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# PRACTICAL APPLICATIONS OF AN ENHANCED UNCERTAINTY MODEL FOR BUILD-UP SYSTEMS

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Abstract: This paper describes the development of a new uncertainty model for build-up systems (BU systems) within the scope of the EMRP SIB 63 project, which deals with transfer standards in the meganewton range. The paper, in general, describes an optimized way of lowering uncertainties when using BU systems. We present the results of our investigation on how to optimize mechanical design for such systems, as well as a measurement procedure and a derived uncertainty model. Finally, the usefulness of this theory is demonstrated in three practical applications at NPL (London, UK), at the MPA (Braunschweig, Germany) and at FJIM (Fuzhou, China).

**Keywords:** Transfer standard, force measurement, build-up system

## 1. INTRODUCTION

Over the past several years, the use of force transducers in the upper MN range has increased remarkably. The reasons for this increase include safety issues pertinent to the field of civil engineering, such as bridge construction. Research on future technologies (such as wind energy) and on new materials requires capacities for investigation that the existing infrastructure cannot provide. Testing facilities with forces of up to 30 MN are already in service at various sites in Europe, and the capacity of such facilities is expected to increase to accommodate larger forces of up to 60 MN. These facilities will then have to be calibrated at regular intervals at a high level of precision and at low cost. The current metrological infrastructure does not match the future demand of industry. The use and development of force transfer standards in the uppermost MN range lacks scientific background. To address this shortcoming, a EURAMET research project (EMRP SIB 63) has been realized over the past few years.

One topic of this project is the investigation of build-up systems (BU systems) used as transfer standards. The project's results, which include an optimized design, a measurement procedure and a dedicated uncertainty model, are presented in this paper.

## 2. OPTIMIZED DESIGN OF BU SYSTEMS

BU systems have a wide variety of structures. As the EMRP project has shown, the influence of different structures on the measurement uncertainty is more significant than expected. In general, two types of force transducers and several different types of adaptation parts are used in today's commercially available BU systems. Force transducers can be divided into bending-ring transducers and strain-cylinder transducers. The adaptation parts generally consist of a ground plate and an upper force-introduction plate for the whole BU system. However, the transducers can be enhanced by means of special adaptation parts such as differently formed load cups, including pendulums either for the whole system or for the single transducers. In addition, within the scope of the EMRP project, a new, patented force-introduction plate was developed to minimize the generation of cross forces. This principle is shown in Figure 1.

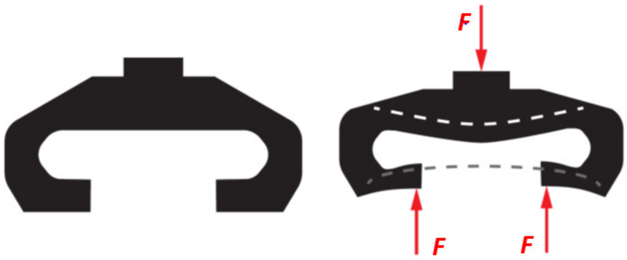



Figure 1: So-called "bending-neutral plate" used to disable cross forces by reducing sideways movements or any tilt angle at the force introduction point under load.

To date, in order to successfully meet their customers' demand, manufacturers have developed their own special theories and approaches. However, no database on the overall effect of adaptation parts has been available. Therefore, it was considered highly beneficial to gather the knowledge of several European NMIs, European industry collaborators and even international collaborators such as the Fujian Metrology Institute, with its unique 60 MN force standard machine (FSM).

Within the scope of the EMRP project, an extensive database of different BU systems was established. Over 20 different systems, including two 50 MN systems (Figure 2), and over 50 complete evaluations of more than 20 different machines ranging from 20 kN (20 kN FSM at PTB) to 60 MN (60 MN FSM at FJIM, China) were compiled in this database.

The project partners investigated typical effects of BU systems, such as the deviation between single-transducer and whole-system calibrations. This indication deviation is called $d_L$ below, and is the most important systematic uncertainty source to be corrected. However, other uncertainty influences must be taken into account as well.

