Challenges in dynamic torque and force measurement with special regard to industrial demands

Presented by:
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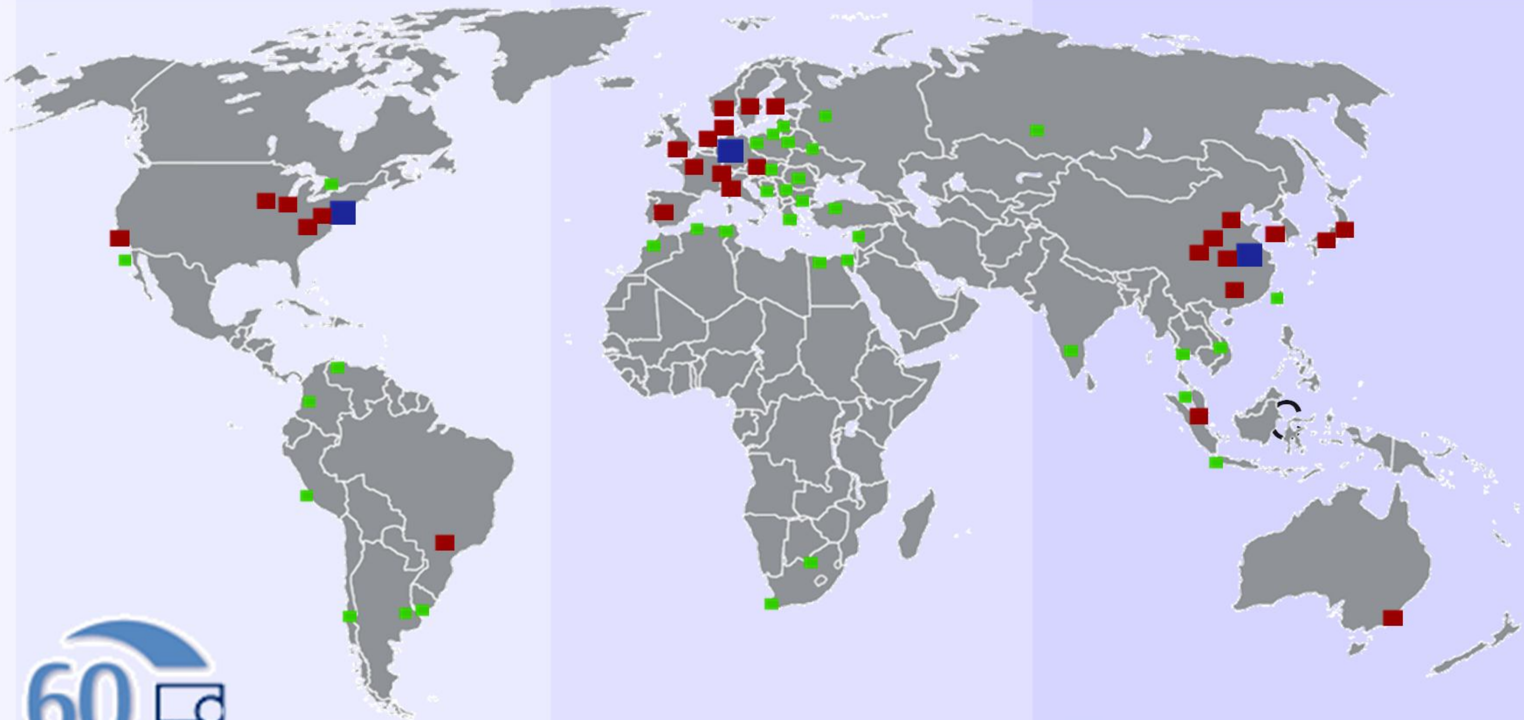
Darmstadt, Germany

AGENDA

Presentation Overview

Short introduction to Hottinger Baldwin Messtechnik (HBM), Darmstadt

Calibration at HBM



More than…

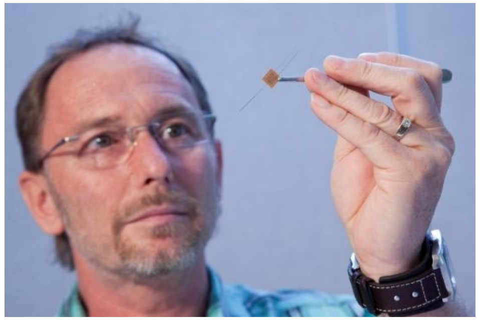
60 YEARS HBM …of trusted results

European headquarters Darmstadt, Germany American headquarters Marlboro, U.S.A.
Asian headquarters Suzhou, China

HBM sales office

HBM representative

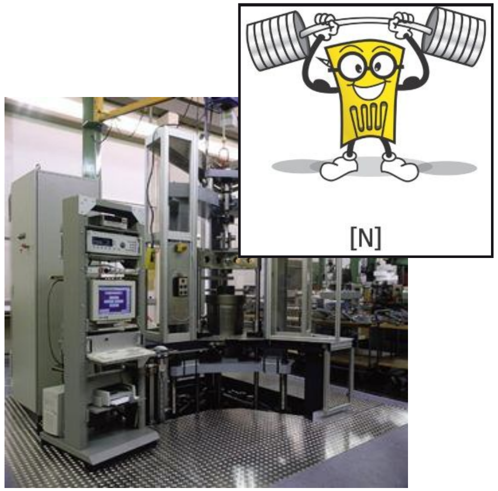
Fields of HBM's competence…



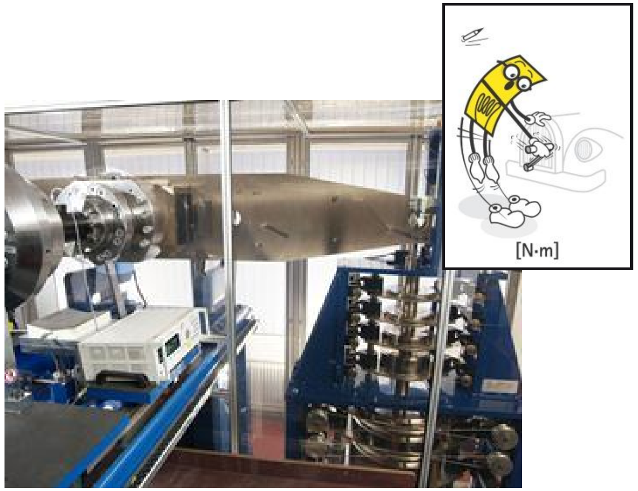
Market leader for strain gauges

Manufacture of transducers

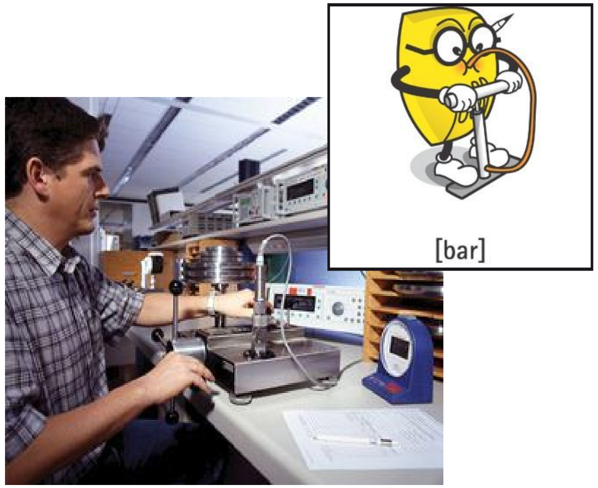
Wide range of products and services….



