FINAL PUBLISHABLE JRP REPORT

JRP-Contract number	SIB63
JRP short name	Force
JRP full title	Force traceability within the meganewton range
Version numbers of latest contracted Annex Ia and Annex Ib against which the assessment will be made	Annex Ia: V1.2 Annex Ib: V1.01
Period covered (dates)	From 1st July 2013 To 30th June 2016
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Report Status: PU Public

Issued: August 2016

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

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1 Executive Summary

Introduction

This project has provided for the first time traceability of force measurements up to 50 MN to meet the increasing demand from large-scale industrial and civil-engineering applications. Moreover, the project has improved transfer standards, accuracies for mechanical testing and estimates of measurement uncertainties.

The Problem

In Europe, there are many industrial applications for force measurements. An increasing demand has arisen for material testing caused by larger test objects from the developing wind industry and from new high-performance materials. This leads to a request for measurement capabilities at nominal forces above 1 MN, up to 30 MN and even greater. The problem is that uncertainties on these measurements even at the low end of the range are not well defined and for higher forces currently only one National Metrology Institute (NMI) in Europe, the National Physical Laboratory (NPL, UK) can calibrate at forces up to 30 MN and then only with a relative expanded (k = 2) uncertainty of W = 0.15 %, at which no classification according to required industry standards is possible and fundamental questions regarding the uncertainty evaluation of such systems remain. For higher forces to 50 MN there are also no standards or guidelines available for the uncertainty calculation and as such there is no traceability in Europe for forces between 30 MN and 50 MN. Therefore existing metrological capabilities do not fully meet the current demand of industry.

The Solution

A solution to the described problem is the use of build-up (BU) systems to bridge the gap from existing force standard machines to the demands of industry. However, the method of calibrating several single force transducers and using them in one combined BU system entails several other issues, e.g. the determination of a measurement uncertainty and a new calibration procedure for such systems. Various tests and calibrations have been performed within this project to address and solve all these questions.

Furthermore, the option of extrapolating calibration results has been investigated. Additional influences occurring during force measurements especially in testing facilities have also been researched and quantified.

Impact

Applications of force measurements in the MN range include force calibration machines, material testing machines, monitoring of civil engineering structures during their lifetime, testing of mechanical components for e.g. wind turbines or aeroplanes. Having extended the traceable force range as well as improving the accuracy and precision of measurements across the 1-50 MN range, the following impact can be achieved:

- More precise measurements in material testing machines improves on the one hand the safety of all people using infrastructure or housing etc. and makes on the other hand construction more economical.
- Very precise monitoring of civil engineering constructions can prolong the usable lifetime of structures and thus enable more adaptable investing in infrastructure (e.g. bridges). Moreover, a critical load state can be detected more precisely.
- Traceable testing of mechanical components improves the design and development of new technology and therefore it is important for an economical process. Furthermore, it also ensures a higher safety level.

An example of an early impact that has been made directly during the project runtime is the calibration of a 30 MN material testing machine at MPA in Braunschweig, Germany. Using PTB's 3x10 MN BU system, a calibration of the machine was performed and a measurement uncertainty estimation was established. The results were verified using a 27 MN single tension transducer calibrated in PTB's 16.5 MN force standard machine.

Additionally, mathematical models, calibration procedures, and a large database of measurement data is now available for contribution to future revisions of relevant ISO standards and EURAMET technical guides.

2 Project context, rationale and objectives

In the large-scale industrial and civil-engineering sectors European companies rely on a constructive and productive design and development process for new technology to work economically and to compete successfully on an international field. This process also involves extensive testing of prototypes as well as material and component tests for licensing as well as for the market. One of the mechanical loads that is either applied to the test object or monitored during tests or in action is the axial force. Several industry sectors in Europe require very precise force measurements of up to 30 MN or even 50 MN. These include material testing and structure monitoring, in novel applications for the offshore and wind industry as well as the aerospace industry. An overview of the special needs is given in the following:

- Material testing is important for the certification of new structural elements. More and more components need forces in the MN range (up to 30 MN) for the testing procedure e.g. steel cables for cable-stayed bridges or pre-stressed concrete elements.
- Monitoring of structures such as bridges can prolong the usable lifetime and increase the safety. Force transducers in the MN range are needed for the monitoring of bridge bearings.
- Mechanical components for wind power stations, especially for offshore purposes, are increasing in size. At the same time the economical side of these facilities gets more important. Extensive testing of prototypes is therefore essential. Axial forces in the MN range are used in all large European nacelle testing facilities. Moreover, large forces are also used for the testing of wind power foundations.

In all listed branches a still-rising demand for traceable force calibrations can be observed.

In contrast to the needs of industry are the calibration capabilities of European NMIs. The force standard machine with the highest nominal forces, that also has a Calibration and Measurement Capability (CMC) entry, is at NPL and has a maximum force of 30 MN with a relative expanded (k = 2) uncertainty of W = 0.15 %. The most precise European force standard machine with a nominal maximum force over 10 MN is PTB's 16.5 MN machine with a relative expanded (k = 2) uncertainty of W = 0.01 %. Neither machine fully meets the current demand of the industry, not to mention any future increase in demand.