Figure 2: The two 50 MN BU systems investigated (same scale).

Drawing conclusions from this BU system database, the following effects can be stated:

In general, the reproducibility of BU systems is better than the reproducibility of the single transducers. Typically, the uncertainty value is reduced to between 60 % and 80 %.

If pendulums are used – as shown in the middle sketch in Figure 3 – the reproducibility of BU systems is typically reduced to even lower values of less than 30 %. However, although this is an advantage, it has the disadvantage of increasing the hysteresis effect. In general, the advantage outweighs the disadvantage; only in the case of transducers with extremely good reproducibility should pendulums not be used.

Within the scope of the EMRP project, as stated above, a special so-called bending-neutral plate was developed and investigated that reduces bending forces to a minimum [1]. The indication deviation $d_L$ is reduced to a minimum, as are all other relevant uncertainty sources. This is shown in Figure 3, which contains some results that were measured by means of different adaptation parts on the small models used in the project. However, in principle, the general behaviour is similar to all other systems investigated.

Concerning hysteresis, Figure 3 also shows behaviour that can be generalized for the systems investigated. The number of contact surfaces between single adaptation parts increases the hysteresis effect – as seen before in the case of the pendulums. Only BU systems that have very stiff plates, a very compact design and no additional adaptation parts (such as pendulums) generally show the same hysteresis as the single transducers. However, as stated above, pendulums also enable a much lower reproducibility; especially for middle range systems with good surface quality. Here, the advantage outweighs the disadvantage – as shown in Figure 3. The first 50 MN BU system had a very special effect: the hysteresis of one of the transducers was the opposite of the hysteresis of the other transducers, and the mean value for the hysteresis of the whole system was lower than the hysteresis of the single transducers, which was quite high.

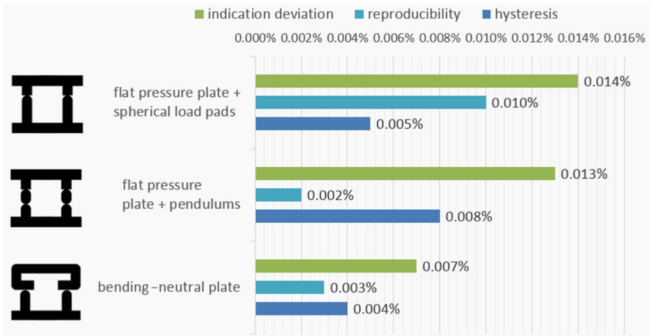



Figure 3: Influence of different adaptation parts on the uncertainty.

The second 50 MN BU system, shown on the right in Figure 2, was also designed to be used with pendulums. However, because the new transducer type has a very good compensation against cross forces, the reproducibility is lower than the uncertainty of PTB's 16.5 MN FSM with an expanded relative uncertainty of 0.01%. For this reason, the design was changed to conventional load cups in order to minimize hysteresis influences and maximize the mechanical stability.

The results of the investigations of all BU systems also demonstrate that it is important to have a very exactly defined and reproducible load introduction in the upper plate. Otherwise, the influence of the machine to be calibrated will have a stronger effect on the $d_L$, which sometimes results in a much higher uncertainty for the correction. For this reason, it is important to add a load button on the top of the system, although doing so entails a disadvantage: The point of the force introduction becomes quite small and there is a greater elastic deformation of the upper plate of the system (as if there were a complete surface to surface contact). This disadvantage was counteracted by developing the BU system described in [2]. This system provides a convex-concave contact area between the upper plate and the system's load cup in order to compensate for tilt angles and to have a well-defined force introduction area. In addition, this area is wider than before and has lower elastic deformation in the upper connection plate, even when compared with a plain plate-convex contact area, as numerical simulations show. For the 15 MN system, the diameters of both convex-concave areas are 800 mm and 1000 mm. Figure 4 shows a picture of this force introduction area.