Force lab



Torque lab



Pressure lab

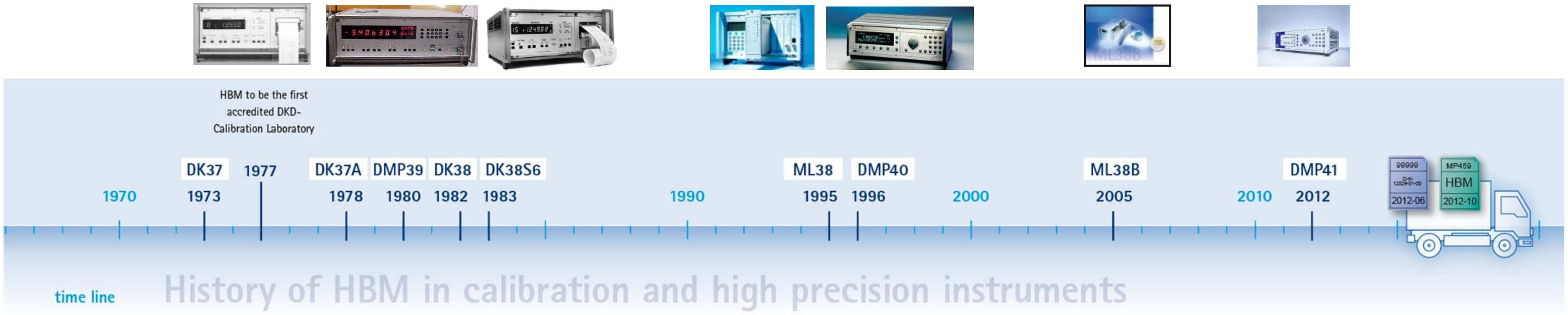
Source: all HBM

Selected highlights of HBM history

In 1955 HBM was the first company **in Europe to start the production of strain gauges.**

HBM was the **first** calibration laboratory in the German Calibration Service (DKD) in 1977.

By 1990 HBM's torque dead weight machine **played the role of a "national standard".**



HBM‘s involvement in EMRP Projects (EURAMET)

running

EMPR JRP IND09 Project
"Traceable Dynamic Measurements of Mechanical Quantities"

running

EMRP JRP IND03 "HighPRES“ Project
“High pressure metrology for industrial applications”

applied for

EMRP JRP-s14 Force Metrology
„Force traceability within the meganewton range“

ility
ganewton range

2011 | 2013 | 2014 | 2016

"Traceable Dynamic Measurements of Mechanical Quantities"

Partners

PTB	Germany	Th. Bruns
NPL	United Kingdom	T. Esward
LNE	France	C. Bartoli
MIKES	Finland	S. Saxholm
CEM	Spain	N. Medina
SP	Sweden	F. Arrhen
INRIM	Italy	A. Malengo
CMI	Czech Republic	J. Zuda
UME	Turkey	C. Dogan

Collaborators and contact persons

HBM	HBM - Hottinger Baldwin Messtechnik GmbH	A. Schäfer; www.hbm.com
SPEKTRA	SPEKTRA Schwingungstechnik & Akustik GmbH	M. Brucke; www.spektra-dresden.de
VW	VW - Volkswagen AG	N. Ramm; www.volkswagen.de
Porsche	Dr. Ing. h.c. F. Porsche AG	G. Ziegler; www.porsche.com

