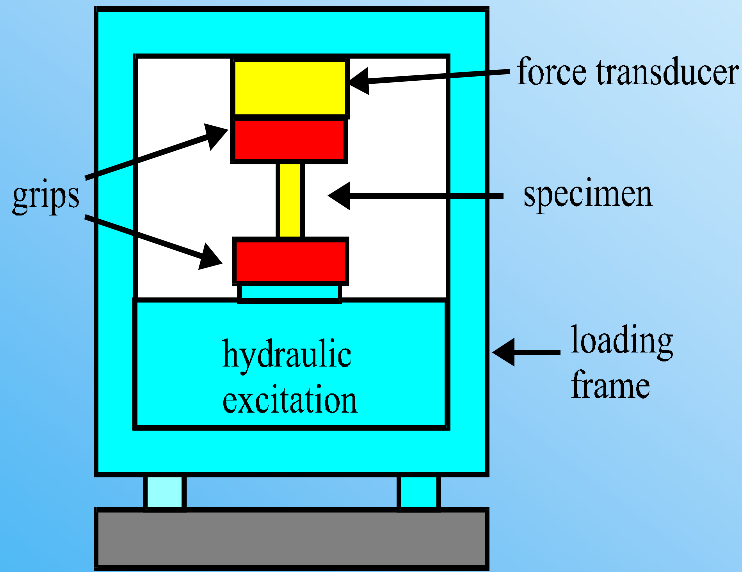
3. Modal analysis

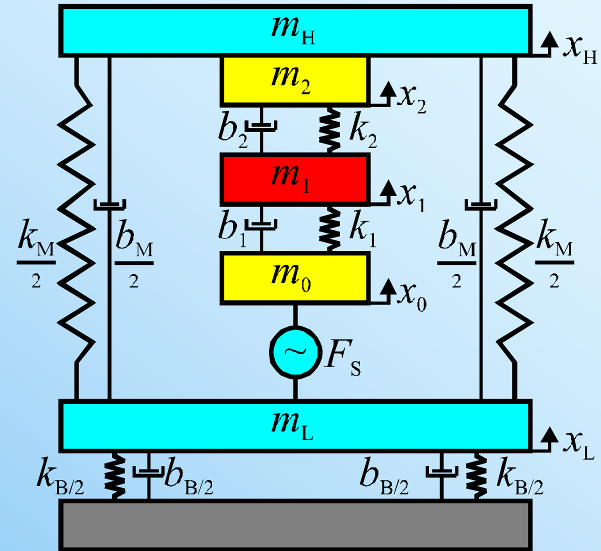
- sinusoidal excitation
- impact excitation

4. Dynamic weighing

- different loading times and sequences

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





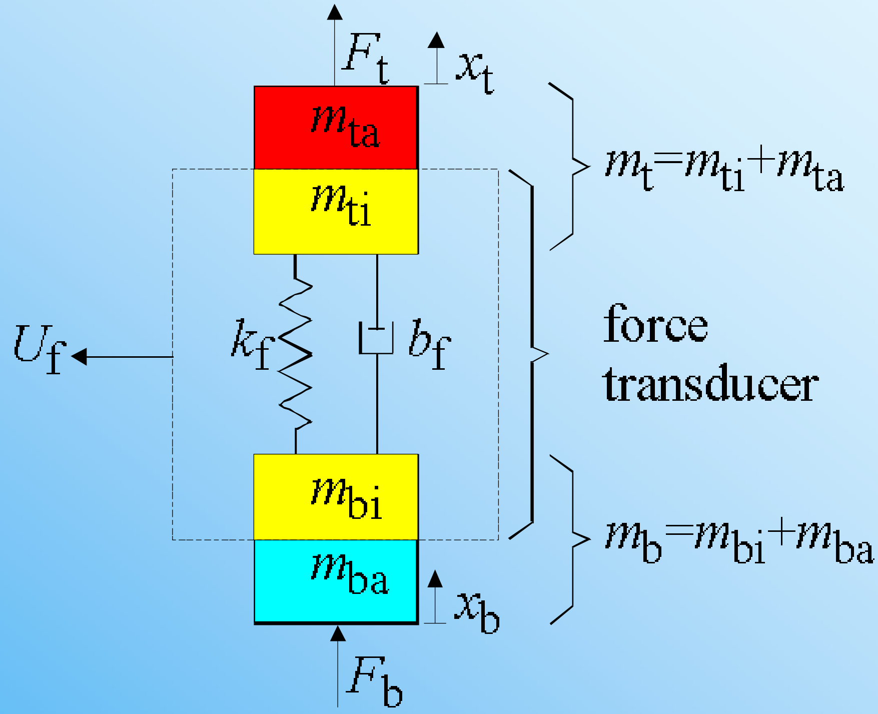
1. force measuring devices of good dynamic properties

2. interaction with materials testing machine

=> analysis of application, resonance effects

3. Compensation of systematic dynamic influences

Compensation of mass forces.



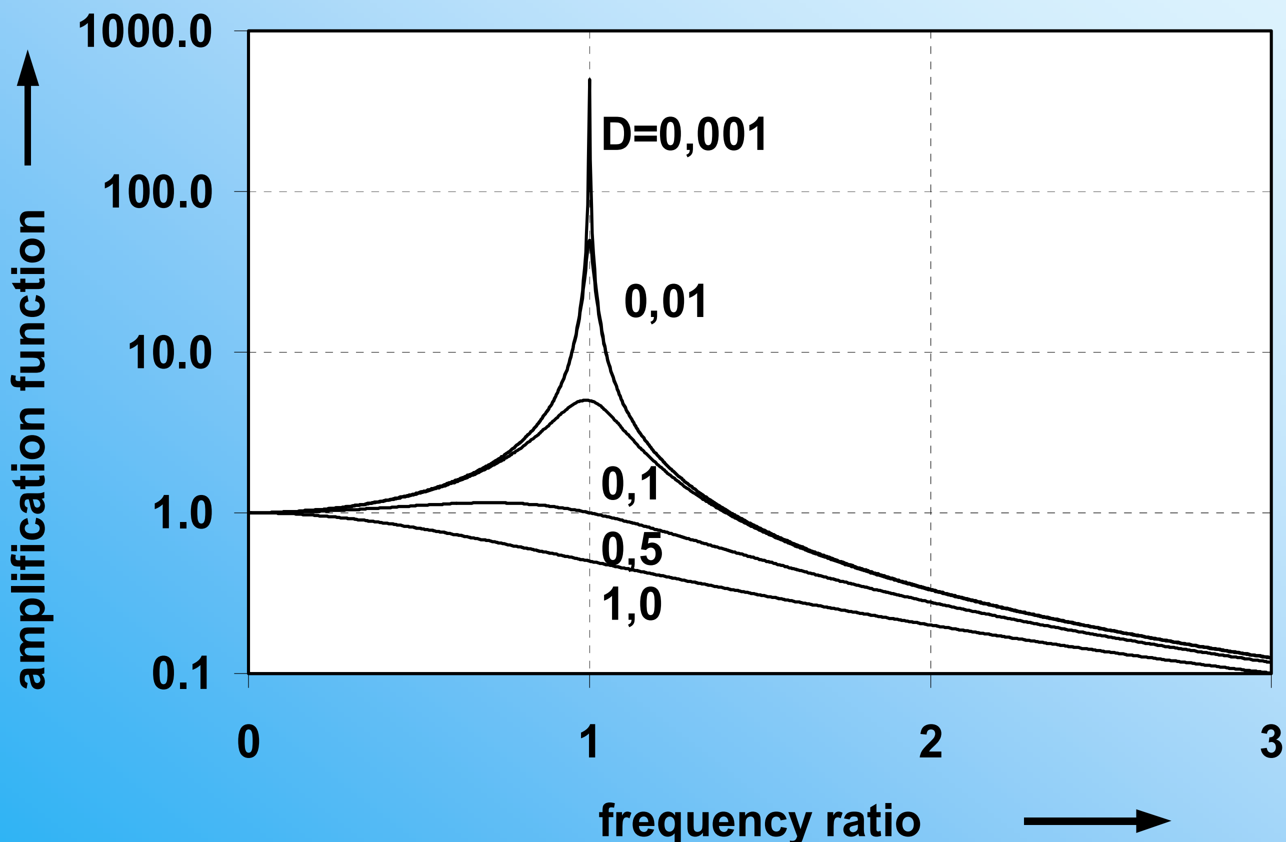
$$m_t \cdot \ddot{r}_f + b_f \cdot \dot{r}_f + k_f \cdot r_f = F_t - m_t \cdot \ddot{x}_b$$