Due to the discrepancies between industrial need and metrological capabilities, solutions to bridge the gap have been found and are used. The two most commonly-used ones are also the two most promising ones:

- The utilisation of a BU system allows the calibration of several single transducers which are connected by adaptation/loading plates to act as one transducer which can be used to extend the traceable force range. This method is for example used at Laboratoire National de métrologie et d'Essais (LNE) in Paris, France.
- The extrapolation of calibration results is often used for transducers employed in testing laboratories when a full-range calibration is not possible. Basically, the part-range calibration of the transducer is extended to the range needed in the laboratory.

However, both approaches are missing standardisation or official guidelines as well as a scientifically based measurement uncertainty budget.

Apart from the problem of missing traceability, the influences of effects such as parasitical loads, different time-loading schemes or non-air-conditioned environmental conditions on force measurements are not thoroughly researched. These effects are quite commonly found in testing laboratories but sometimes also in calibration laboratories. Especially with the increasing space requirements for large transducers in the MN range, some very controlled laboratory conditions cannot be fulfilled. Furthermore, the demand for multi-component transducers recording several loads (e.g. axial force and torque) is also rising. Traceability for these transducers for all components cannot be ensured at the moment.

To summarise the project rationale: the capabilities for traceable calibration of the unit force in Europe are not sufficient when compared to the industrial need. Methods and technologies used to bridge the gap are neither standardised nor equipped with an uncertainty budget. Moreover, additional effects (mechanical, environmental) have to be investigated in more detail. From this context, several specific starting points for further research can be formulated: extend the traceability of the unit force further into the MN range, establish guidelines and uncertainty budgets for BU systems and extrapolation methods and investigate the effect of additional influences, of which multi-component loading and time-dependent effects are the most complex ones.

From the above listed starting points, five scientific and technical **objectives** have been derived:

1. To extend the range of primary force standards to cover the range from 1 MN to 50 MN, with uncertainties of the order of 0.002 % up to 2 MN, 0.01 % up to 15 MN, 0.05 % up to 30 MN and 0.1 % up to 50 MN.
2. To develop improved transfer standards for forces up to 50 MN. The effect on the overall uncertainty of parasitic components and variations in loading procedure will be evaluated, for example in the case of continuous or non-axial loading.
3. To develop methods for the determination of uncertainty for a high force range BU system, rather than addressing the calibration of single transducers.
4. To develop methods to extrapolate calibration results for values higher than 15 MN force, including evaluation of the associated uncertainties.
5. To develop new procedures and EURAMET technical guides for users in industrial calibration laboratories and testing laboratories on the use of high force measurement devices, the methods of uncertainty calculation and on the improvements in the dissemination of force from primary standards to calibration services and testing laboratories.

3 Research results

These results are described on an objective by objective basis with a clear account of how the research was undertaken and how the research contributed to achieving the scientific and technical objectives.

3.1 Objective 1: Primary force standards up to 50 MN

BU systems are used for the multiplication of primary force standards. These consist of at least three force transducers which are connected by a common force introduction part. Due to the influences induced by the adaptation parts, the sum of sensitivities of the single transducers differs from the total signal when used as a BU system. Small elastic deformations within the system generate cross forces and bending moments. Force introduction effects due to surface quality even using the best production finish are well-known for single transducers and are multiplied in a BU system by the number of contact surfaces. All of this results in a sum force deviation which is essential for all developments and which will be called **indication deviation d_L**. The indication deviation strongly depends on the different construction principles of the force transducers and adaptation parts.

Before the project was started, there was no comprehensive database available about the properties of BU systems. It was well-known that an increase in stiffness reduces the indication deviation d_L and thereby the measurement uncertainty. Therefore, increasingly large force introduction plates were built and used, suitable for the specific force standard machines. Some NMIs developed and improved their own procedures on how to calibrate their own machines. But the extended range up to 50 MN, or even more in future, calls for a more compact design, regarding the specification and installation conditions of force calibration machines or material testing facilities in industry. In these new designs, the indication deviation d_L cannot be neglected, especially if so-called bending ring transducers are used which have a larger diameter than column type transducers.

In the following, a description of the set-up of a database with several different BU systems is described (Section 3.1.1) as well as the results of a new calibration procedure which was tested with a 5x10 MN BU system (Section 3.1.2).

3.1.1 Method of investigation and build-up system database

To gain knowledge about the effects generated by transducers and adaptation parts, several BU systems of the JRP-Partners were first investigated in the force standard machines (FSMs) of the participants. Therefore PTB, BAM, NPL, VTT, LNE, INRIM and MG have investigated the deviation between single transducer and whole system calibration using their BU system. The results of these investigations have been summarised in a database which is available as an Excel-file in the member's area of the projects website. Some of the BU systems were investigated several times. This was done because in many cases, poor stability of the measurements of the devices was observed and it was the aim to get more knowledge about the long-term stability of d_L.

For the investigations, calibrations according to the ISO 376 standard in the full and partial range have been performed. ISO 376 was chosen because the typically-desired ten load steps enable a safe estimation of a polynomial describing the transducer sensitivity. In addition, this standard provides an established method to calculate uncertainties of the calibration of force measurement devices. The aim of the investigations was to get knowledge of the relationship and ratio of typical uncertainty components as named in ISO 376 (w_1 - w_8, Annex C of ISO 376:2011) when the transducers are calibrated alone or combined in the BU system. All these results were collected in a database, called the "BUS chronicle", which can be downloaded from the project website. It contains a picture (if available) of the BU system, a description of the BU system type and adaptation parts, and the indication deviation d_L of all performed measurements in a diagram. Furthermore, repeatability and reproducibility of the single transducers as well as the whole BU system are presented.