Picture only for pre-sentation

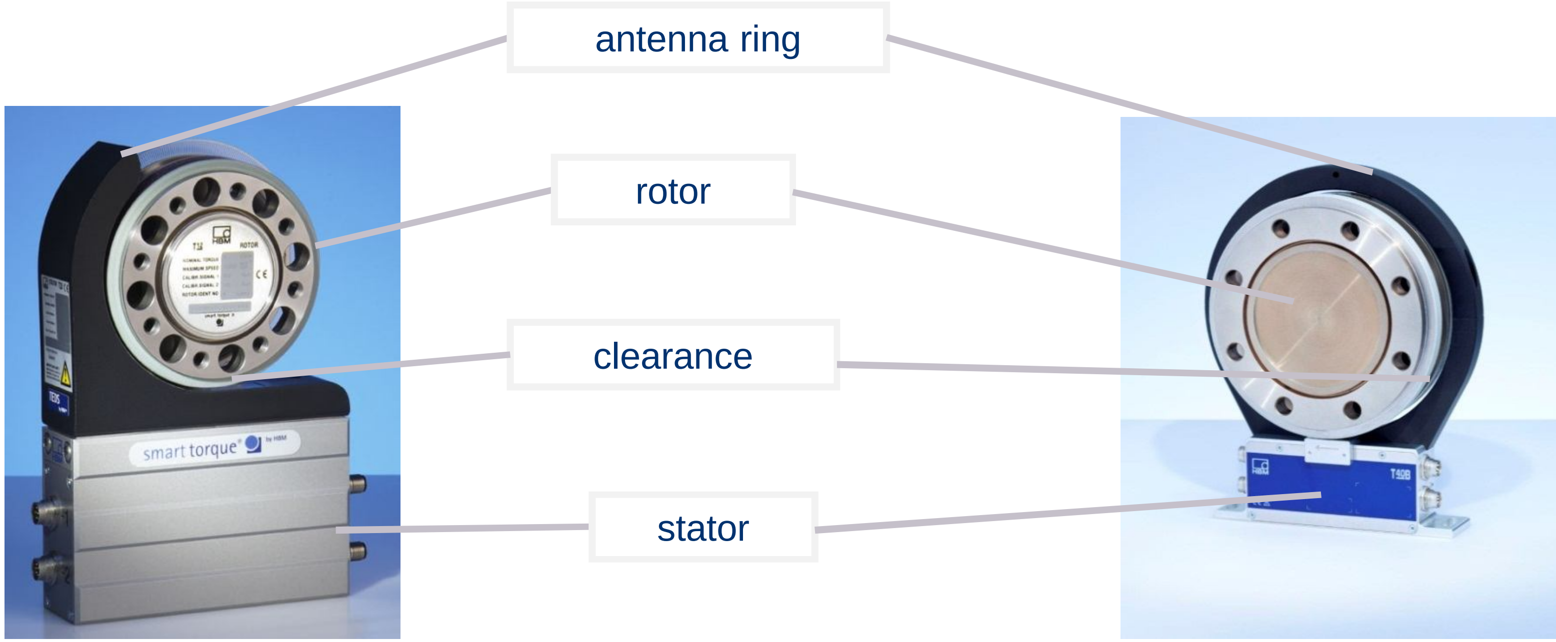
Source: HBM

Chapter II

CHALLENGES IN DYNAMIC TORQUE MEASUREMENT

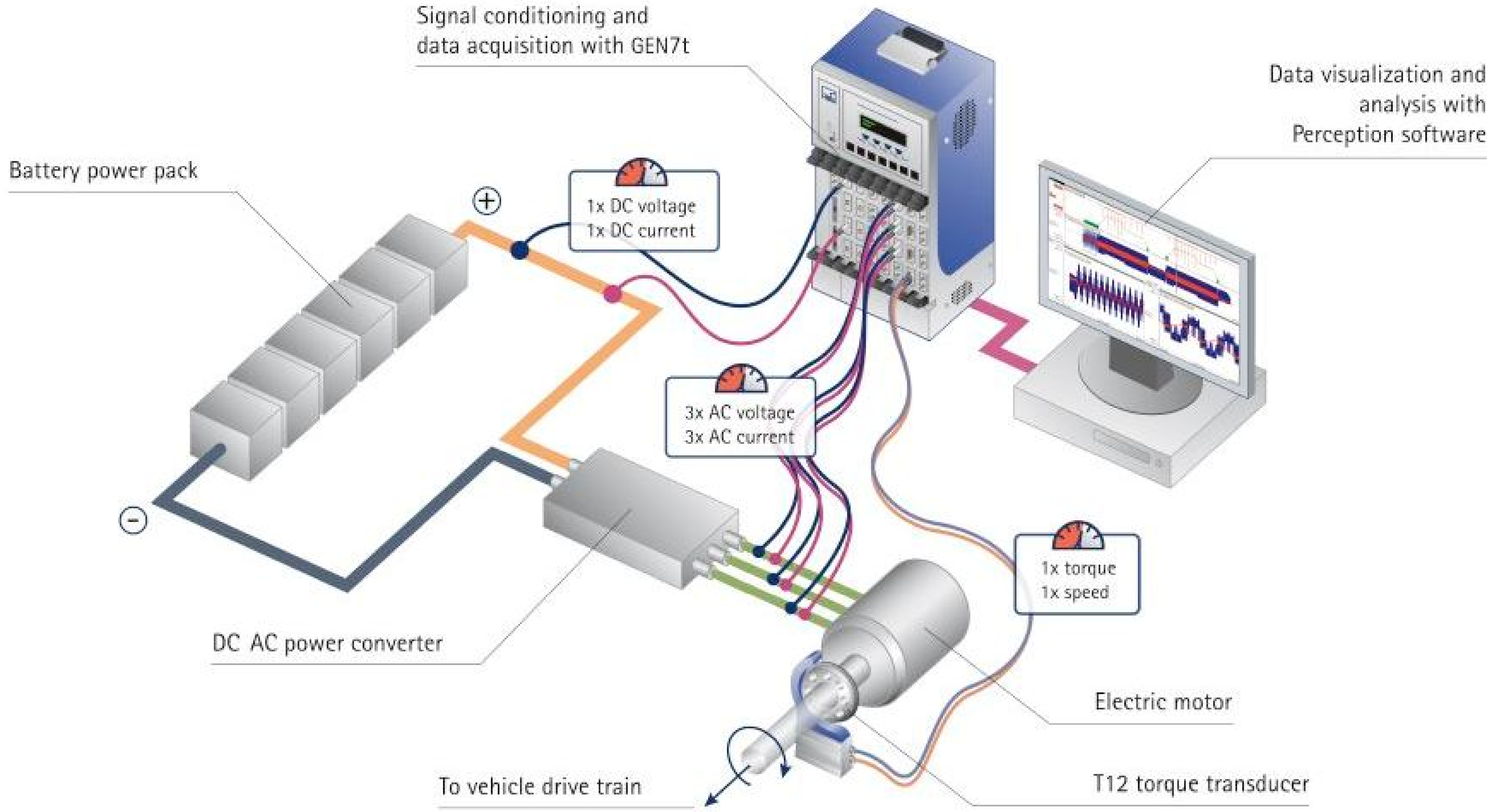
Main parts of rotating torque transducers for industrial testing

Flange type torque flange **T12**	Flange type torque flange **T40B**



Model	Measuring range	Max. speed	Accuracy class	Material of measuring body
T12	100 Nm	18,000 rpm	0.03	Titanium
T12	200 Nm	18,000 rpm	0.03	Steel
T40B	100 Nm	20,000 rpm	0.05	Titanium
T40B	200 Nm	20,000 rpm	0.05	Steel

Power test of electric drives/electric motors



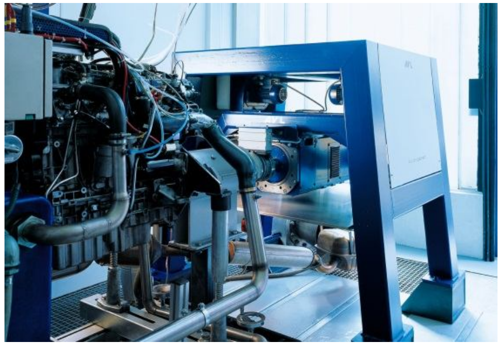
eDrive Testing Concept from HBM

Dynamic torque calibration should be applicable to

automobile engine and transmission testing

Combustion engines

Measurement of power, efficiency, exhaust gas



Source: HBM, Engine Test stand with T12, first published at IMEKO 2006

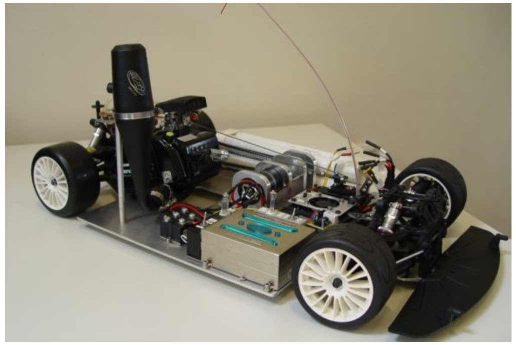
Hybrids

Measurement of power, efficiency, exhaust gas

Source: Darmstadt University of Technology; VKM/ HBM

Electric drives

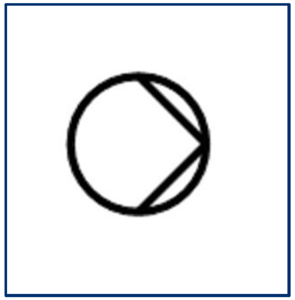
Measurement of power, efficiency



Source: Ostfalia University of applied science and PTB, Germany

Further testing of

Pumps



Source: KSB, Germany

Generators

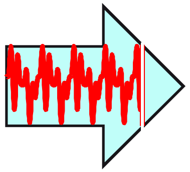
Source: The Switch, Finland

Turbines

Source: Siemens, Germany

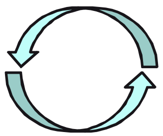
What is special about the measurement of torque? Definition of goals

Today´s standard calibration methods for torque transducers are static in a double sense:



Today torque is measured only in a state when it is constant with respect to time (“static torque”; “stationary torque”).

- Industrial users need **“dynamic torque” (**changing with respect to time)



Today the transducer is mounted in a calibration machine in a non-rotating setup

Industrial users are interested in **“rotating conditions**”, so **“dynamic”** in the real application.

