

FORCE TRACEABILITY MEASUREMENTS TO ACHIEVE 0.005 % BEST MEASUREMENT CAPABILITY

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Abstract:

The increasing accuracy of force transducers and their calibration had two major effects: the chance to better extract the capability of a reference standard machine (compared to a formerly mixed evaluation of machine plus transducer) and on the other hand the need to build up reference standard machines capable to calibrate those high precision transducers. Using the experience of designing force transducers, of constructing calibration machines and of calibrating force within the German Calibration Service (DKD) since 1977 HBM decided to take the challenge. Two new dead-weight force reference standard machines of 2.5 kN and 25 kN have been built up and their best measurement capability of significantly better than 0.01 % has been verified by transfer transducers from HBM's product range.

1 PROJECT

As a new concept in 2000, PTB agreed with HBM that they started a project under the following constraints:

- 4 dead-weight force calibration machines installed at HBM and accredited by DKD, the first of them since 1977;
measuring ranges of the existing machines: 2 kN, 20 kN, 240 kN and 1 MN with a best measurement capability U_{bmc} of at best 0.01 %
- design and construct two new dead-weight force calibration machines, measuring ranges 2.5 kN and 25 kN
- strive for a best measurement capability of significantly better than 0.01 %
- use HBM force transducers for the comparison measurements
- qualify the new machines by comparison measurements to the existing machines and deduce U_{bmc} from them
- design an evaluation scheme and assess according to well-known calculation procedures [1; 2; 3; 4]
- calibrate the transfer transducers at PTB to confirm U_{bmc}

So the responsibility of performing accreditation-relevant measurements was chiefly transferred to the DKD calibration laboratory at HBM.

2 DEAD-WEIGHT FORCE REFERENCE STANDARD MACHINES (2.5 kN and 25 kN)

Both of the machines were supposed to extend the existing equipment or to replace it in the lower measuring ranges. Loading in both directions, i.e. compression and tension, as well as increasing and decreasing force values for each measuring series had to be possible to enable hysteresis to be determined. Both machines had to be as identical to each other as possible. Therefore, the 25 kN machine had to be a copy of the 2.5 kN machine with adapted dimensions (see figure 1).

The machine design had to ensure that some influence quantities well-known from long years of experience only had little weight in the resulting measuring uncertainty. These influence quantities include:

- Calibration of the masses
- Local gravitational acceleration
- Force application (input), pendant → bracket lowering

- Force application (output)
- Load change sequence → swinging masses
- Ambient conditions



Figure 1: 2.5 kN force reference standard calibration machine

20 disk-shaped masses can be sequentially added to a loading frame. So the resulting load steps are well suitable for calibrations according to EN 10002-3 [5] or ISO 376 [6].

Exactly at the place of installation of the machines, the local gravitational acceleration was determined by the institute for physical geodetics of the Darmstadt university. It is $9.810286(7) \text{ m/s}^2 \pm 2 \cdot 10^{-7}$.

Based on these data the masses have been adjusted at PTB by filling up with lead grit. They have been calibrated with a measurement uncertainty of $5 \cdot 10^{-6}$, e.g., a 10 kg mass with a measurement uncertainty of 0.05 g. In addition, all essential mounting parts have been adjusted and can be reproduced at any time.

The construction of the force application as a frame required high precision in lowering when performing repetitive measuring series or when rotating the transducer. Therefore, tilting, tipping or rotating movements had to be avoided as far as possible. An ingenious combination of several guides was the solution leading to a significant reduction of the measurement uncertainty.

The example of compression loading is intended to describe the principle. Using three spindles that are working synchronously, the base plate with the horizontally installed transducer is pressed from below against the compression pad that has been fitted into the

upper part of the frame. The base plate together with the frame is lifted until the masses required to achieve the desired force are no longer in their initial position.

At each of the frame's two upper horizontal extremities there is a bolt with a thread partially sticking out downward. With no load applied, this part of the thread is inserted into a sleeve connected to the housing frame and, upon load application, it is lifted off the sleeve. A U-type bracket then functions as guide mechanism. It has been fitted with rubber rollers at the ends of its legs for trapping the frame if it might swing. Afterwards, this U-type bracket is also removed pneumatically from the load frame to enable it to rest freely on the transducer thrust piece.

The force application (output) via the base plate also is very important. Insufficient horizontal alignment or uneven surfaces would result in a misalignment of the transducer and would have unpredictable effects on the flux.