As mentioned before, the systems have been investigated by calibrating the single transducers and the whole system in an FSM. To minimise or even prevent the effect of interpolation errors, the same load steps were used for each transducer in the single and combined calibrations. In several cases, this was not possible due to machine capabilities or machine types e.g. hydraulic machines. For these cases, an evaluation of the measurement data was based on the use of polynomials for all single series of the ISO 376 measurements. An Excel-file with a template of this evaluation file for BU systems can also be downloaded from the website of the project.

3.1.2 Test of calibration methods using the 50 MN BU system

A new calibration procedure for BU systems was developed in the project (see Section 3.5.1 for more details). To develop and verify this procedure, several test calibrations have been performed. The latest calibration was a comparison measurement between NPL and PTB using the 50 MN BU system. At NPL, a measurement of the overall system was carried out to 30 MN alongside individual calibrations of the force transducers. The 30 MN FSM of NPL was the machine with the highest nominal load available within this project. At PTB, the individual transducers and the BU system were calibrated in the 16.5 MN FSM.

The indication deviation of the BU system (Figure 1) determined at NPL and PTB shows an offset. The measured deviation is very low and quite similar to the deviation measured with the single transducers. Therefore, it is assumed that it is caused by the machines and not by the BU system.

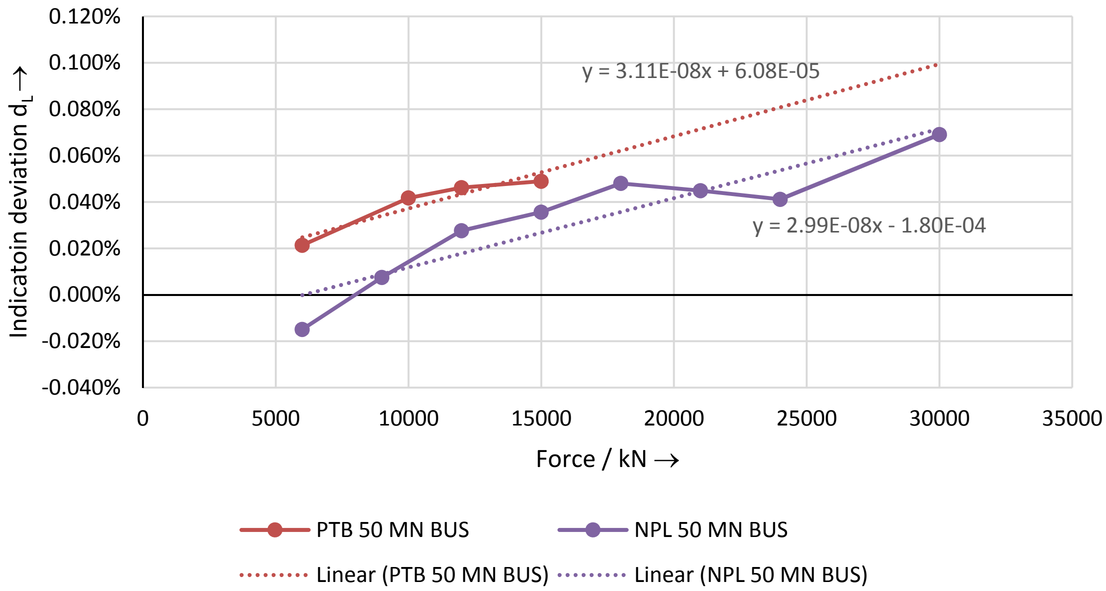

Figure 1: Indication deviation of 50 MN BU system in PTBs 16.5 MN FSM and NPLs 30 MN FSM

It was observed that the hysteresis increases when transducers are combined in a BU system, due to friction between the additional contact surfaces. The transducers also show an increasing hysteresis above 8 MN in the NPL measurements compared to the PTB measurements. This deviation can be explained with the different time loading characteristic of both machines.

Figure 2 presents the results of the comparison up to 30 MN showing the measured deviation between the force machines at PTB and NPL using the mean value of the five single transducers and the results obtained with the 30 MN and 50 MN BU System. Based on the uncertainty model described in Objective 4, the measurement uncertainty of the BU system is calculated. The relative expanded (k=2) measurement uncertainty is plotted as error bars in the figure. It is 0.06 % at 30 MN. Finally, it can be stated that the deviation between NPL and PTB measured with the two BU systems and the single transducers is in good agreement.