Summary of demands

Static torque ↔ Dynamic torque

Non-rotating ↕

Source: HBM

e.g. Dead weight calibration machine

To be investigated

Rotating

To be investigated

Picture only for pre-sentation

Actual automotive test stand

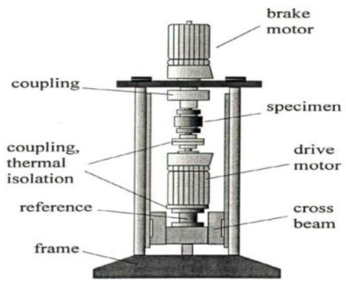
Dependence of torque transducer parameters on rotational speed

- Influence on the zero point is not so critical, as it can be mainly compensated, HBM transducers are tested up to its nominal speed -> see [1]; [2]
- Up to 6000 rpm: Influence on sensitivity is maximum at the same order of magnitude as other contributions to the uncertainty -> see [3]

Further measurements necessary for range 6,000 rpm to 20,000 rpm

References:

[1] *Andreas Brüge, PTB „Influence of rotation on rotary torque transducers, calibrated without rotation" XIV IMEKO World Congress, Tampere, Finland, 1997*



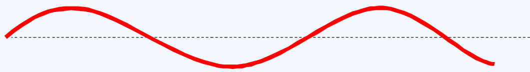
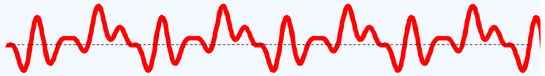
Setup for sensitivity measurements at slow motions: torque transducer mounted as a non-rotating reference in direct line with the torque transducer under test, drive motor placed in between the transducers and brake motor supported by frame

[2] Georg Wegener (HBM) Thomas Bruns (PTB) „Traceability of torque transducers under rotating and dynamic operating conditions" presented at Workshop Traceability to support CIPM MRA and other international arrangements, Torino , Italy, 2008

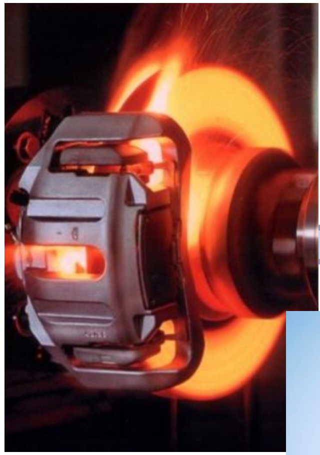
[3] *Jürgen Andrae, Werner Nold, Georg Wegener, all HBM „Traceability of rotation torque transducers calibrated under non-rotating operating conditions", XVII IMEKO World Congress, 2003, Dubrovnik, Croatia; Measurements jointly carried out with AVL, Graz, Austria*

Experimental setup of two identical asynchronous electrical machines - one driving and one as absorption dynamometer - and two transducers in between via coupling

Extent of demand

Criteria	Intermediate goal	Long-term goal
Nominal torque	10 Nm to 500 Nm	200 Nm to 10 kNm
Wave form	Assuming Sinus shape 	Periodic, stochastic and shock 
Frequency range	0…500 Hz	0…10 kHz
Conditions	Angular acceleration, speed and local temperature component	Angular acceleration, speed and local temperature component
Uncertainty	Large total measurement uncertainty $U = \sqrt{U_{TK_0}^2 + U_{TK_C}^2 + \ldots}$	Not as accurate as static calibration today

Especially in dynamic calibration practicability is a must!
Not as accurate as possible, but only as accurate as necessary.



Source:„Bremsenhand-
buch…“ ATZ/MTZ publishing

Source: HBM

Chapter

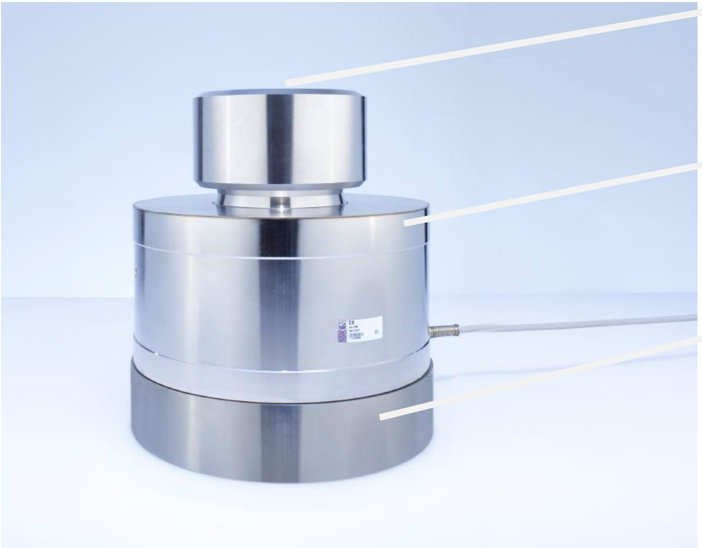
III

CHALLENGES IN DYNAMIC FORCE MEASUREMENT

Main parts of force transducers for industrial use

Compression only type force transducer C18

Universal (tension and compression) type force transducer U15



Source: HBM

Top thread/ plate

Measuring body in housing

Base thread/ plate

Source: HBM

The same as for torque transducers:
mounting parts and mounting conditions play an important role.

Important features to ensure suitability for dynamic applications

By the design of – the suitable- Radial symmetric shear beam force transducers:

- Shear type allows high natural frequency
- Dominating first mode

By additional features of HBM:

- **6-wire circuit** down to the strain gauge
- "**100% permissible dynamic load**": full nominal range can be used for dynamic applications
- **Optimized geometry of the strain gauges** for high output signal. highest strain in the areas where the gauges are installed. Everywhere else lower strain and stresses.
- **Superb static featur**es: classified according to ISO 376
- Optional **bending-sensitive strain gauge bridge**
- **Welded design**: Water proof, resistant against major chemicals and oil