The indication deviation $d_L$ strongly depends on the stiffness of the whole system, as demonstrated in several tests [1]. There is strong evidence that strain cylinders are more suitable than bending-ring transducers for use in BU systems for higher rated loads, as they can usually be assembled in a more compact arrangement. This is especially noticeable in the very compactly designed NPL and LNE BU systems, and in the second 50 MN BU system. The $d_L$ of the left BU system in Figure 2, which has wide bending rings, is 8 times higher at nominal load than the right system, which has cylinder-type transducers. However, bending-ring transducers, which generally have good reproducibility and can easily compensate cross forces, are suitable if the BU system is not much larger than the ground plate of the machine to be calibrated.

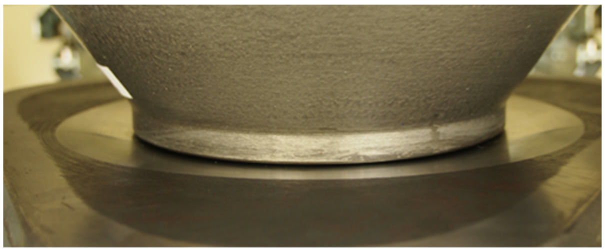


Figure 4: Picture of the convex-concave load introduction of the 15 MN BU system made by Ukrmetrteststandard

## 3. MEASUREMENT PROCEDURE AND UNCERTAINTIES

A new calibration procedure for the use of BU systems was developed within the scope of the EMRP project at the same time that an adapted uncertainty model was developed. In [3], an uncertainty model for BU systems is described; this model is a very detailed square root addition for a special case in the machine described in [3]. In typical applications of BU systems, higher elastic deformations cause uncertainties not previously described. In the EMRP SIB 63 project, a preliminary uncertainty model was used at the beginning of the project. This model defined the interaction between the force transducers and adaptation parts for parallel use as a systematic uncertainty that has to be calculated within the scope of the uncertainty model described in [4].

During the project, a more detailed approach was developed: The systematic error of $d_L$ was to be measured and corrected in such a way that only the uncertainty of the correction remained as an uncertainty source. However, the data evaluated in the database was doubtful in terms of the repeatability of $d_L$. The aim of the project was to collect data from different machines and to use a statistical approach to determine the indication deviation up to the nominal load of the BU system. Ultimately, however, the values of the different machines differed too much, due to the fact that the single transducers had to be evaluated in the lowest range of the machine to be calibrated. The higher uncertainty – in particular the nonlinearity – was added to the system behaviour of the BU system because the calculation for $d_L$ compares the single-transducer calibrations at lower forces with the full-system calibration in the upper force range. Thus, the statistical approach to the estimation of $d_L$ is not suitable. The indication deviation $d_L$ has to be determined within the FSM of a given NMI; however, this can only be done up to the nominal load of the machine. The factor for multiplication by the number of force transducers cannot be covered. The aim in this case is to extrapolate $d_L$ using a method similar to the extrapolation procedure for the calibration result of a conventional single force transducer. This procedure was also developed as part of the EMRP SIB 63 project [5] with markedly higher uncertainties and a more restricted extrapolation range than was possible with BU systems.

The procedure for the use of BU systems was created together with a safe uncertainty model based on existing standards. Here, the aim was to use the established ISO 376 standard [6] whenever possible. The procedure for the use of BU systems and the additional uncertainty model is explained below. Due to the complexity of this procedure, the system user is provided with an Excel file as a worksheet for the easy application of our theory. The worksheet includes all steps necessary to execute the procedure and calculates all relevant calibration results and associated uncertainties. It can be downloaded on the project's website [7].