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

Amplitude response of the force transducer

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

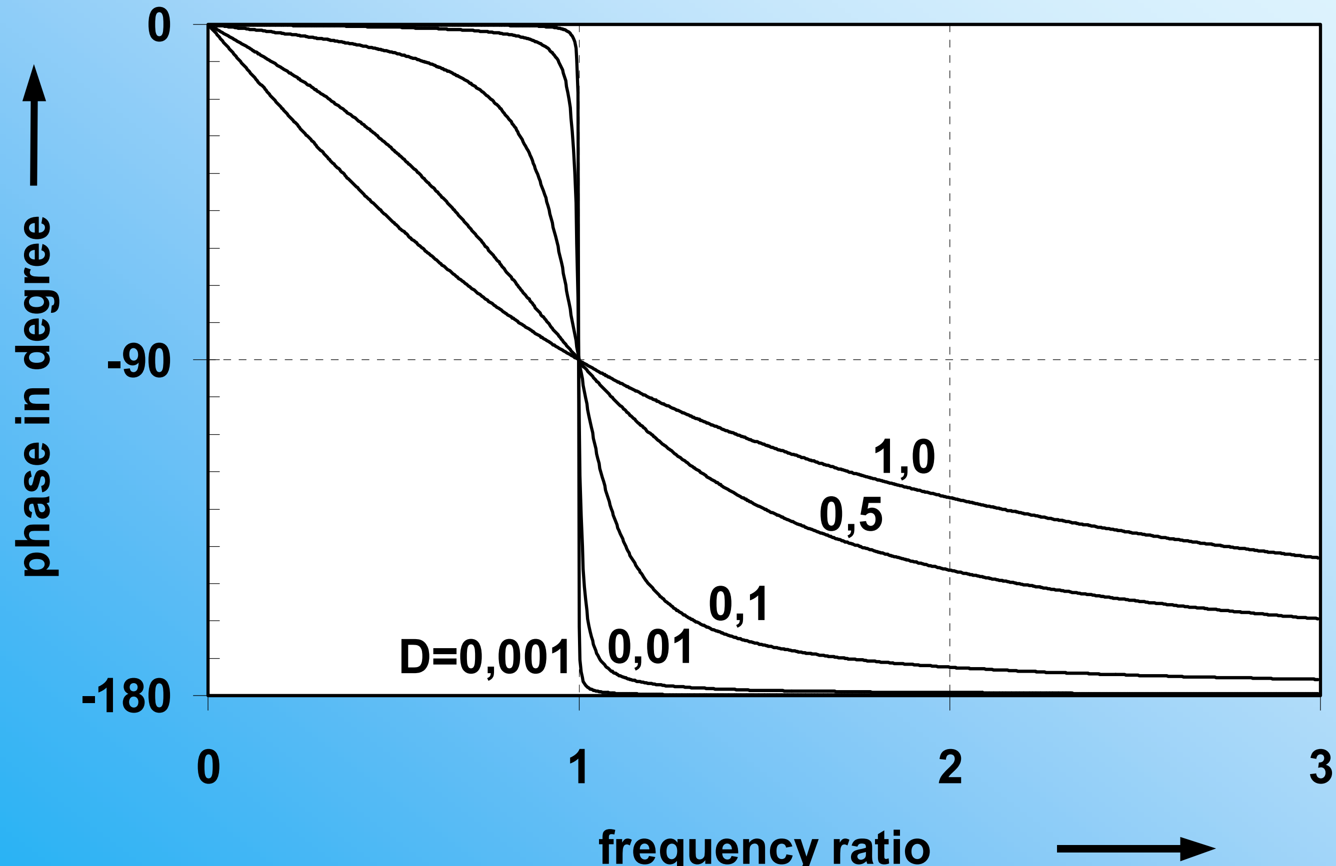
$$m_{\mathrm{t}} \cdot \ddot{r}_{\mathrm{f}} + b_{\mathrm{f}} \cdot \dot{r}_{\mathrm{f}} + k_{\mathrm{f}} \cdot r_{\mathrm{f}} = F_{\mathrm{t}}(t) = \hat{F} \cdot \cos(\omega \cdot t + \varphi_{\mathrm{F}}) = \mathrm{Re}\left\{\underline{\hat{F}} \cdot e^{j\omega \cdot t}\right\}$$



Phase response of the force transducer.

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

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



Resonance behaviour of a force transducer.

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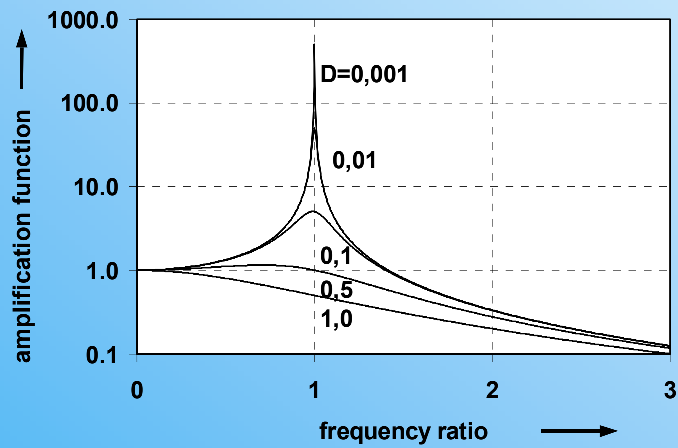
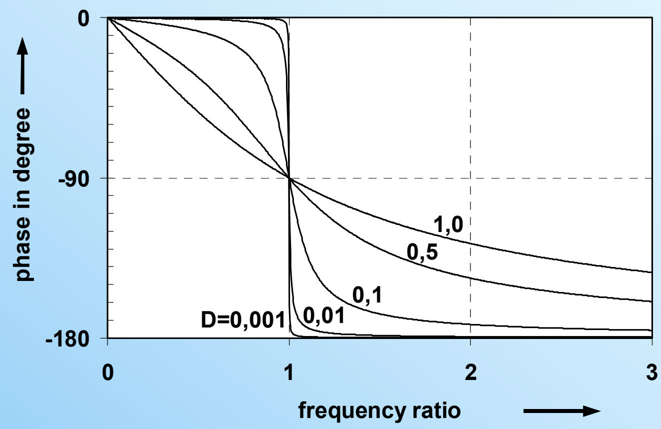
amplification function



matching phase curve



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

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

resonance frequency f_r , eigenfrequency f_d , characteristic frequency f_0

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

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

$$f_r = f_\mathrm{d} = f_0 = \frac{1}{2\pi}\cdot\sqrt{\frac{k_\mathrm{f}}{m_\mathrm{ti} + m_\mathrm{ta}}}$$