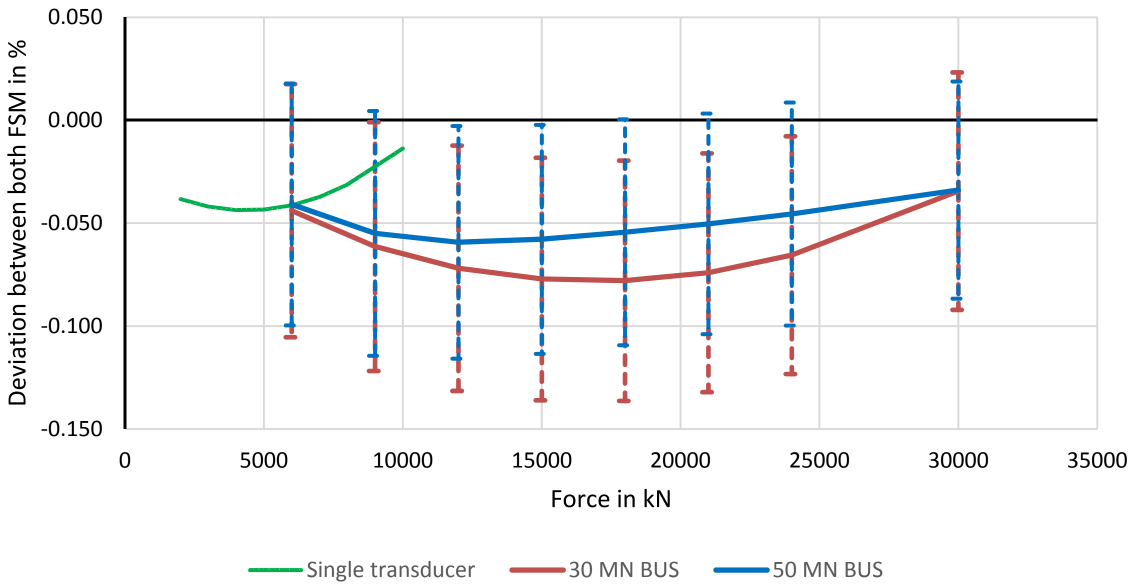

Figure 2: Deviation between NPL and PTB measured with single transducer, 30 MN and 50 MN BU system

Summary of objective 1:

Measurements with BU systems were performed. A wide range of different systems and load ranges was investigated as almost all partners gave input. The resulting data base is, therefore, a direct product of the collaborative approach. Based on the findings of the BU system measurements, a calibration procedure for BU systems was established and tested. Thus, the traceable measurement range was successfully extended to 50 MN. Measurement uncertainties of 0.06 % were achieved for the range of 15 MN to 50 MN. For the range of 15 MN to 30 MN, this is 0.01 % higher than the targeted 0.05 %. This deviation is mostly caused by the single force transducers in the 30 MN BU systems which did not match the aspired quality. Furthermore, the proposed calibration procedure was successfully applied. This procedure should be verified with further measurements and could be a basis for a calibration guide.

3.2 Objective 2: Improved transfer standards for forces up to 50 MN

The second objective of this project was to find ways to improve force transfer standards up to 50 MN. Three different approaches were used for this: finite element method (FEM)-simulation of existing BU systems including transducers and adaptation parts (Section 3.2.1 – under supervision of PTB); development of a multi-component BU system to detect parasitic loads (Section 3.2.2 – under supervision of INRIM) and an in-depth analysis of time-loading effects on the force measurement (Section 3.2.3 – under supervision of LNE).

3.2.1 Improvement of build-up systems

The design and construction of BU systems can be widely varied. They consist of force transducers, which may be bending-ring transducers, strain cylinder transducers etc, and the adaptation parts normally include a ground plate and a force introduction plate for the whole BU system but can also include pendulums for the whole system and/or the single transducers and the introduction plate can be shaped differently. Several examples of possible construction layouts are shown in Figure 3. Furthermore, the usage of conical spheres and ball cups as additional elements for force introduction are common.

When analysing the database "BUS chronicle" (see Section 3.1.1), it was found that a compact layout such as strain cylinder type transducers of a BU System leads to low hysteresis as well as good reproducibility values. This is demonstrated particularly well by the very tightly designed NPL and LNE BU systems. Bending-ring transducers are suitable if the size of the BU-system is not much bigger than the ground plate of the machine. This type of transducer certainly shows very good performance in the lower or middle force range but, with the state of the art, it can be assumed that 5 MN might be the border where strain cylinder transducers become more advantageous. The product lists of most manufacturers support this assumption. In the highest force range it can be clearly seen that the strategy of the most compact design should be preferred against the strategy of the best transducer irrespective of size. Furthermore the usage of decoupling elements such as pendulums or different load cups has a strong influence on the reproducibility and the indication deviation d_L. The pendulums reduce the cross forces generated by elastic deformations of the upper compression plates.

The use of pendulums leads to much lower reproducibility values of the BU system compared to the results of the single transducers. Also a linear shift of the indication deviation can be seen in the results, such an example being the 3 MN HBM BU18 system. Using the pendulums enlarges d_L but reduces the reproducibility. This effect was found for all investigated systems, not only the HBM BU 18, even if additional conical spheres or ball cups were used on the top of the system. The effect of these additional parts was in the range of the measurement uncertainty.

But the use of pendulums is not the only option for reducing cross forces. Another option was realised with a 15 MN BU-system which was developed in cooperation between PTB and Ukrmetrteststandard [1]. The deformation of both compression plates and the always ball-formed contact areas enable nearly the same sideways movement of the upper ball cups and the heads of the transducers at their contact areas. With this system, also a strong reduction of the reproducibility error of the measurement signal can be obtained from a range of 0.04% to values lower than 0.02% at nominal load.