First, the BU system itself has to be calibrated in the FSM. This is called "A-measurement" in the Excel file. The A-measurement begins by calibrating all single transducers separately. The ISO 376 uncertainties and the sensitivity polynomials for each transducer are calculated automatically in the Excel file. The worksheet allows up to five different force transducers to be used in the BU system. The A-measurement is used for two reasons: First, to calculate the sensitivity and the uncertainty of each transducer for later use in the BU system; and second, to calculate the $d_L$ in the FSM for later extrapolation. For five transducers, this could be a problem: as an example, using PTB's 50 MN BU system, the single transducers are calibrated up to 10 MN – but altogether, the whole system can only be calibrated up to 16.5 MN. Using the polynomials of these calibrations for the calculation of $d_L$ would result in a higher deviation because the transducers are used in a completely different load/time schedule. For this reason, a second A-measurement was added to the worksheet. For this second A-measurement, all single transducers in our example were calibrated up to 3.3 MN in ten steps that had the same time schedule as that of each transducer applied in the 16.5 MN BU system calibration in the FSM. This A-measurement is used to calculate $d_L$. The Excel file allows two A-measurements to be included: A1 in a partial range for the estimation of $d_L$ in the FSM; and A2 for the polynomials and uncertainties to be used later to calibrate the machine in the further C-measurement.

At this point, the uncertainties must be calculated. The indication deviation must be determined in the A-measurement from $m$ consecutive measurement series in different mounting positions. The result of each measurement series $j$ ($j = 1, \ldots, m$) and calibration force $F_{\mathrm{cal}}$ is a sum $F_{\mathrm{S},j}$ of $n$ forces $F_{i,j}$ ($i = 1, \ldots, n$) calculated from the indications of the $n$ single force transducers using the corresponding regression functions. The relative indication deviation $d_L$ can be calculated according to:

$$d_{\mathrm{L}} = \frac{1}{m}\sum_{j=1}^{m} d_{\mathrm{L},j}\ dL = \frac{1}{m}\sum_{j=1}^{m} \frac{F_{\mathrm{S},j} - F_{\mathrm{LS}}}{F_{\mathrm{LS}}} \qquad (1)$$

For the calculation of the calibration result, the mean values of the sum forces $F_{\mathrm{S},j}$ obtained in the measurement series in different mounting positions,

$$F_{\mathrm{S}} = \frac{1}{m}\sum_{j=1}^{m} F_{\mathrm{S},j} = \frac{1}{m}\sum_{j=1}^{m}\sum_{i=1}^{n} F_{i,j} \tag{2}$$

and

$$u(F_{\mathrm{S}}) = \sum_{i=1}^{n} u(F_{\mathrm{T},i}), \tag{3}$$

have to be calculated for each load step. For these values, a cubic (4) function describing the dependency of the sum force $F_{\mathrm{S}}$ on the acting calibration force $F_{\mathrm{cal}}$,

$$F_{\mathrm{S}}(F_{\mathrm{cal}}) = a_1 \cdot F_{\mathrm{cal}} + a_2 \cdot F_{\mathrm{cal}}^2 + a_3 \cdot F_{\mathrm{cal}}^3 + a_0, \tag{4}$$

has to be determined by applying suitable regression methods (for example, the least-squares method), with an additional contribution to the uncertainty existing due to regression. In reasonable cases, the constant value $a_0$ can be omitted. The calibration result (4) contains the indication deviation (1).

The uncertainty $u(d_{\mathrm{L}})$ of the indication deviation $d_{\mathrm{L}}$ can be calculated from

$$u^2(d_{\mathrm{L}}) = \left(\frac{1}{m \cdot F_{\mathrm{LS}}^2} \cdot \sum_{j=1}^{m}\sum_{i=1}^{n} F_{i,j}\right)^2 \cdot u^2(F_{\mathrm{LS}}) + \left(\frac{1}{m \cdot F_{\mathrm{LS}}}\right)^2 \cdot \sum_{j=1}^{m}\sum_{i=1}^{n} u^2(F_{i,j}) \tag{5}$$

At this point, the BU system is calibrated and the A-measurements are finished. As stated above, for a BU system that has four or five transducers and/or a large difference between the nominal load of the FSM and that of the machine to be calibrated, it could be suitable to use two measurement sets, with the single transducers for the determination of $d_{\mathrm{L}}$ and the sensitivity polynomials being used for the C-measurements.