From experience with existing machines we knew that, in addition, a solution had to be found which would enable the stack of masses' tendency to oscillate after load changes to be reduced. This tendency has a distinctive effect on the measurement signal stability and on the uncertainty of measurement. Therefore, two disk-type masses have been connected by three ring connections distributed on the outer circumference; their carrying effect only develops when the center rod is lifted. After initial problems resulting from inappropriate mounting of the headed dowels had been solved, the tendency to oscillate could rapidly be eliminated. Vertical guide pins reaching between the two rest bars fitted radially on the mass were used to prevent the stack of masses from turning about the center rod and thus abandoning the rest position upon removal of the load.

Doubts as to negative effects on the measurement uncertainty due to wear and tear could be allayed although the machine has now been used intensively for two years. In this respect we had to consider the tension and compression working pieces with the corresponding bolts and the guide pins between the masses' rest bars which cause friction. The material for the guide pins has been selected in such a way that potential mass losses occur at these guide pins instead of the rest bars which are included in the effective mass upon loading.

3 TRANSFER FORCE TRANSDUCERS

In principle three constraints should be met to enable transfer transducers to be used for determining U_{bmc} :

- Use them only in the range starting from approx. 40 % of the nominal force,
- Use them only in one loading direction, i.e. compression or tension alternatively,
- Overlapping measuring ranges of different transducers.

Based on long years of experience, all the force transducers have been chosen from HBM's product range. Because of the demanding requirements as to their metrological characteristics, some of them were selected from the on-going production by analyzing test results. In addition, it was important that the transducers were sensitive to angular deviation. Therefore, reproducibility after rotation could be used as a measure for angular deviation. Transducers lacking this sensitivity have not been suitable. Thus, transfer transducers have been selected as shown in table 1.

The indication of the transducer's mV/V output signal had to be of highest possible resolution in order to see even minute deviations. Therefore, HBM's DMP40 digital high precision measuring instrument has been chosen. It is capable of dividing the nominal signal of 2 mV/V into 2 000 000 increments. PTB used their own instrument of the same type when performing their measurements. Results confirm that there is an excellent replaceability and that for traceability calibrations at the National Standards Institute only the transducer has to be shipped, but not the very sensitive electronical instrument.

Force ref. standard	Transducer type	Force direction	Measuring range
2.5 kN machine	Z3H2R / 100 N	Compression	50 .. 100 N
	Z3H3R / 200 N	Compression	50 .. 200 N
	Z30 / 500 N	Compression	150 .. 500 N
	Z30 / 1000 N	Compression	450 .. 1000 N
	Z3H3R / 2000 N	Compression	900 .. 2000 N
	C3H2-A / 5 kN	Compression	500 .. 2500 N
	Z3H3R / 500 N	Tension	200 .. 500 N
	Z3H2R / 1000 N	Tension	450 .. 1000 N
	Z3H3R / 2000 N	Tension	900 .. 2000 N
25 kN machine	Z30 / 1000 N	Compression	0.5 .. 1 kN
	C3H2-A / 5 kN	Compression	0.5 .. 2.5 kN 2 .. 5 kN
	Z3H2 / 10 kN	Compression	4.5 .. 10 kN
	Z4 / 20 kN	Compression	9 .. 20 kN
	C3H2 / 50 kN	Compression	18 .. 25 kN
	Z3H3 / 5 kN	Tension	2 .. 5 kN
	Z3H3 / 10 kN	Tension	4.5 .. 10 kN
	Z4A / 20 kN	Tension	9 .. 20 kN

Table 1: Transfer transducers used to qualify the force reference standard machines

4 MEASUREMENT PROCEDURE

If possible the transfer transducers have been measured in the new machine and verified in one of the existing DKD accredited machines. In the overlapping measuring range the two new machines were compared to each other, too. Based on data gained from this procedure, U_{bmc} was calculated and then all transducers and their data were sent to a verifying calibration to PTB at Brunswick.

The transducers were measured several times at longer time intervals in order to check the stability of the transducers and the machines as there were some minor corrections in the control system and the mechanics.

Each measurement series covered the following procedure:

- 0° position: increasing and decreasing loads using all available force steps within the measuring range according to table 1
- 90° position: only increasing loads using all available force steps
- 180° position: only increasing loads using all available force steps
- 270° position: only increasing loads using all available force steps

5 CALCULATION OF BEST MEASUREMENT CAPABILITY

The total measurement uncertainty is influenced by 3 major effect blocs:

- Force generating machines,
- Transfer transducer,
- Calibration procedure.