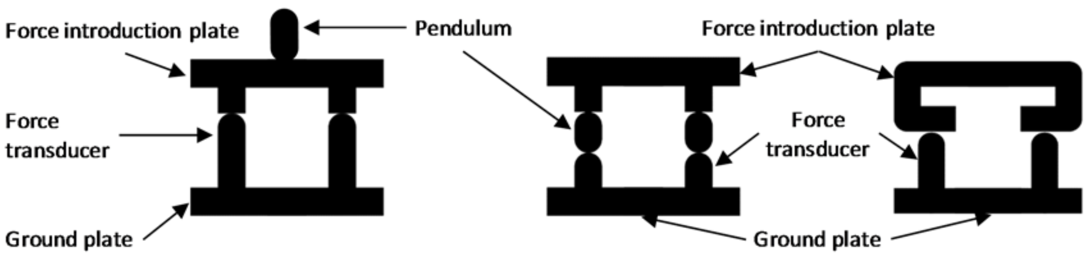

Figure 3: Examples of possible BU system layouts

The principle of reducing the cross forces was brought to an optimised design using finite element analysis. This optimised design, which is depicted in the right of Figure 3 and is called "neutral plate", was the result of a complex study applying the finite element method. The device has then been manufactured with an all-new outline of the upper force introduction for a 3x10 kN system which can also be used as a 5x10 kN system to be investigated as a model in a deadweight machine and to be compared with conventional force introduction designs. The purpose of these all-new adaptation parts is to reduce the indication deviation by means of a specially designed deformation behaviour of the loading plate. Figure 4 shows the simulation result of this solution. The angle of attack of the load introduction point on the transducer tends towards zero.

The results of the calibration of the single transducers and the whole BU system are presented in Table 1. The calibrations were performed in PTBs 20 kN FSM as it has a low measurement uncertainty as well as the option of calibrating the 10 kN transducers and the 30 kN BU system. The right column in Table 1 shows the reproducibility values gathered from the same system by the use of a usual, flat loading plate. The reproducibility increases approximately by a factor of four.

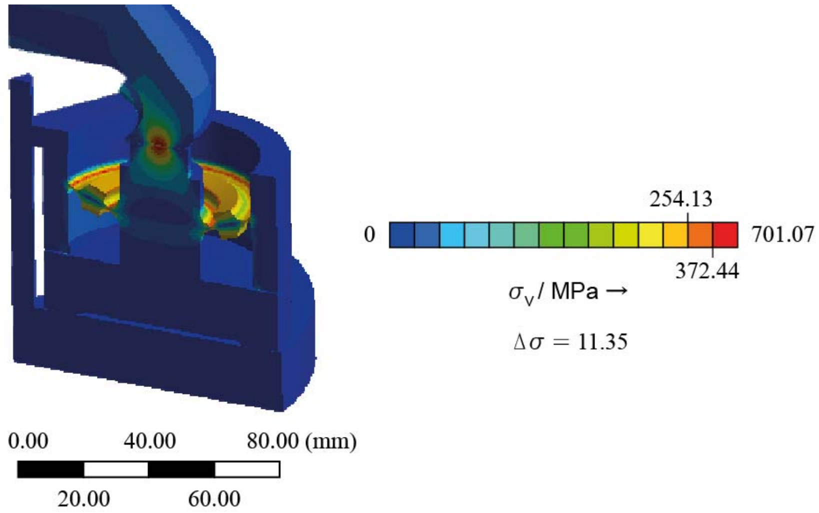

Figure 4: 3x10 kN BU system, numerical simulation v. Mises stresses

Table 1: Reproducibility and reversibility of the 30 kN BU system investigated in PTBs 20 kN FSM

Force in kN	Whole system		Single transducer (Force/3)		Ratio		Whole system
	Reproducibility	Hysteresis	Reproducibility	Hysteresis	Repr.	Hyst.	Reproducibility, usual plate
6	0.000%	0.003%	0.002%	0.015%	<0.20	0.20	0.004%
12	0.000%	0.003%	0.002%	0.018%	<0.20	0.17	0.004%
18	0.001%	0.001%	0.001%	0.014%	1.00	0.07	0.004%
20	0.001%	-	0.001%	-	1.00	-	0.004%

Due to the decrease of the generation of cross forces using the “neutral loading plate”, a strong decrease of the indication deviation can be seen with increasing force. Since the values of this deviation from all six series according to an ISO 376 calibration come closer together, the standard deviation also decreases, which is shown by the error indicators in Figure 5.

Concluding the investigations to improve BU systems, recommendations for the setup of BU systems would be as follows:

- Using strain cylinders that are applied with bending moment bridges, which are assembled on as stiff as possible base plates will lead to an optimized load flow into the ground bearing, also the generation of cross forces can be estimated qualitatively.
- Additional constructional elements should be used to reduce cross forces such as:
    - Assembling pendulums reduce the reproducibility and so the measurement uncertainty as detailed in Section 3.3
    - As a load plate, a very strong and stiff (but thereby heavy) plate shall be used or a lightweight neutral loading plate can be assembled.
    - Especially for the use in material testing facilities with not always optimal parallel orientation of the load cup there should be some kind of ball cup to prevent bending moments. But as the example realised in the BU system of [1], a double ball formed shape or a very big diameter

of the ball form allows for a wider surface of the force introduction, resulting in lower deformations of the upper load plate.