The next step for a calibration of the machine to be calibrated or of the material test stand is the so-called B-measurement. This measurement must be performed on the machine to be calibrated and is used to check the plausibility of the procedure. The BU system and all single transducers are measured by means of the same procedure used previously for the A1-measurement in the FSM. The indication deviations $d_{\mathrm{L}}$ and the associated uncertainties have to be calculated for A1- and B-measurements. The two results have to be compared by means of a suitable criterion (for example, the $E_n$ value). If the criterion is fulfilled, the list of $d_{\mathrm{L}}$ values that are known in the partial range can be extrapolated.

The Excel worksheet calculates these $E_n$ values for the deviation of $d_{\mathrm{L}}$ between the FSM and the machine to be calibrated, and for the uncertainties of both machines. A typical result table is shown in Table 1.

The Excel file also contains an additional B2-measurement. This measurement uses the BU system's signals from the later C-measurement and calculates the $d_{\mathrm{L}}$ in such a way that it is completely measured in the machine to be calibrated. The results may show some large deviations especially in the lower range. It is also advisable to test the extrapolated $d_{\mathrm{L}}'$ at the nominal load of the machine to be calibrated. In the comparison described below between PTB's 16.5 MN FSM and the 60 MN FSM of FJIM, the extrapolated value $d_{\mathrm{L}}'$ for the indication deviation at PTB was 0.018 % with an expanded absolute uncertainty of 0.038%. The value measured in the 60 MN FSM was estimated to be 0.013%.

Table 1: Result table for the plausibility check of the worksheet.

| Load Step | | B-Indication deviation | | Calibration result | | A-Indication dev. | | |
|---|---|---|---|---|---|---|---|---|
| $F_{\mathrm{LS}}$ kN | $W(F_{\mathrm{LS}})$ % | $d_{\mathrm{L}}$ % | $U(d_{\mathrm{L}})$ % | $F_{\mathrm{S,int}}$ kN | $W(F_{\mathrm{S,int}})$ % | $d_{\mathrm{L}}$ % | $U(d_{\mathrm{L}})$ % | $E_{\mathrm{n}}$ |
| 3000 | 0.050% | 0.103% | 0.103% | 3003.88 | 0.070% | 0.025% | 0.022% | 0.74 |
| 4500 | 0.050% | 0.116% | 0.103% | 4505.29 | 0.066% | 0.028% | 0.022% | 0.84 |
| 6000 | 0.050% | 0.112% | 0.102% | 6006.35 | 0.064% | 0.028% | 0.022% | 0.80 |
| 7500 | 0.050% | 0.097% | 0.102% | 7507.02 | 0.061% | 0.026% | 0.022% | 0.69 |
| 9000 | 0.050% | 0.084% | 0.102% | 9007.31 | 0.060% | 0.025% | 0.022% | 0.57 |
| 10500 | 0.050% | 0.068% | 0.102% | 10507.19 | 0.058% | 0.022% | 0.022% | 0.44 |
| 12000 | 0.050% | 0.054% | 0.102% | 12006.65 | 0.057% | 0.018% | 0.022% | 0.35 |
| 13500 | 0.050% | 0.040% | 0.102% | 13505.69 | 0.055% | 0.020% | 0.022% | 0.19 |
| 15000 | 0.050% | 0.028% | 0.102% | 15004.28 | 0.055% | 0.017% | 0.022% | 0.11 |
| 16500 | 0.050% | 0.016% | 0.102% | 16502.42 | 0.054% | 0.016% | 0.022% | 0.00 |

The extrapolation of $d_{\mathrm{L}}$ uses the same principle as that developed for Task 1.6 of the EMRP SIB 63 project, as described in [5]. Several types of functions used in the extrapolation are compared and the most suitable function selected for use. Typically, this function is the extension from $d_{\mathrm{L}}$ to larger $d_{\mathrm{L}}'$ values following the tangent to the function in the end point of the partial range. To calculate the uncertainties of $d_{\mathrm{L}}'$, it is assumed that the uncertainty of $d_{\mathrm{L}}$ or $d_{\mathrm{L}}'$ will act within the extrapolation in the same manner as all other ISO 376 uncertainties, as it is calculated from them. Thus, the uncertainty in the extrapolation range can be safely assumed to be similar to the extrapolation of the uncertainties using single force transducers in accordance with the results of Task 1.6 of the EMRP SIB 63 project; this latter extrapolation has proven its effectiveness in over 40 cases.