Picture only for pre-sentation

Dynamic force calibration should be applicable to

Automobile testing

Crash test

Picture only for pre-sentation

Brakes

Source:„Bremsenhand-buch…“ ATZ/MTZ publishing

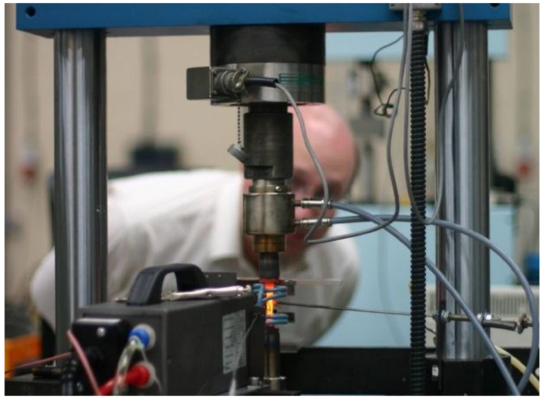
Large vehicles…

Source:„HBM

Source: HBM

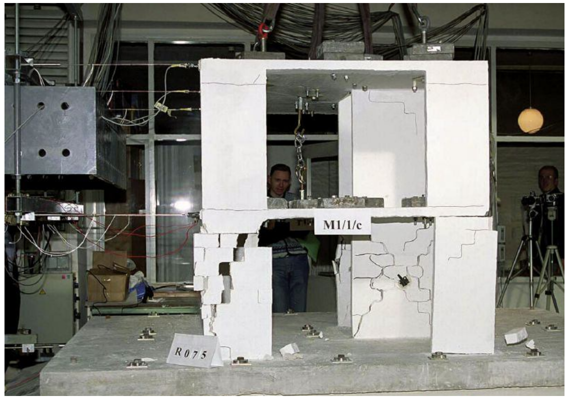
Further applications for

Material testing



Source: HBM nCode

… for buildings



Source: HBM

Aerospace

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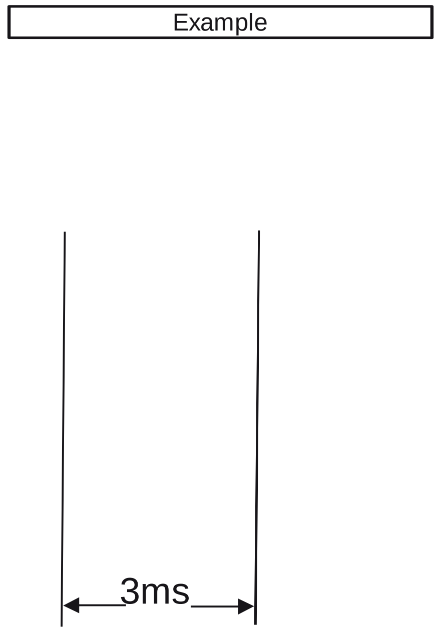
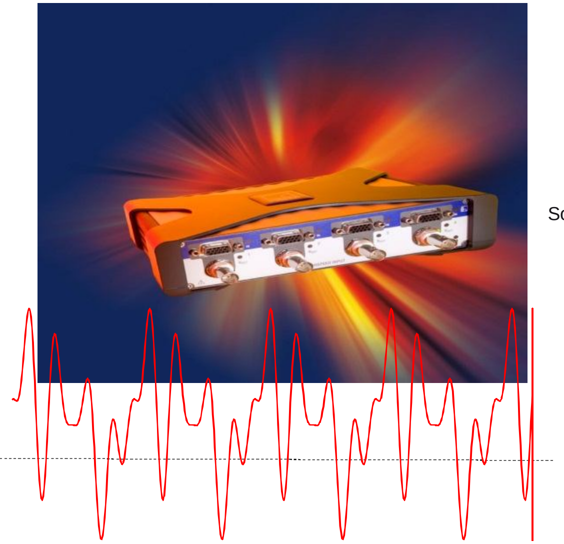
Highly dynamic force measurement using a C6A/2MN

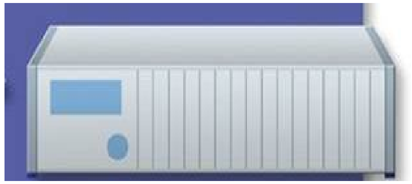


Measurement in the kHz range is possible

using strain gauge based transducers



Source: HBM

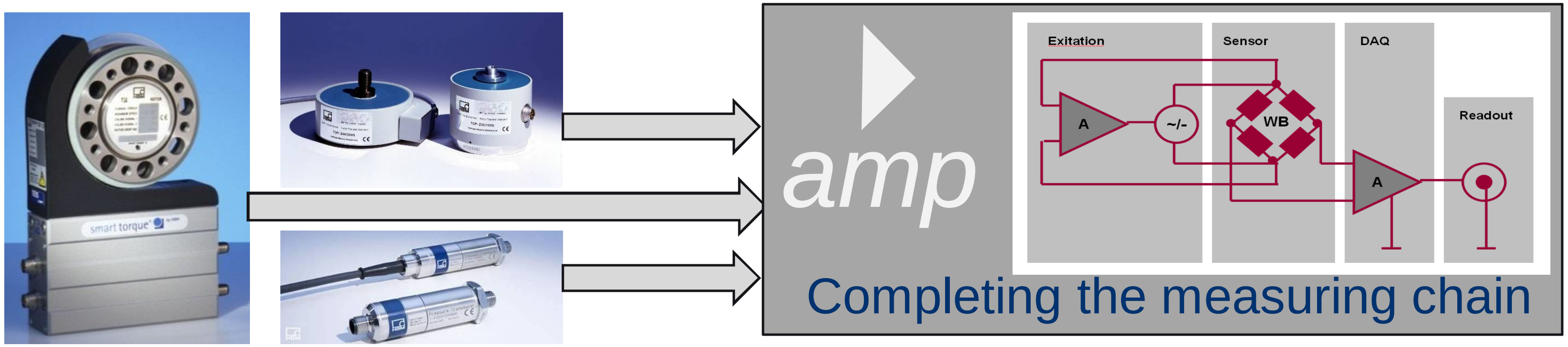


Source: HBM

Chapter IV

INSTRUMENTS FOR DYNAMIC CALIBRATION

How to reach the best overall uncertainty of the measuring chain



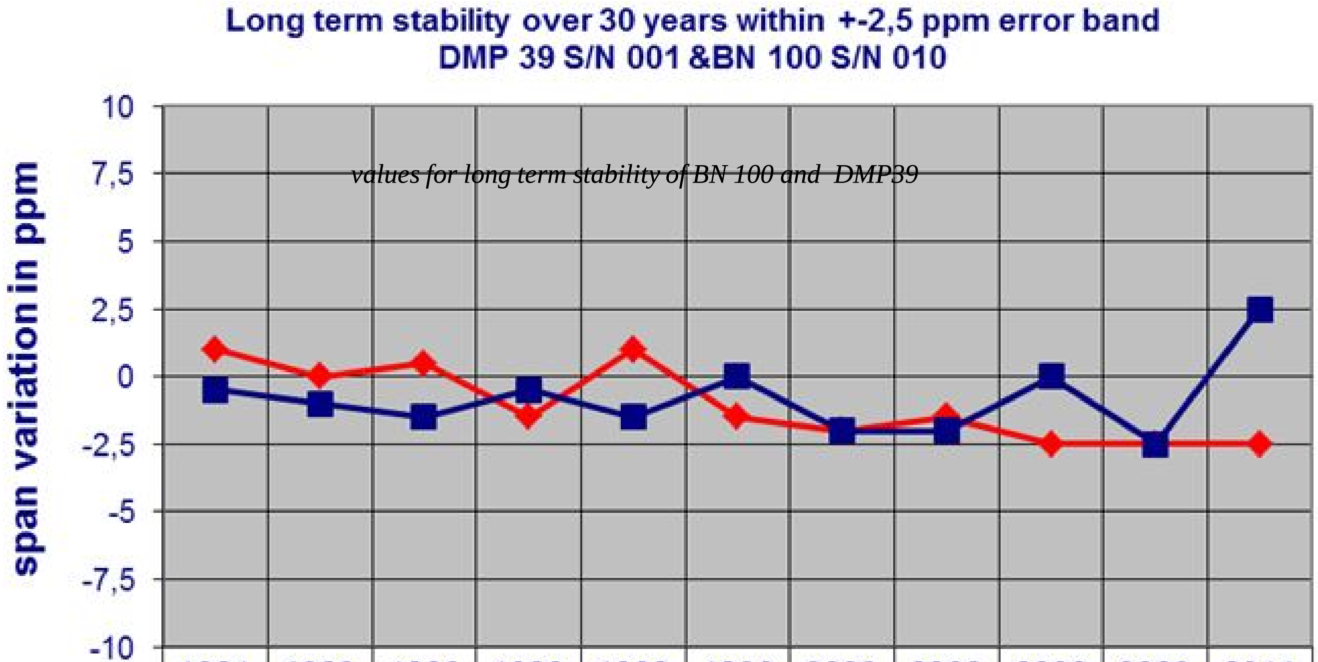
Static calibration

Brand new DMP 41 - Reference for strain gauge based static calibration

Dynamic calibration

QuantumX - Universal system for wide choice of transducer principles, suitable for dynamic calibration