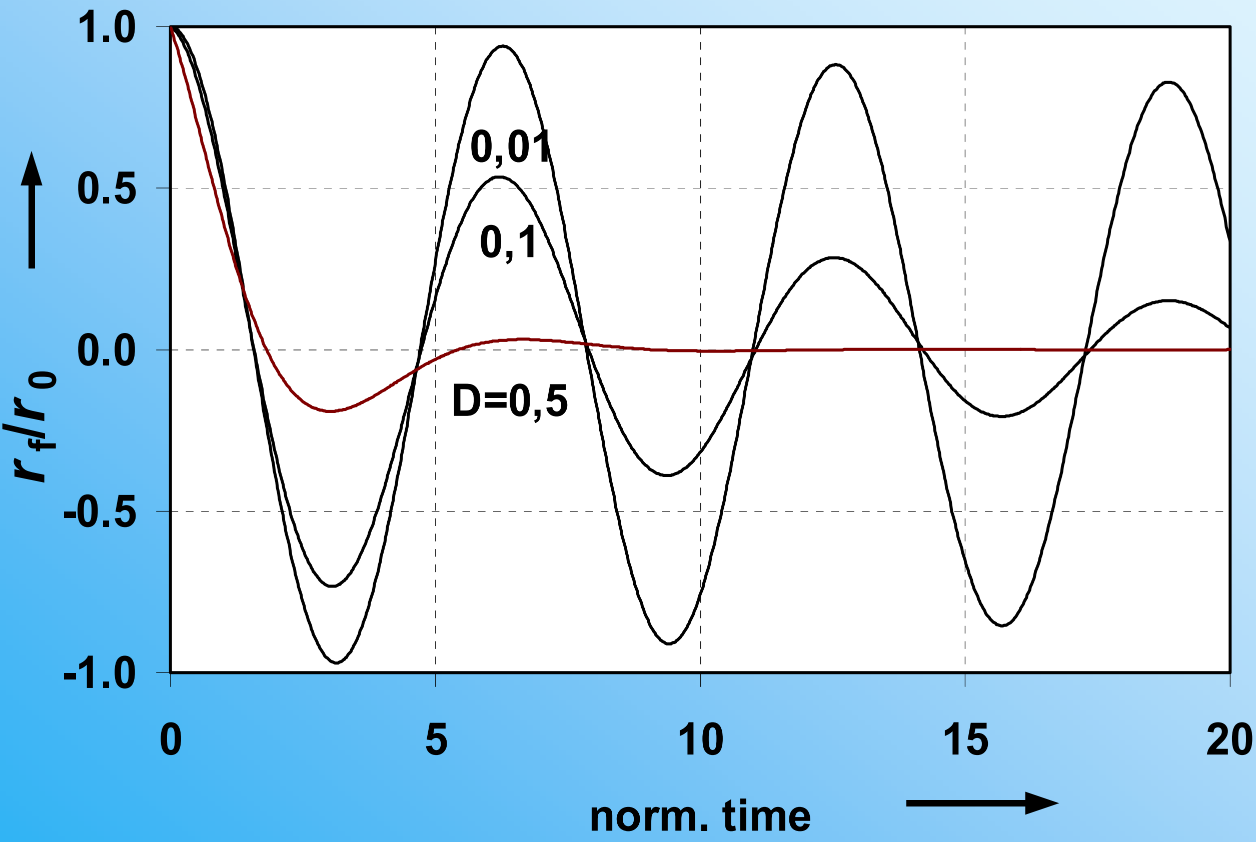
fundamental eigenfrequency $f_{0\mathrm{g}}$

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

Abrupt unloading of a force transducer.

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

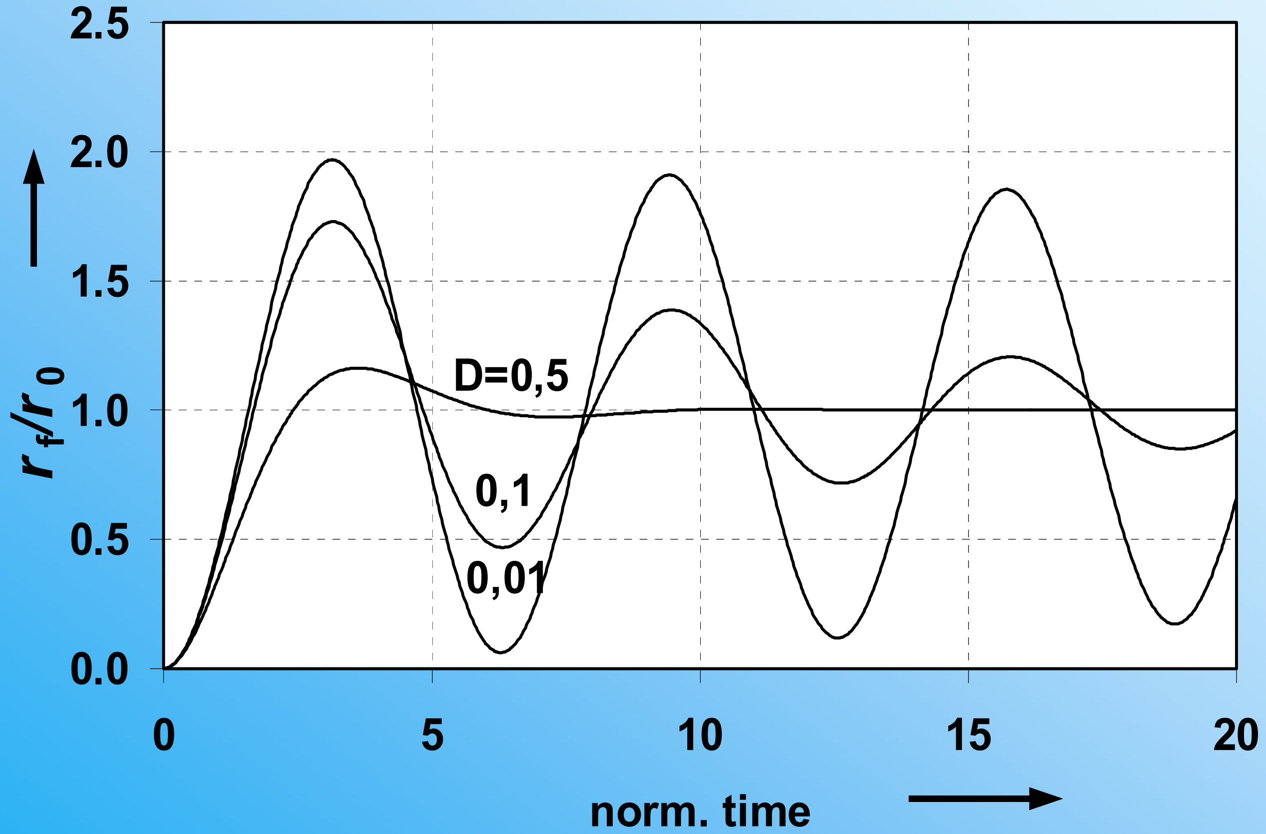
$$\frac{1}{\omega_0^2} \cdot \ddot{r}_{\mathrm{f}} + \frac{2D}{\omega_0} \cdot \dot{r}_{\mathrm{f}} + r_{\mathrm{f}} = \frac{F_0}{k_{\mathrm{f}}} (= r_0) = 0$$