We then obtain from [4]:

$$F = m \cdot g_{loc} \cdot \left(1 - \frac{\rho_L}{\rho_m}\right) \cdot (1 - \Delta_{Traceability}) \quad (1)$$

with

$$\Delta_{\text{Traceability}} \approx \frac{\bar{F}_{\text{FCM}} \cdot (1 - \Delta_{\text{RelDev}}) \cdot (1 - \Delta_{\text{HysFCM}})}{\bar{F}_{\text{FSM}}} - 1 + \Delta_{\text{Drift_TraStd}} + \Delta_{\text{Realization}} \quad (2)$$

where

\bar{F}_{FCM} : mean value of forces indicated by the transfer transducer in the force calibration machine (FCM)

Fehler! Keine gültige Verknüpfung. : mean value of forces indicated in the force standard machine (FSM)

$\Delta_{\text{Drift_TraStd}}$: relative long-term drift of the transfer force transducer

$\Delta_{\text{Realization}}$: relative standard uncertainty of force realization at PTB

Δ_{HysFCM} : relative hysteresis of the FCM taking into account the hysteresis of the transfer transducer in the FSM

Δ_{RelDev} : relative deviation of the mean force values indicated between FCM and FSM

Refer to figure 2, for the relative deviations $\Delta_{\text{Traceability}}$ of the force generation between HBM and PTB using the 25 kN force calibration machine, for example. First of all, please note the excellent linearity, which could have been made worse by the machines at PTB or HBM or by the transducers.

U_{bmc} of both the 2.5 kN and the 25 kN force calibration machine then had been specified as follows:

- Compression: 0.005 %
- Tension: 0.008 %

Analyzing the normalized error E_n (see figure 3 for data of the 2.5 kN force calibration machine) shows that U_{bmc} has been specified in a conservative way. The distance to the required value of $E_n < 1$ is comfortable in order to allow little drifts without violating the accreditation limits. Repetitive measurements performed in the mean time confirmed a very good stability of the transducers as well as of the machines.

REFERENCES

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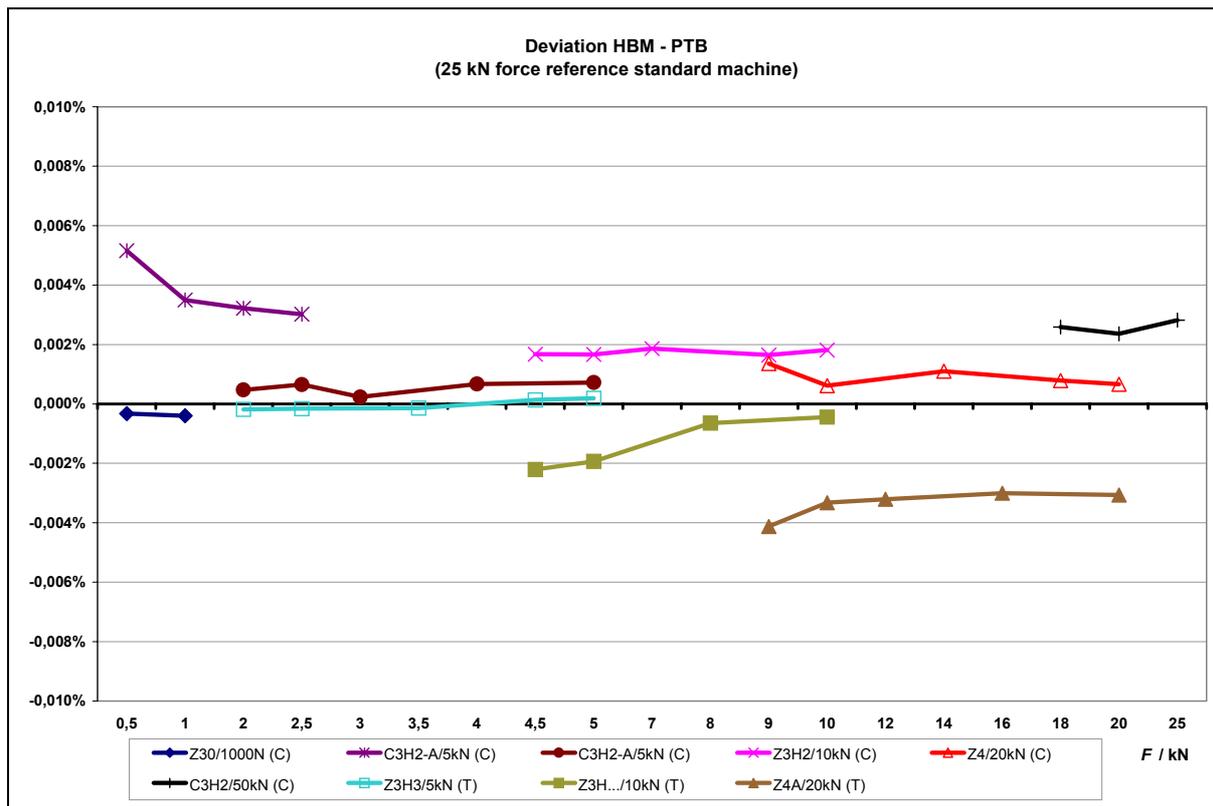