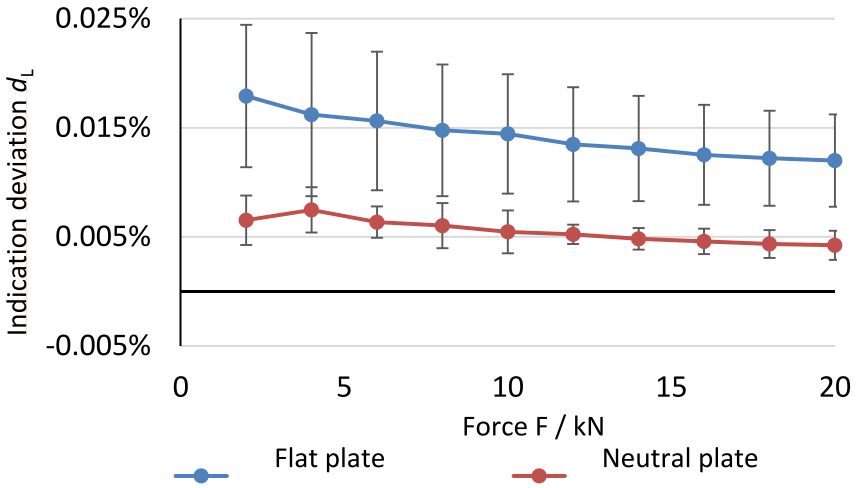

Figure 5: Relative indication deviation using different loading plates

3.2.2 Multi-component transducers

The need to have traceable force calibration machines with high capacity, leads to the realisation of BU systems. Several uniaxial force transducers (UFTs) that can be calibrated directly by primary force standard machines compose such systems. Generally, a BU system is composed by three UFTs in the same direction, therefore allowing the measurement of a force that has three times the capacity of the single UFT. If it is required to reach higher loads starting from the same UFT capacity, to maintain an isostatic condition, it is necessary to create a more complex structure by adding additional UFTs in order to increase the total capacity. Another possibility is to use a hexapod structure that uses six UFTs, reaching five times the capacity of a single UFT (considering the mounting angles), as already developed at INRIM. This structure also has the advantage of allowing the measurements of all six components (multi-component force transducer, MFT), i.e. not only the principal axial force F_z, but also all force and moment vectors (transversal, F_x and F_y), and three moment components, (tilting, M_x and M_y, and torsion, M_z). The main aim is to measure the force in a given direction, in our case F_z, therefore the accuracy of all other force and moment components is not at the same metrological level. Nevertheless, the information given by the measurement of all the components can be used to get a better accuracy of the F_z measurements.

The aims of the project are mainly to enhance the internal traceability of primary force laboratories using the hexapod-shaped multi-component (HSM)-BU system as reference force transducer (the present realisation extends the range up to 5 MN, but similar designs can be applied to reach higher capacities) and, since this type of BU system is a multi-component transducer, to minimize the parasitical component of the force applied by the FSM during the calibration of uniaxial force transducers.

A hexapod-shaped structure is considered a structure having six feet; the ideal structure consists of three pairs of each direction, each one of them creating a triangle. A HSM-BU system, like every BU system, is composed of several UFTs; in a HSM-BU system with hexapod geometry there are six UFTs, fixed in pairs, to recreate a hexapod structure, realising a pseudo-isostatic structure. The system geometry of the new 5 MN HSM-BU system realised at INRIM (Figure 6) has been designed to work with a nominal force value of 5 MN, using 6 UFTs with maximum load of 1 MN, in order to be calibrated using the 1 MN deadweight FSM at INRIM. Another peculiarity of the HSM-BU system, is that its UFTs work in tension, and not in compression as in a generic BU system. So it was necessary to create an inversion frame, in order to put the UFTs in tension. The load, applied on the upper loading pad (1A), is transferred by three columns (2A) to the lower plate (3A), where are fixed the lower clamping heads of the UFTs. The upper clamping heads of the UFTs are fixed to the upper plate (1B) which, through three columns (2B), is supported by the base (3B) (see Figure 7).

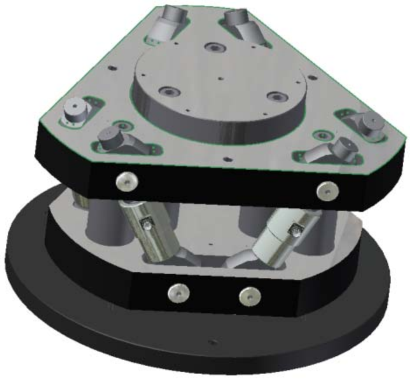

Figure 6: The new 5 MN HSM-BU system realized at INRIM

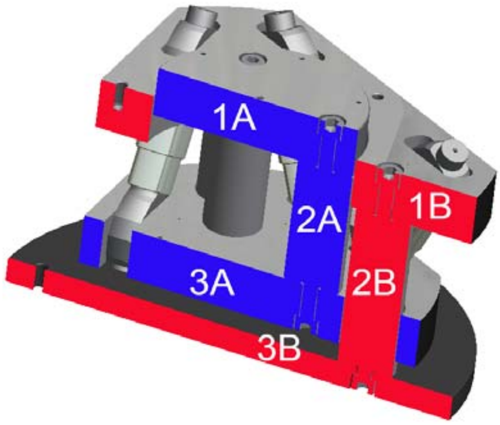

Figure 7: Cross section of the new 5 MN HSM-BU system showing the scheme of the inversion frame

A further difference is the inclination of the UFTs with respect to the horizontal plane, which leads to the necessity of re-orienting the single UFT continually in order to avoid parasitical components and frictional effects. This re-orientation movement could have been obtained using a couple of elastic hinges at the two ends of every UFT but, due to dimensional limitations, the use of elastic hinges was not possible, and spherical joints were used instead (Figure 8). The force is transmitted to each UFT through plugs connecting the plate and the spherical joints.