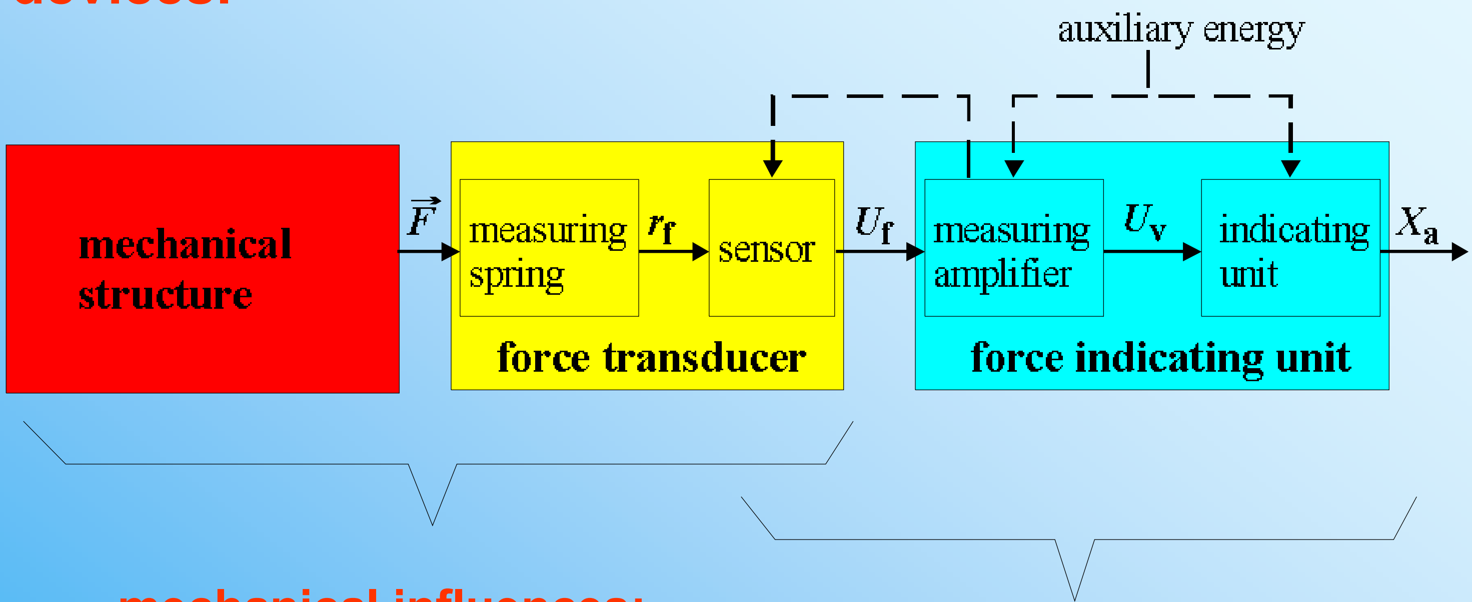
Abrupt loading of a force transducer.

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

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



Dynamic properties of force measuring devices.



mechanical influences:

design of force transducer

material properies

force introduction

interaction with surrounding mechanical structure

electrical influences:

sensor type

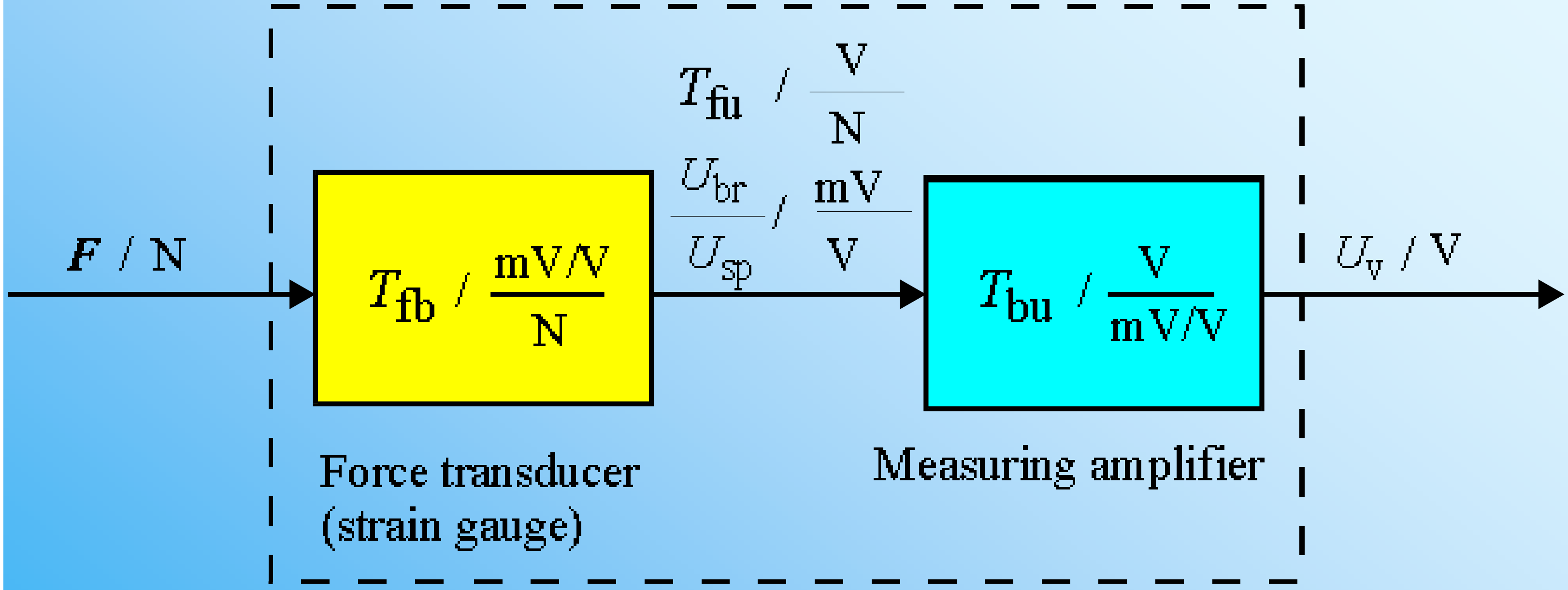
amplifier principle

filter characteristic

dynamics of indicating unit

=> Model description of the force measuring device.