In a future statistical approach, the $d_{\mathrm{L}}$ values will be calculated for the system in the machine calibrated after the correction takes place. This approach can be combined with the knowledge of the extrapolated $d_{\mathrm{L}}$ and can even reduce the uncertainty. To date, the safe estimation of the uncertainty has been the uncertainty source with the greatest effect on the final uncertainty for the calibration result. For the very good second 50 MN BU system, this value is in the range of 0.044%. If the full-range indication deviations $d_{\mathrm{L}}'$ are known, it is possible to calculate the theoretical calibration result in the extended range from

$$F_{\mathrm{cal}}' = \frac{1}{m(1 + \mathrm{d}_{\mathrm{L}}')}\sum_{j=1}^{m} F_{\mathrm{S},j}' = \frac{F_{\mathrm{S}}'}{(1 + d_{\mathrm{L}}')} \tag{6}$$

In order to apply equation (6), a linear or cubic function describing the dependency of the acting calibration force $F_{\mathrm{cal}}'$ on the sum force $F_{\mathrm{S}}'$ according to (4.1)

$$F_{\mathrm{cal}}'(F_S') = b_1 \cdot F_S' + b_2 \cdot F_S'^2 + b_3 \cdot F_S'^3 + b_0, \tag{7}$$

has to be calculated for these values. This is done by applying suitable regression methods, with an additional contribution to the uncertainty existing due to regression. For a large hysteresis, two functions can be given: one for incremental forces and another for decremental forces. From eq. 4.1, the uncertainty of $F'_{\mathrm{cal}}$ is obtained as

$$u_c^2(F'_{\mathrm{cal}}) = \left(\frac{u(F'_{\mathrm{S}})}{1+d'_{\mathrm{L}}}\right)^2 + \left(\frac{F'_{\mathrm{S}} \cdot u(d'_{\mathrm{L}})}{(1+d'_{\mathrm{L}})^2}\right)^2 \qquad (8)$$

The machine to be calibrated can then be adjusted using the correlation with the indication deviation of the machine $q$,

$$q = \Delta F(F'_S) = F_i(F'_S) - F'_{\mathrm{cal}}(F'_{\mathrm{S}}) \qquad (9)$$

The worksheet can also be used for a comparison of two FSMs. In this case, the deviation $q$ is the result of the comparison; equation (8) calculates the uncertainty for the result.

Several test calibrations were performed to verify this procedure, including a comparison measurement between NPL and PTB using up to 30 MN at NPL, and a comparison of up to 30 MN and 50 MN at FJIM, China.

Over the past few years, the Fujian Metrology Institute has built a 60 MN FSN using a force reference system. This machine was primarily calibrated by the NIM, Beijing, the national metrology institute of China.

The comparison in China was realized with PTB's new 30 MN/50 MN BU system. It is shown on the right in Figure 2. The system consists of five transducers classified as 00 according to ISO 376. The system has a very compact and stiff structure. Its five transducers and one set of plates can be used as a 3·10 MN or a 5·10 MN system. To this end, different forming plates for three and five transducers can be mounted on the ground plates and upper plate.

All measurements were performed strictly in accordance with the procedure described. For both machines, the same time schedule was used; the time schedule depended especially on the speed needed to replace one mass-stack combination with another in the hydraulic amplified machine at PTB. For the estimation of $d_{\mathrm{L}}$ at PTB´s 16.5 MN FSM, the single transducers were also calibrated with 3.3 MN, which is one-fifth of 16.5 MN, the maximum force that can be applied to the whole BU system.

The comparison was realized in three different force ranges. First, all single transducers were measured up to 10 MN. The mean value of the deviation between PTB and FJIM was used as the result. In the range from 9 MN to 30 MN, the deviation was measured using the 30 MN BU system. Finally, the 50 MN BU system was used for the range from 21 MN to 50 MN.