a) b)

Uniaxial force transducer, *Spherical joint*

Figure 8: Uniaxial force transducer used in the new 5 MN HSM-BU system and spherical joint

To ensure traceable measurements in this type of BU system, the force calibration of UFTs is not sufficient, since the output measurements also depend on the geometry of the hexapod structure. Therefore, it has become necessary to consider the geometry and its possible variations described by the geometrical tolerances and elastic distortion under load. In fact, the simulation of the HSM-BU system behaviours under load had shown that it is necessary to estimate the variation of the functional angle for each UFT (Figure 9). It can be a source of a significant error and needs to be taken into account in the calculation process.

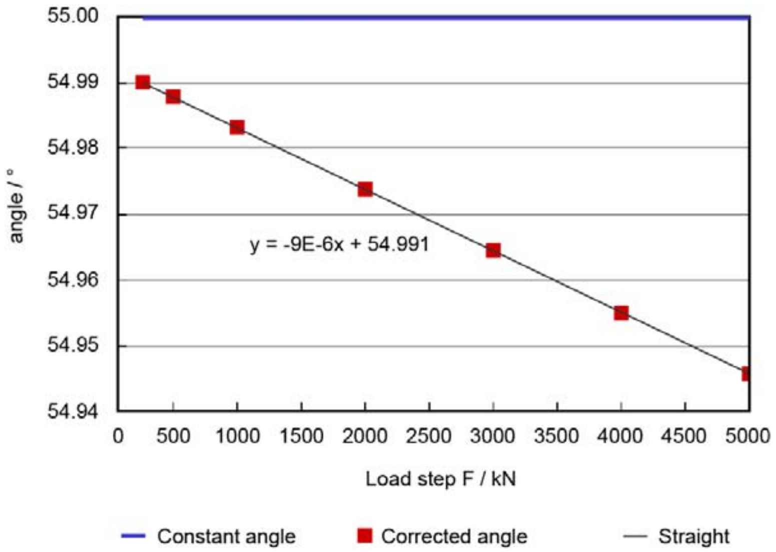

Figure 9: Angle correction due to deformation under load

The metrological characterisation of the new 5 MN HSM-BU system has been obtained using three different procedures, i.e. the calibration of each UFT, the measurement of the system geometry and the evaluation of the functional angles under load. Following this, a complete uncertainty budget has been evaluated (following the ISO GUM). More information on the uncertainty budget is presented in Section 3.3.3 Since one of the aims of the project is to use the new 5 MN MFT as a 5 MN force reference transducer with internal traceability, the maximum relative expanded uncertainty should be 5×10^{-4}. To reach this level of uncertainty, using UFTs in class 00, this would lead, from the theoretical estimation of uncertainty, to a relative uncertainty of 2.7×10^{-4} on the axial force output F_z. From the experimental results, a maximum relative expanded uncertainty of 5.2×10^{-4} at full capacity (5 MN) has been reached; this is at the limit of the target uncertainty. To improve the uncertainty, a better measurement of the angle variation under load became necessary. For this purpose, as a further development, the application of MEMS sensors for angle measurement directly on the elastic elements of the UFTs is proposed.

3.2.3 Time loading effects

Force transducer calibrations are generally performed according to ISO 376. This standard includes procedures to determine the effects of creep and hysteresis but does not propose how to correct their effects. In this section, the phenomena preload, creep and hysteresis are studied in detail.

The first stage of the investigation was to perform measurements in order to isolate the above-mentioned effects. The second was to study the main models suitable to correct hysteresis, non-linearity and creep. The third and final step was to apply these models to the measurements performed by the participants.

Force transducers are likely to display non-linearities and drifts of both zero signal and sensitivity. They also tend to creep and to show different behaviour depending on the increasing or decreasing direction of the applied force. To estimate these parameters, procedures were defined for isolating these effects.

- Section A: Preload Test
- Section B: Creep and zero return
- Section C: Reversibility
- Section D: Additional tests, includes the sections A, B or C by modifying one or more parameters such as speed of loading or rotation transducer

The tests were performed in seven national institutes: CEM, CMI, MG, LNE, METAS, VTT and PTB between June 2014 and February 2015. 65 files were collected including 229 tests overall. 44 different sensors were tested from six manufacturers in ranges between 50 N and 5 MN.

From a calibration, two data sets as functions of time were obtained: $t(x(t); y(t))$. These are the standard reference value and the corresponding response of the transducer respectively. To model the response of the transducer, the signal is split into two parts. A static part decomposed into a linear portion equal to the sensitivity s and offset y_0 and a non-linear part equal to the linear deviation $dy(x)$ and hysteresis $dh(x, y\ sign\ \dot{x})$. The second portion corresponding to the dynamic component of the signal is the creep $c(t)$. The assumed model for the response of a force transmitter is equal to the sum of the components specified above.

$$y(x,t) = y_0 + s \cdot x + dy(x) + dh(x, y, sign\ \dot{x}) + c(t) \quad (1)$$

Static components modelling

To calculate the model in eq. (1), first the hysteresis is determined by means of algorithms from generalised Duhem models. The selection includes the Bouc-Wen, Dahl, Lugre, Maxwell-slip and Ramberg-Osgood models. To identify the parameters of the hysteresis model, several algorithms were tested, such as trust-region reflective, Levenberg-Marquardt, simplex, genetic algorithm or quasi-Newton by comparing their results with those obtained on a standard curve calculated from known parameters. Methods of trust region reflective and Levenberg-Marquardt gave the best results.