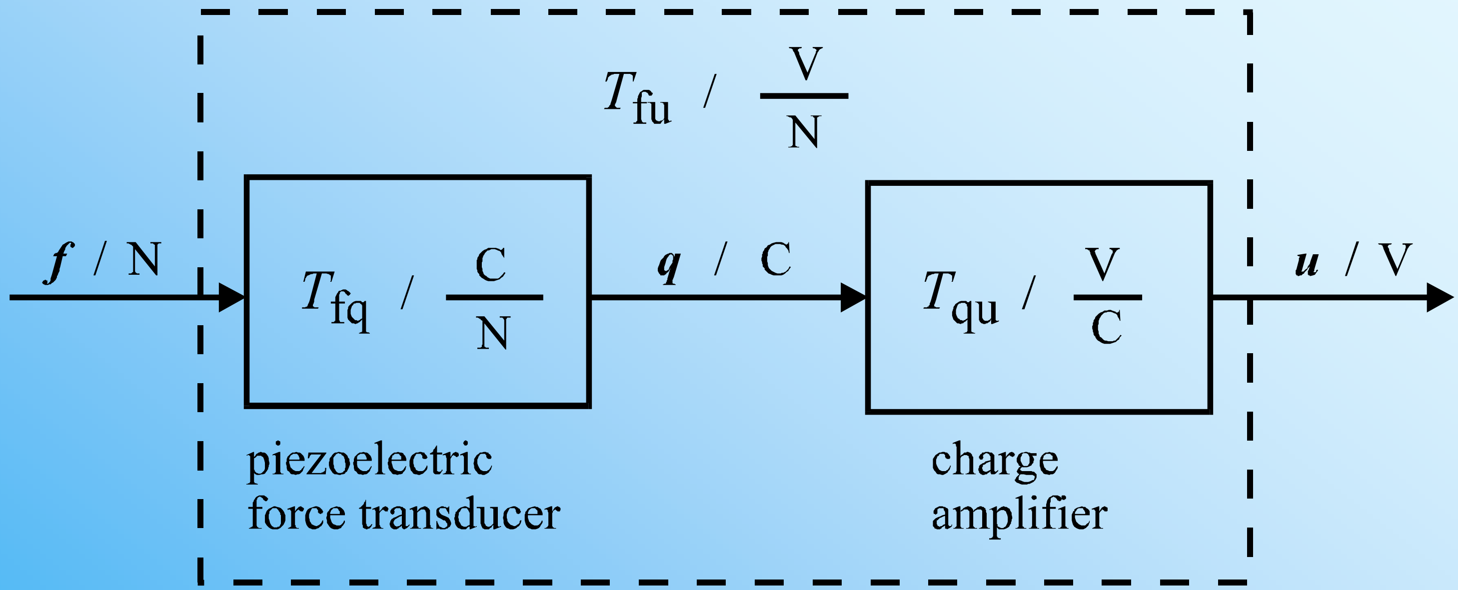
Stain gauge force measuring devices.



=> Multiplication of frequency responses:

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

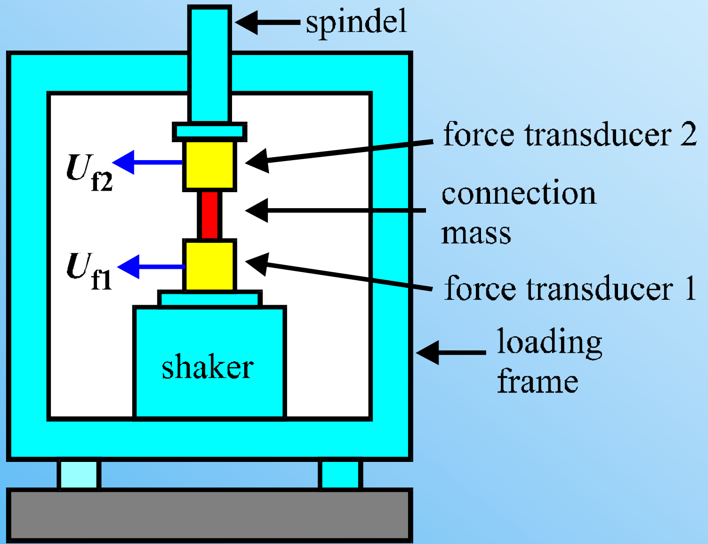
Signal flow piezoelectric force measuring device.

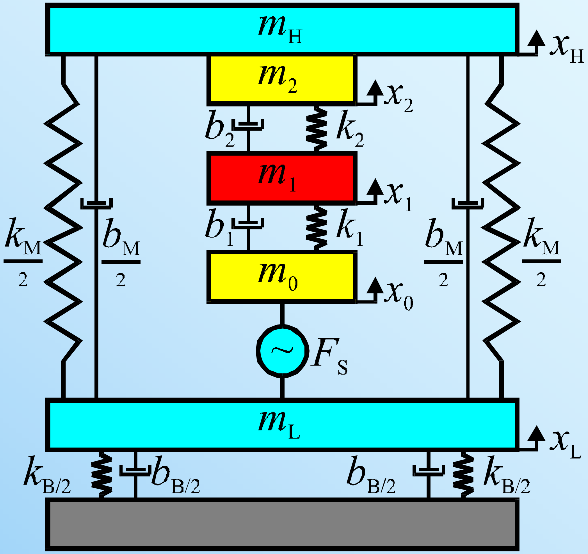


=> Multiplication of frequency responses:

$$T_{fu} = T_{fq} \cdot T_{qu}$$

Principle of the comparison calibration with equivalent model.





system of differential equations:

$$(m_H + m_2)\cdot \ddot{x}_2 = -k_M \cdot (x_2 - x_L) - b_M \cdot (\dot{x}_2 - \dot{x}_L) - k_2 \cdot (x_2 - x_1) - b_2 \cdot (\dot{x}_2 - \dot{x}_1)$$