Figure 2: Relative deviation HBM – PTB (25 kN reference standard machine)

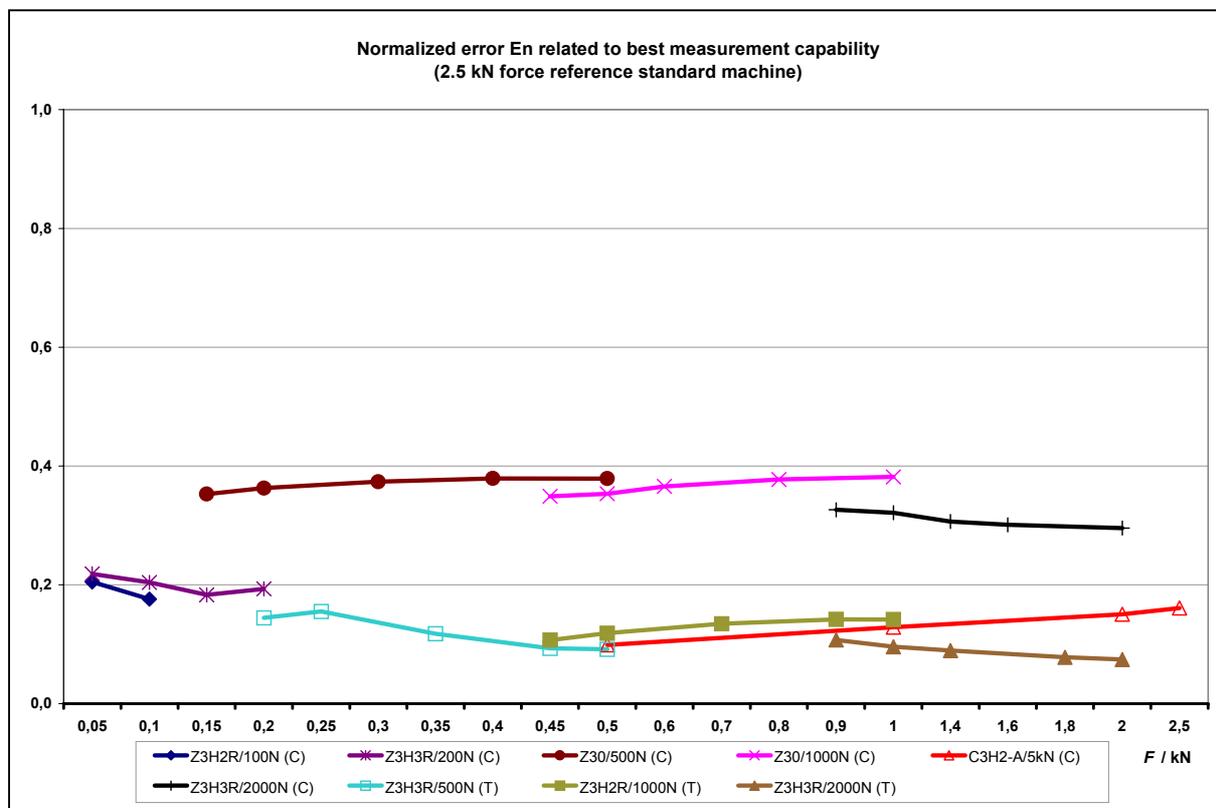


Figure 3: Normalized Error E_n related to best measurement capability (2.5 kN machine)