Static calibration:
long-term stability over 30 years
within +-2.5 ppm



	1981	1983	1986	1989	1992	1996	2000	2002	2006	2009	2011
"+2mV/V"	1	0	0,5	-1,5	1	-1,5	-2	-1,5	-2,5	-2,5	-2,5
"-2mV/V"	-0,5	-1	-1,5	-0,5	-1,5	0	-2	-2	0	-2,5	2,5

year

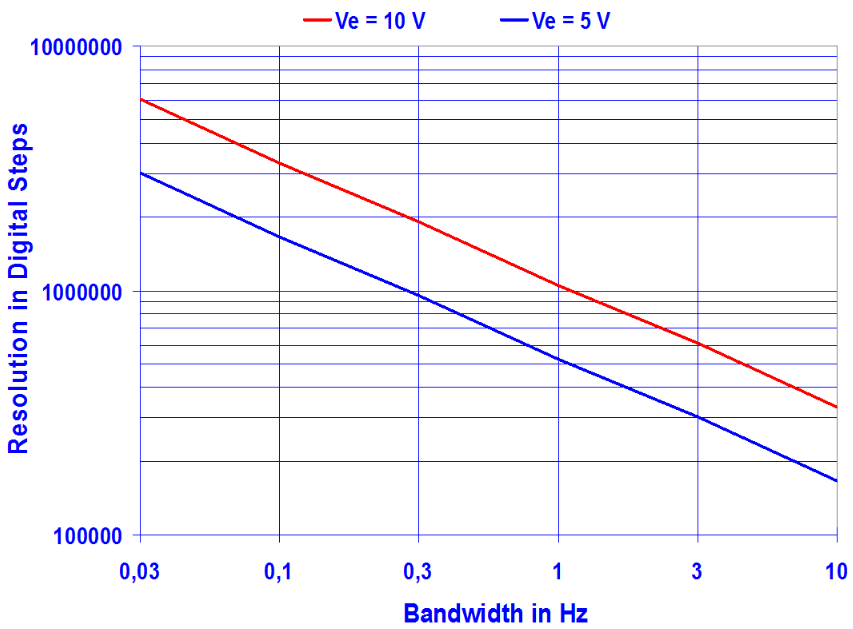
Long-term stability measured on DMP39 (predecessor of DMP41)

Physical limits - resolution versus bandwidth

Physical limits of the resolution of a strain gauge transducer caused by the thermal noise:

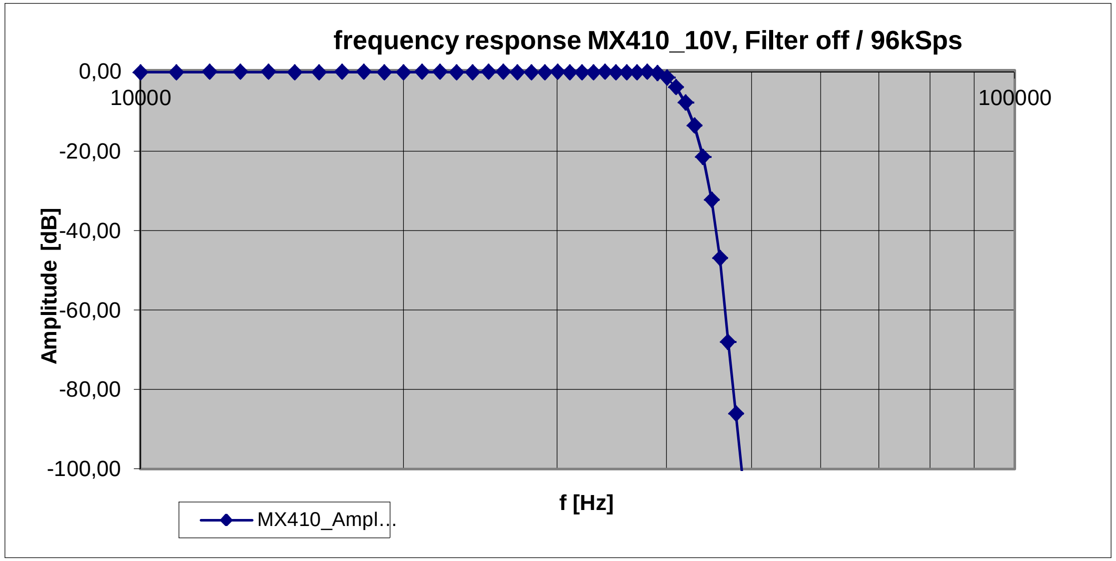
$$V_{rms} = \sqrt{4 \cdot k \cdot T \cdot R \cdot B}$$

V_{rms}	=	Root Mean Square Noise Voltage
k	=	Boltzmann Constant (1.380662 × 10^{-23} J/K)
T	=	Absolute Temperature in K
R	=	Resistance in W
B	=	Bandwidth in Hz

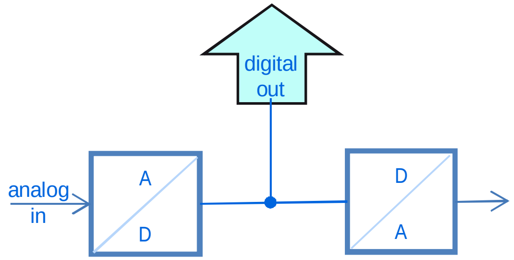


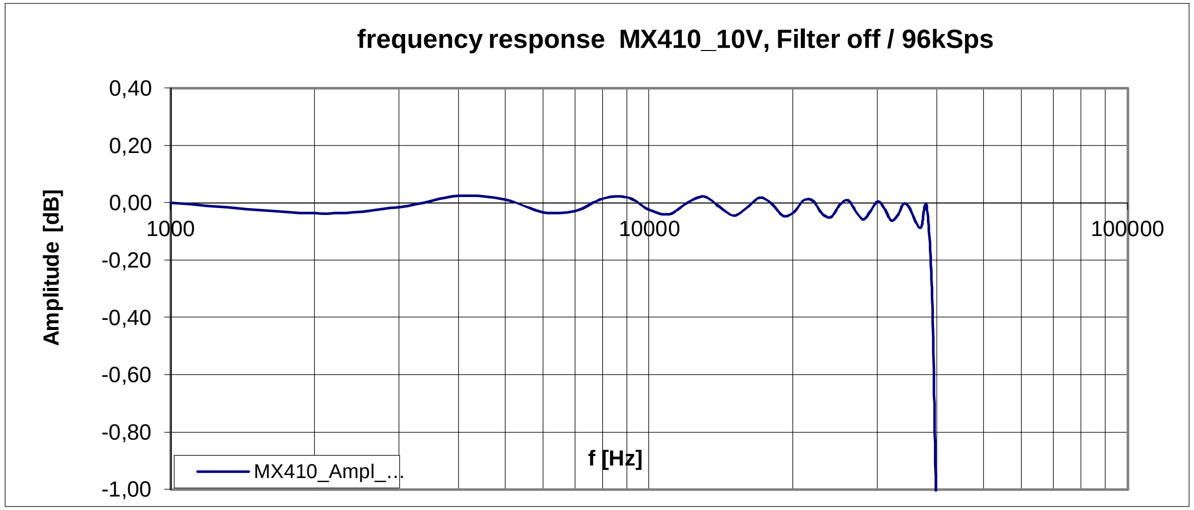
A higher bandwidth reduces resolution

DC amplifier: Low-pass filter characteristics of HBM MX410



Block diagram of the measurement:





Source: HBM

Source: HBM

Source:„Bremsenhand-buch…“ ATZ/MTZ publishing

Source: HBM

Chapter V

SOME GENERAL IDEAS FOR DYNAMIC CALIBRATION

First ideas on dynamic calibration of force transducer/load cell

HOTTINGER BALDWIN MESSTECHNIK GMBH
61 DARMSTADT · IM TIEFEN SEE 45

Handbuch
für elektrisches Messen
mechanischer Größen

von

Christof Rohrbach

unter Mitwirkung von

G. Andreae · A. Becker · H. Bothe
N. Czaika · H. H. Emschermann
W. Markowski · W. Strogies · G. Wagner

1967

VDI-VERLAG GMBH DÜSSELDORF
Verlag des Vereins Deutscher Ingenieure

C.Rohrbach; et al. „Handbook of electrical measurement of mechanical quantities“

issued in 1967

Page 103:

C 7.3.4. Dynamische Eichung von Kraftgebern

Während die absoluten Bewegungsgeber in sich abgeschlossene Systeme mit genau definierter Frequenzcharakteristik sind, hängt das Frequenzverhalten der Kraftgeber sehr stark von den an den Geber angekoppelten Massen der gesamten Meßeinrichtung ab. Wie schon in Abschn. C 1.1 erwähnt, ändert sich z. B. bei Wägungen die angekoppelte Masse mit der Kraft. Sollen Aussagen über einen Geber in einer bestimmten Meßeinrichtung gemacht werden, muß der Geber mitsamt den angekoppelten Massen geeicht werden. Soll dagegen die Frequenzcharakteristik eines Gebers allein, ohne Bezug auf eine spezielle Meßaufgabe, ermittelt werden, wird man den Geber möglichst ohne jede Zusatzmasse eichen, um z. B. den größten mit dem Geber erfaßbaren Frequenzbereich zu erhalten.

„….the frequency response of a force transducer heavily depends on the masses of the **whole measurement setup** coupled to the transducer…“

„… in order to make statements on the transducer’s behavior (in the application) the transducer has to be **calibrated along with all coupled masses**…“

…even some ideas on dynamic calibration of torque

C 7.3.5. Dynamische Eichung von Momentgebern

Wiederum wegen der Äquivalenz zwischen linearen Bewegungen und Drehbewegungen um eine feste Achse (vgl. Abschn. C 7.3.2) gelten für die dynamische Eichung von Drehmomentgebern dieselben allgemeinen Grundsätze, die eingangs des Abschn. C 7.3.4 für die Kraftgebereichung aufgestellt worden sind. Insbesondere sollte oder muß die mechanische Ausgangsimpedanz der das Eichmoment erzeugenden Eicheinrichtung klein gegen die Eingangsimpedanz des zu eichenden Gebers sein, und es dürfen keine störenden Winkelbeschleunigungen auftreten. — Die mit den Drehbewegungen verbundenen Zentrifugalkräfte sind bei der Eichung erwünscht, da sie gleichermaßen auch bei jeder Messung auftreten. — Bei der Eichung sollten nach Möglichkeit reine Momente aufgebracht werden, damit durch biegende Querkräfte nicht scheinbare Momente oder zusätzliche Resonanzfrequenzen vorgetäuscht werden.

Eichanordnungen mit harmonischer Eichgröße

Bild C 7-10a und b zeigt zwei Eichanordnungen zur dynamischen Eichung von Momentgebern, die der Kraftgeber-Eichanordnung in Bild C 7-8b entsprechen. Sie lassen sich auch analog zu den Bildern C 7-8a, c und d abwandeln. Bild C 7-10a zeigt die Möglichkeit, den Momentgeber 1 mit linearem Krafterreger 2 und Kraft-Normalgeber 3 über den Hebel 4 zu

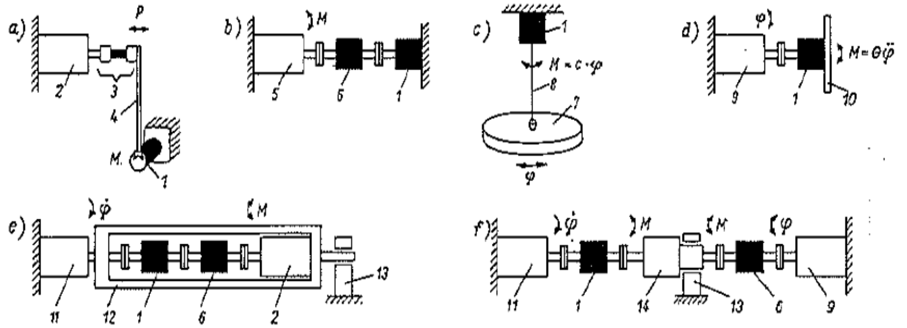


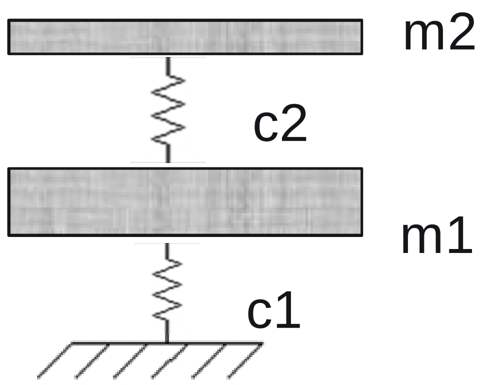
Bild C 7-10. Dynamische Eichung von Drehmomentgebern, schematisch

a) Eichung mit Krafterreger und Kraft-Normalgeber b) Eichung mit Momenterreger und Moment-Normalgeber c) Eichung mit Drehschwingungssystem mit weicher Torsionsfeder d) Eichung mit Zusatzmasse e) Eichung eines rotierenden Gebers mit mitrotierendem Momenterreger [C 7-91] f) Eichung eines sich drehenden Momentgebers mit stehendem Erreger und Momentgeber mittels Bremse nach Bild G 9.5-2

„….due to the analog behavior of **translatory** and **rotatory** movement the same basis has to be applied for the dynamic calibration of torque transducers…“

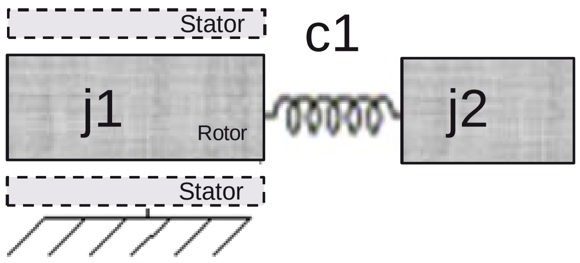
Equivalent circuit diagram - highly simplified

Force transducer (translatory):



Coupled spring-mass system

Torque transducer (rotatory):



Coupled torsional spring-mass moment of inertia and system

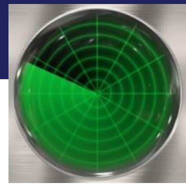
In both cases: Transducer is just one of the components in the system!