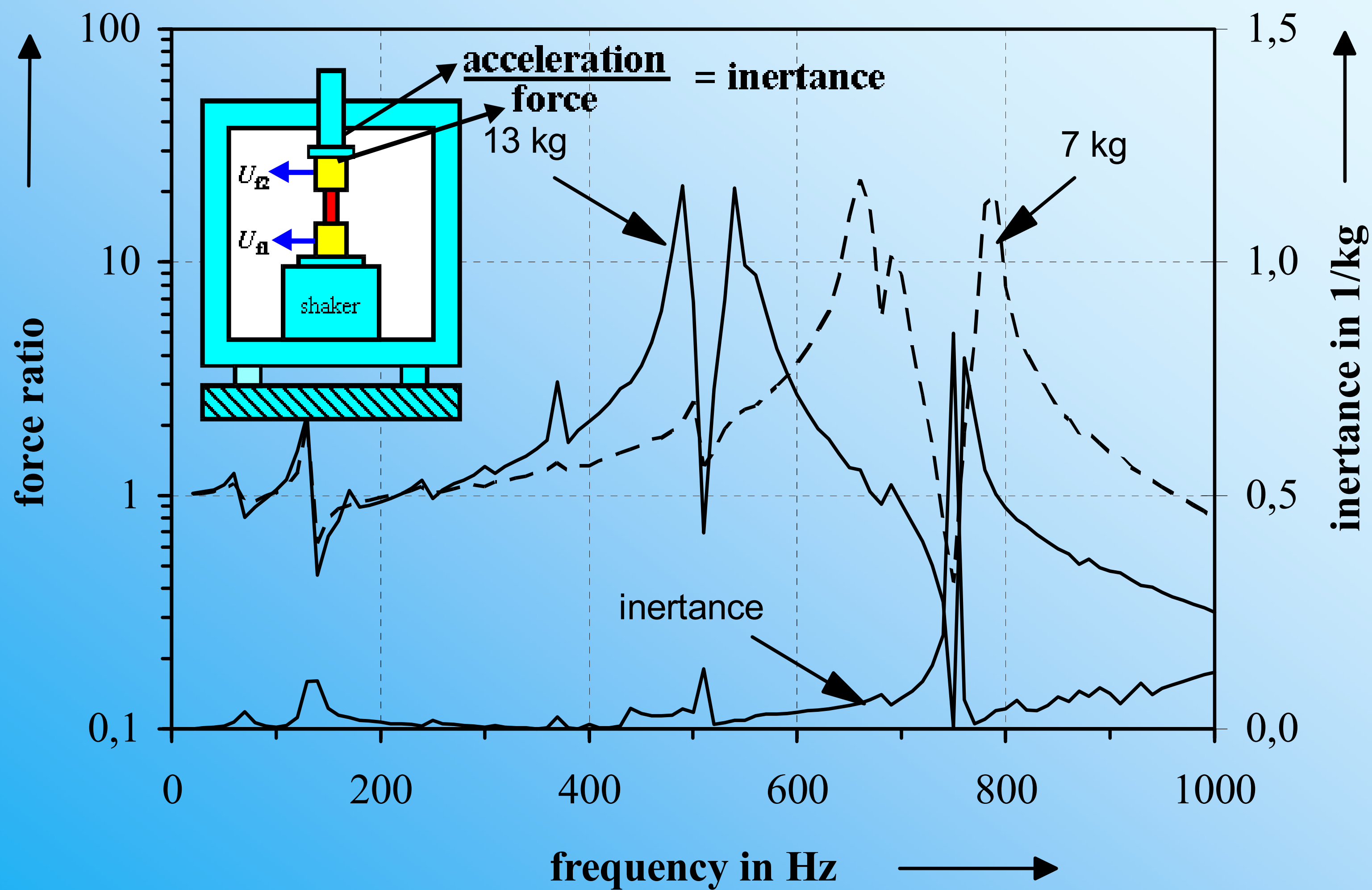
$$m_1 \cdot \ddot{x}_1 = \underbrace{k_2 \cdot (x_2 - x_1)}_{\sim U_{f2}} + b_2 \cdot (\dot{x}_2 - \dot{x}_1) - \underbrace{k_1 \cdot (x_1 - x_0)}_{\sim U_{f1}} - b_1 \cdot (\dot{x}_1 - \dot{x}_0)$$

main equation

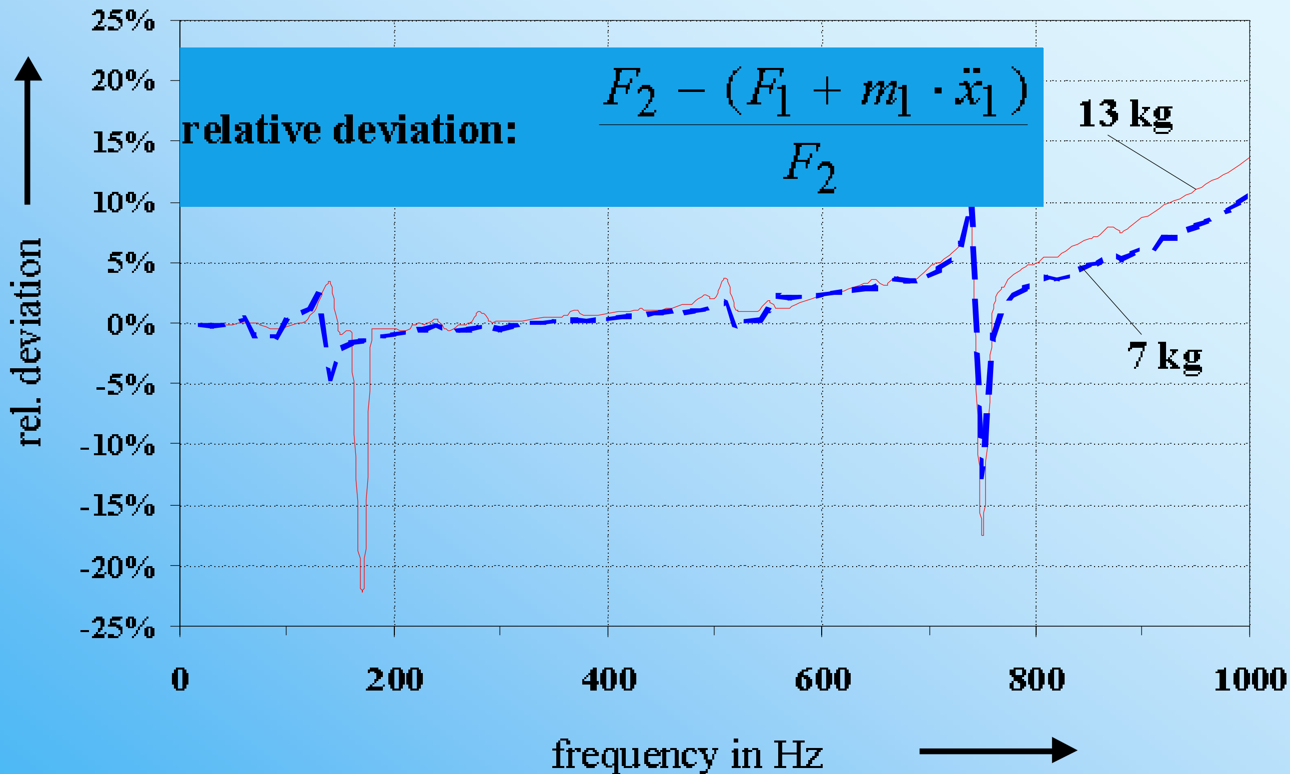
$$m_0 \cdot \ddot{x}_0 = k_1 \cdot (x_1 - x_0) + b_1 \cdot (\dot{x}_1 - \dot{x}_0) + F_s$$

$$m_L \cdot \ddot{x}_L = k_M \cdot (x_2 - x_L) + b_M \cdot (\dot{x}_2 - \dot{x}_L) - k_B \cdot x_L - b_B \cdot \dot{x}_L - F_s$$