Figure 5 shows a picture of the 30 MN BU system mounted in the 60 MN FSM of FJIM. Compared with the picture of the 50 MN configuration of this BU system in Figure 6, its stiffness is due to its force introduction plates, which in this case are oversized. The highest stiffness results in even lower values for $d_{\mathrm{L}}$. Tables 2 and 3 present the results of the BU system worksheet for the 30 MN and 50 MN comparison. Because the indication deviation is about 0.01% higher (at 16.5 MN at PTB) in the 50 MN system, it makes no sense to build even larger and stiffer plates, as the $d_{\mathrm{L}}$ can be corrected. For transport and mounting, the size should be taken into account. The 50 MN BU system has a weight of 2600 kg and is 1345 mm high. Figure 6 demonstrates the size of the system compared with that of a person, Prof. Yao, Vice President of FJIM, who is responsible for the development of the 60 MN FSM of FJIM. In the picture, the BU system is standing on a platform where it is constructed before moving it into the machine. This platform is raised by the lower reference BU system and the hydraulic cylinder system installed underneath.

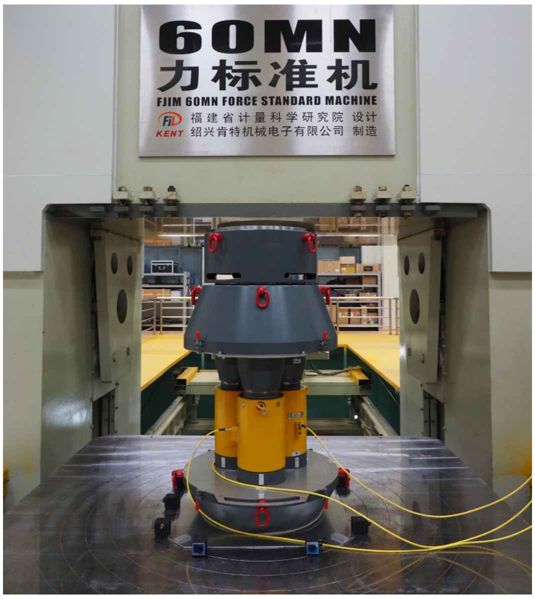



Figure 5: 60 MN force standard machine at the Fujian Metrology Institute, Fujian Province, China with the mounted 30 MN BU system of PTB.


Figure 6: 50 MN BU system and Prof. Yao in front of the 60 MN FSM showing the compact design of the 50 MN BU system.

Table 2: Results of the 30 MN comparison

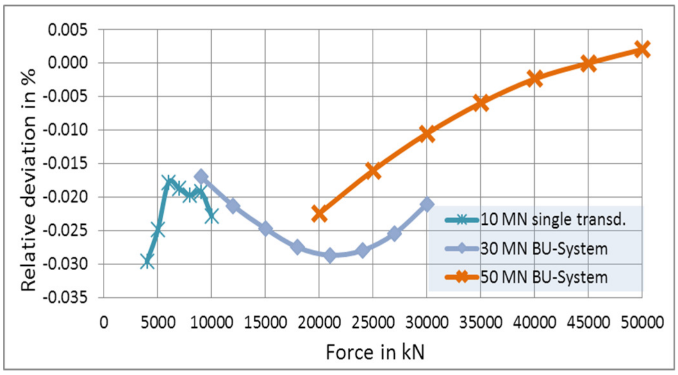
| Load Step | | Calibration result | | Extrapol. Indication deviation | | Correction of $F_S$' with | | Deviations | |
|---|---|---|---|---|---|---|---|---|---|
| $F_{LS}$ | $W(F_{LS})$ | $F_{S,int}$ | $W(F_{S,int})$ | | | Fcal' | W(Fcal') | $(F_S'-F_{LS})/F_{LS}$ | $(F_{cal}'-F_{LS})/F_{LS}$ |
| kN | % | kN | % | $d_L'$ / % | $U(d_L')$ / % | kN | % | % | % |
| 9000 | 0.050% | 9000.61 | 0.022% | 0.024% | 0.039% | 8998.47 | 0.045% | 0.007% | **-0.017%** |
| 12000 | 0.050% | 11999.82 | 0.021% | 0.020% | 0.039% | 11997.45 | 0.044% | -0.001% | **-0.021%** |
| 15000 | 0.050% | 14998.82 | 0.021% | 0.017% | 0.039% | 14996.30 | 0.044% | -0.008% | **-0.025%** |
| 18000 | 0.050% | 17997.77 | 0.021% | 0.015% | 0.039% | 17995.05 | 0.044% | -0.012% | **-0.027%** |
| 21000 | 0.050% | 20996.84 | 0.020% | 0.014% | 0.039% | 20993.99 | 0.044% | -0.015% | **-0.029%** |
| 24000 | 0.050% | 23996.19 | 0.020% | 0.012% | 0.038% | 23993.29 | 0.044% | -0.016% | **-0.028%** |
| 27000 | 0.050% | 26995.98 | 0.020% | 0.011% | 0.038% | 26993.14 | 0.043% | -0.015% | **-0.025%** |
| 30000 | 0.050% | 29996.40 | 0.021% | 0.009% | 0.038% | 29993.69 | 0.043% | -0.012% | **-0.021%** |