Data of the complete system in any case differ from the component.

Influence of the system…	Torque transducer T10F	Force transducer U10M
Without mounting parts	... kHz	... kHz
With mounting parts	… kHz	... kHz
Kind of mounting part	Coupling	Center rod

See also: Wegener, Georg, Andrae, Jürgen: „Dynamische Drehmomenterfassung"; Wissensportal baumaschine.de 3(2007)

How much more will that cost? How do we cope?



Our proposal for a practical approach:

1 • **Conduct dynamic measurements**

2 • **Develop and validate calculation/simulation models**

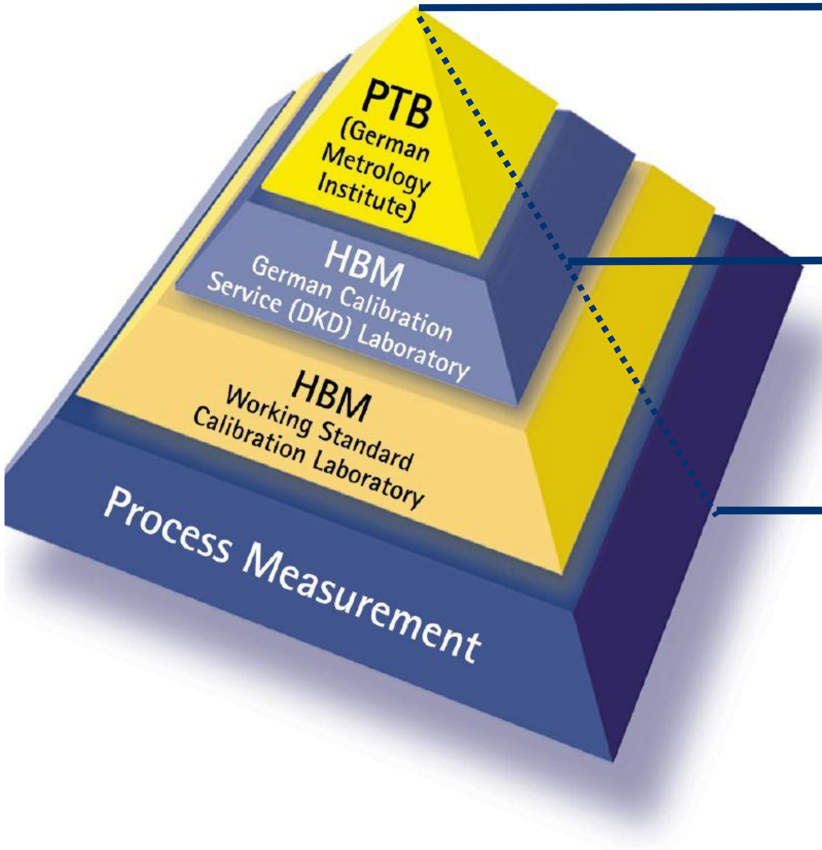
3 • **Evaluate table of influences (e.g. dynamic loads & signals, operational speed, mounting situation, etc.)**

4 • **Conduct established static calibration procedures+ enhance by results from above steps**

Note • **Advantage: System considerations can be taken into account !**

General approach: What is needed to reach this?

Example:
Introduction of dynamic torque calibration into the German Automotive Industry



Development of a primary calibration procedure

Reference transducers
„The connection"

Industrial transducers to do the
„actual measurement"

What does it mean?
What will be necessary?
How much will it cost?

Implement validating calculation& simulation models

Chapter VI

OUTLOOK AND CONCLUSION

Dynamic calibration will be a topic for substantially larger torque & force values

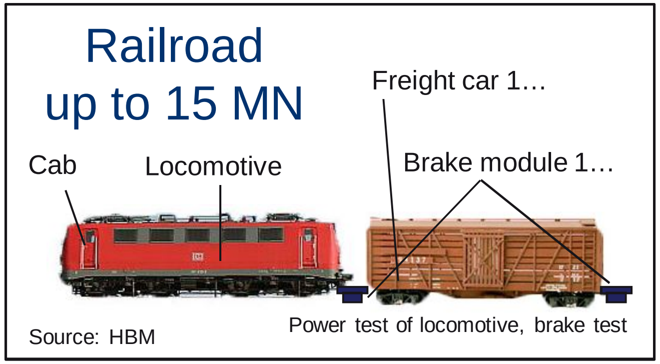
Drivers for torque measurement:

Source: HBM

Source: www.prachensky.com

Drivers for force measurement:

Source: Singapore Airlines



Questions regarding frequency range

Picture only for pre-sentation

Question 1: Will electric motors require a much higher frequency range again, e.g. 10 kHz instead of 100 kHz?

Question 2: Will it be possible to build up mechanical systems and mechanical transducers for the expected frequency range?

$$f_o = \frac{1}{2\pi}\sqrt{\frac{c}{m}}$$

f_o…	natural frequency
c…	spring constant
m…	mass

$$f_o = \frac{1}{2\pi}\sqrt{\frac{c_T}{J}}$$

f_o…	natural frequency
c_T…	torsional spring constant
J…	mass moment of inertia

m_{total}, J_{total}….needs to be smaller and smaller

c, c_T…. needs to be higher and higher

Proposals for further subjects of investigation

- **Disturbing influences:**
  - **Mechanical: Rotational speed, axial vibrations, bending vibrations**
  - **Environmental: Local temperatures**

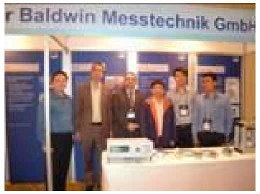
- **Further aspects of interest:**
  - **Dependency on stiffness of measuring body, Further increasing of the natural frequency, permissible dynamic load**

    ->Modeling of dynamically suitable torque and force transducers
  - **Characteristics and dependency on the amplifier in the measuring chain, as measuring amplifiers are always needed-Improvements of dynamically suitable measuring amplifiers**
  - **Realistic picture of the system in the application- Masses and mass moment of inertia of the adapter/ flanges**

Generally: Other criteria than known from static calibration are becoming important

Conclusions

- Dynamic calibration is the **logical successor** of static calibration -> by now, there are no standards or regulations yet. There is a **large gap** between the demands of industry and what **NMI's and suppliers** can offer.
- The **effort** of building up a dynamic calibration system **is tremendous**. Thus realization has to be as simple and effective as possible, other options should always be considered as well.
- For mechanical quantities **foil type strain gauge transducers** are most accurate, they got sufficient bandwidth and thus are the best choice to reach lowest uncertainties in dynamic measurement of mechanical quantities. As a Design rule the **strain zone should be designed as small as possible** to reach high stiffness, still large enough for reproduction of the strain signal.
- Data of the complete system differ from the component. So the **total system** has to be considered. In terms of **measurement uncertainty** however, for the reasons mentioned - it will never be as good as static calibration.







HBM at IMEKO TC 3 in November 2010 in Pattaya, Thailand; IMEKO TC16 in May 2011 in Berlin, Germany ; and XX IMEKO World Congress in Busan, Korea

Thank you for your attention!

HBM

measurement with confidence

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