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

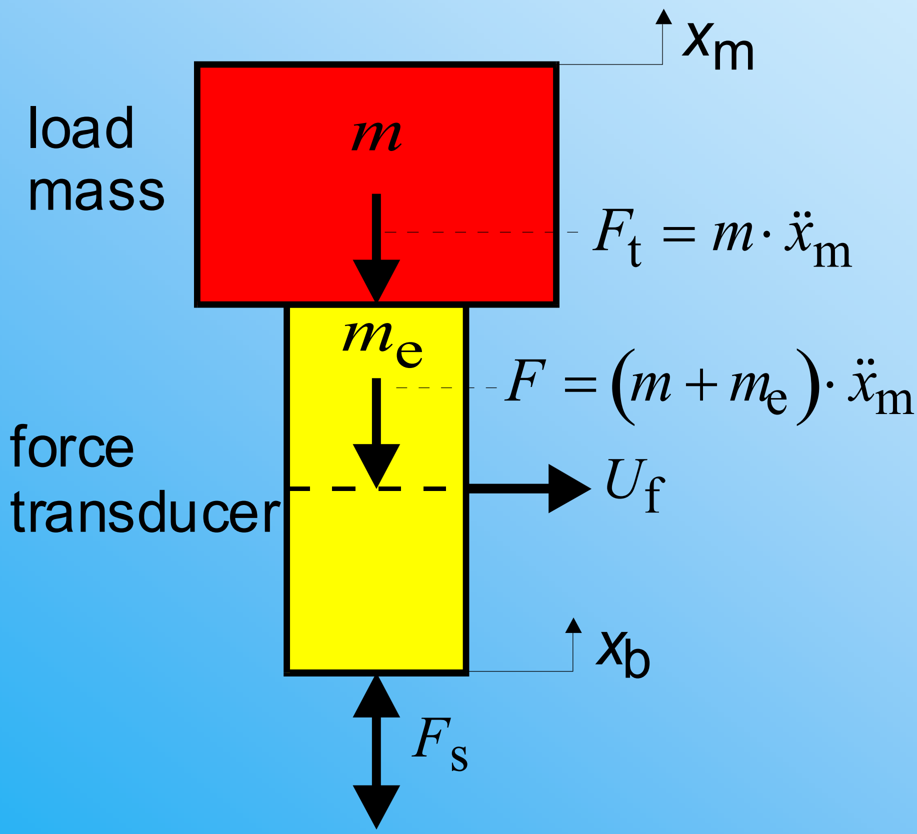
- Consideration of resonance behaviour
  => force measurement
  + transducer resonance
  (+ acceleration measurement)

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: $\vec{F} = m \cdot \vec{a}$

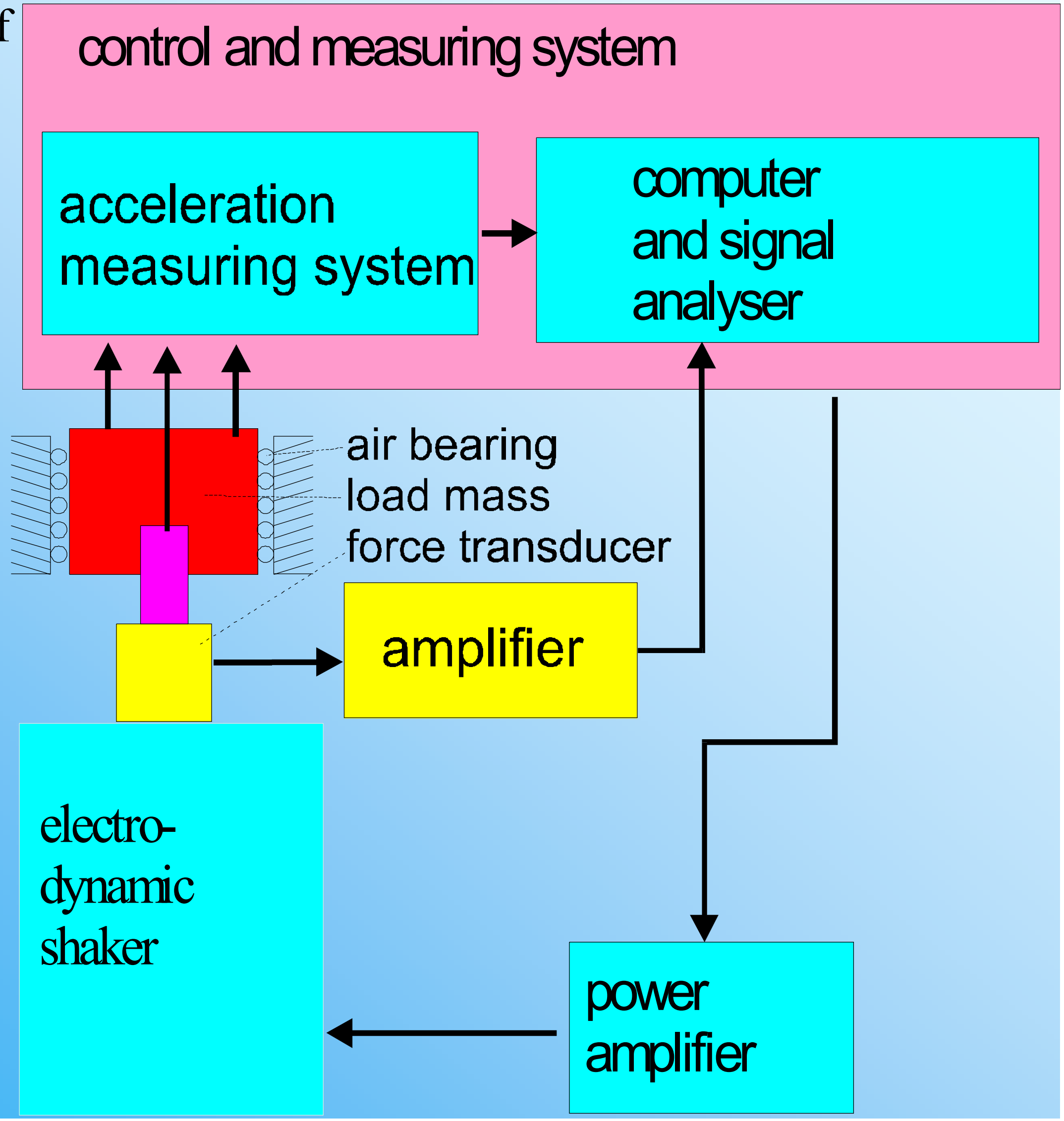
$$F = \int_V \rho \cdot \ddot{u}(x,t) \cdot dV$$