Table 3: Results of the 50 MN comparison

| Load Step | | Calibration result | | Extrapol. Indication deviation | | Correction of $F_S$' with | | Deviations | |
|---|---|---|---|---|---|---|---|---|---|
| $F_{LS}$ | $W(F_{LS})$ | $F_{S,int}$ | $W(F_{S,int})$ | | | Fcal' | W(Fcal') | $(F_S'-F_{LS})/F_{LS}$ | $(F_{cal}'-F_{LS})/F_{LS}$ |
| kN | % | kN | % | $d_L'$ / % | $U(d_L')$ / % | kN | % | % | % |
| 20000 | 0.050% | 20000.47 | 0.018% | 0.025% | 0.046% | 19995.52 | 0.050% | 0.002% | **-0.022%** |
| 25000 | 0.050% | 25001.79 | 0.018% | 0.023% | 0.046% | 24996.00 | 0.049% | 0.007% | **-0.016%** |
| 30000 | 0.050% | 30003.30 | 0.018% | 0.022% | 0.046% | 29996.85 | 0.049% | 0.011% | **-0.011%** |
| 35000 | 0.050% | 35004.88 | 0.018% | 0.020% | 0.046% | 34997.92 | 0.049% | 0.014% | **-0.006%** |
| 40000 | 0.050% | 40006.36 | 0.018% | 0.018% | 0.046% | 39999.06 | 0.049% | 0.016% | **-0.002%** |
| 45000 | 0.050% | 45007.62 | 0.018% | 0.017% | 0.045% | 45000.14 | 0.049% | 0.017% | **0.000%** |
| 50000 | 0.050% | 50008.51 | 0.018% | 0.015% | 0.045% | 50001.02 | 0.048% | 0.017% | **0.002%** |

Tables 2 and 3 show the very good results of the comparison. The gap between the different measurement ranges is very small, much smaller than with any other BU system, especially the first 50 MN BU system. The results clearly indicate that it is possible to calibrate a machine up to 50 MN with an expanded relative uncertainty of lower than 0.05%. The greatest uncertainty source is the extrapolation of the indication deviation; in future, it is likely that this will be reduced by means of additional statistical methods after more is known about the machine.

Figure 7: Final result of the comparison.




## 4. CONCLUSIONS

Within the scope of the EMRP SIB 63 project, a procedure for the use of the BU system and a safe uncertainty model were developed. Constructional details were investigated and desireable characteristics of an optimized design were determined. After the project, a second 50 MN BU system was realized with an improved design. This system was used for a comparison between PTB's 16.5 MN hydraulic amplified FSM and the 60 MN FSM at FJIM.

As we gain knowledge about the BU system, we will be able to reduce uncertainties, allowing us to devise a statistical approach to the indication deviation.

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