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

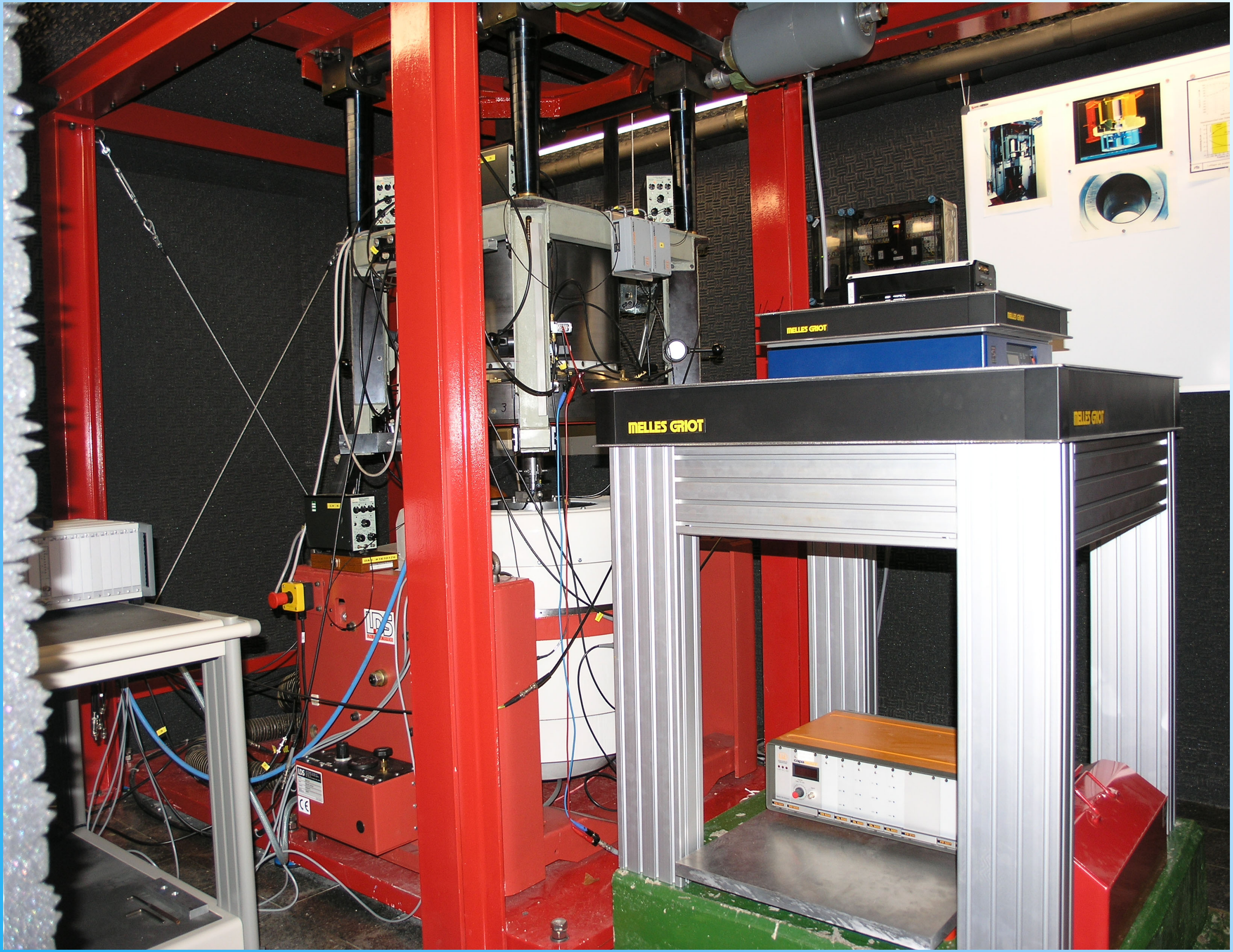
3. Axial force generation

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

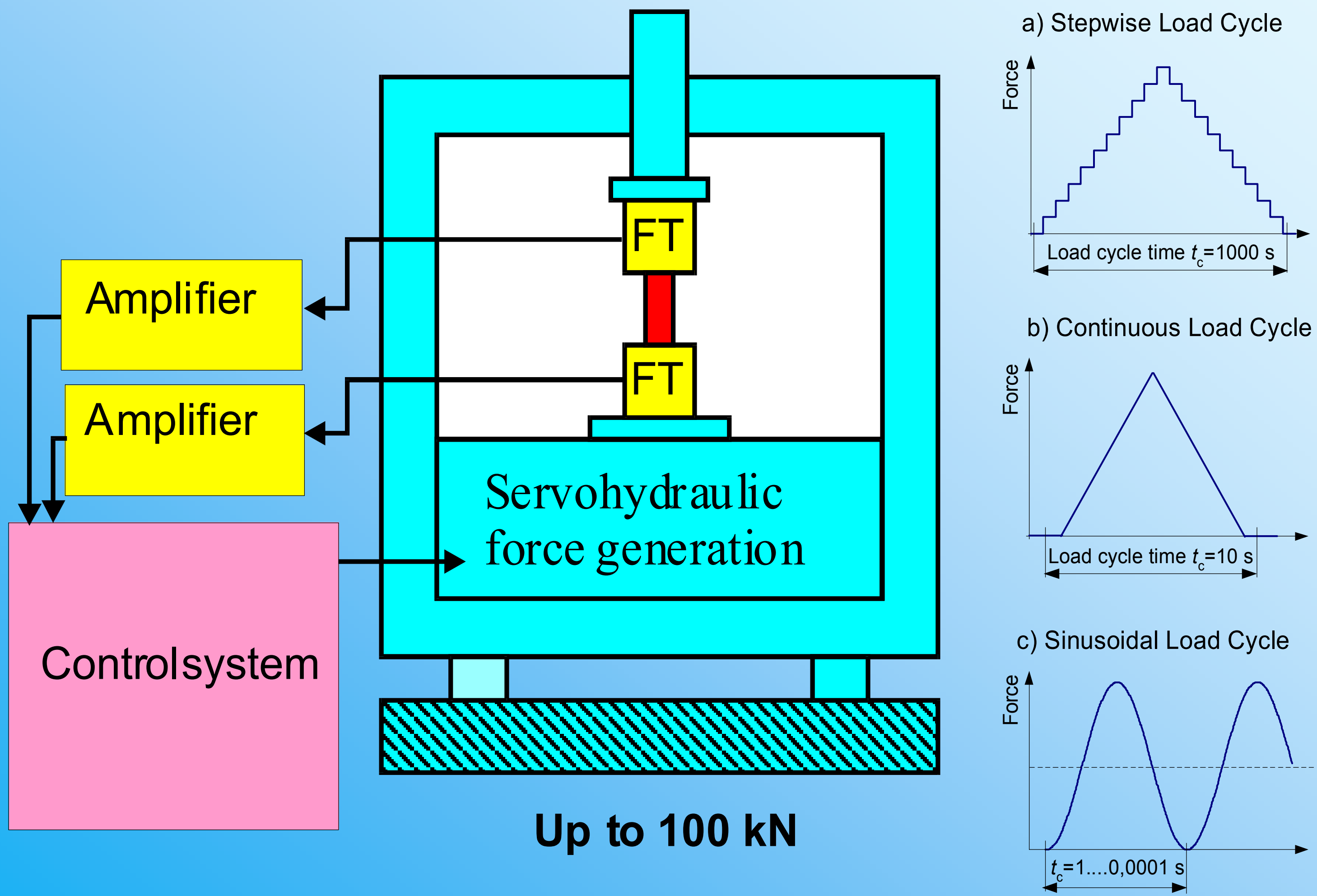
4. Force excition for large dynamic forces
sine: 17,8 kN
half sine: 40 kN



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



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



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.

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.