After determining the parameters, two different methods were used to solve nonlinear differential equations. The first one is the so-called backward Euler method which consists of calculating the root in each point. For this purpose, bisection, chord, secant, regalsi, Newton or Brent methods were used. The second one uses the method of solving ordinary differential equations (ODE) using the Runge-Kutta algorithms based on an explicit method of order 2-3 and 4-5 or an implicit method of order 2-3. Additionally, numerical differentiation formulas based on an implicit method of order 2-3 were used. Software has been developed to allow all these steps. Once the hysteresis is determined, the deviation due to the non-linearity of the transducer $dy(x)$, the sensitivity s and the offset y_0 can be determined by linear regression with a third order polynomial.

Dynamic components modelling

The force transducer's response depends on the elastic properties of the various component parts, such as the test body, glue and strain gauges. The most appropriate model to describe creep and relaxation is a rheological model (Figure 10) that consists of a Kelvin-Voigt cell in series with a spring of elastic modulus E_1. A Kelvin-Voigt cell is composed of a damping element of viscosity η in parallel with a spring of elastic modulus E_2. This model is usually called the standard linear solid (SLS), or Zener, model, and can describe the transfer of the deformation of the test body to the strain gauge through a shear glue joint.

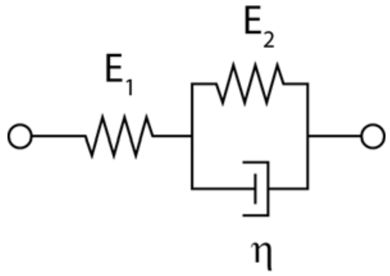

Figure 10: Equivalent rheological model of a force transducer

The differential equation of this system is $\eta\dot{\sigma} + (E_1 + E_2)\sigma = E_1\eta\dot{\varepsilon} + E_1E_2\epsilon$. This equation can be written with the following recurrence relation which characterises the SLS model for creep $a_1\varepsilon_i + a_2\varepsilon_{i-1} = b_1\sigma_i + b_2\sigma_{i-1}$ with $a_1 = E_1E_2 + E_1\eta/T_e$, $a_2 = -E_1\eta/T_e$, $b_1 = E_1 + E_2 + \eta/T_e$ and $b_2 = -\eta/T_e$. To calculate the relaxation, the a_i and b_i coefficients are switched. An example is given in Figure 11.

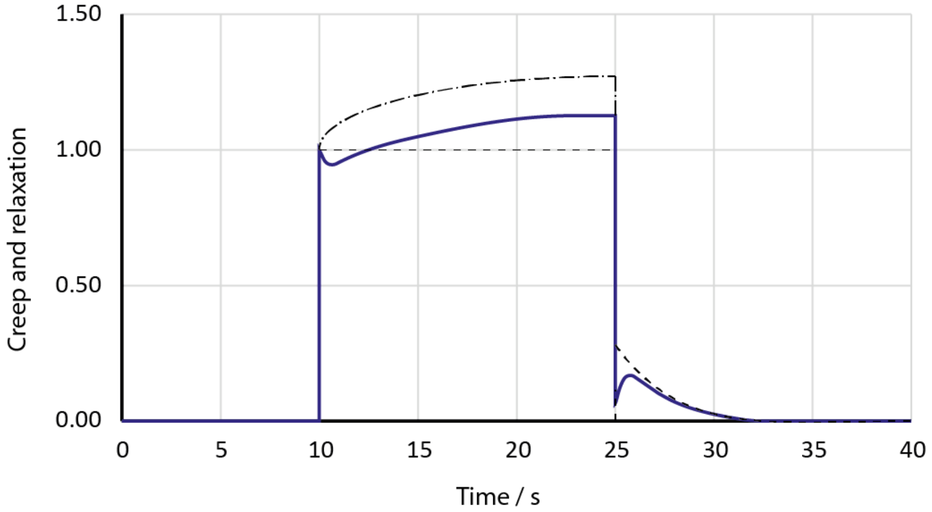

Figure 11: Representation of creep by SLS model (E_1 = 1, E_2 = 4 & η = 10), followed by a relaxation (E_1 = 1, E_2 = 6 & η = 2)

Conclusion

It was demonstrated that it is possible to correct the effects of creep and hysteresis with appropriate modelling. However, modelling shows that the best method to correct the effects would be to achieve tension-compression cycles with zero crossing without removing the load cell from the calibration machine and without applying any preload. This method requires specific calibration machines. However, it can be stated that, for most load cells used in BU systems, corrections are negligible and covered by the calibration uncertainties, so the standard ISO 376 remains suitable for calibrations. Therefore, it was proposed to leave the ISO 376 standard unchanged.

This investigation provides an overview of the state-of-the-art knowledge in modelling the effects of the time loading on force transducers, to improve the models and to provide a toolbox to calculate the hysteresis (see 3.5.3 for more information).

Summary of objective 2:

FEM simulations were performed to develop improved load introduction parts. The results have been discussed with the participants. Thus, the bending neutral plate was developed and tested on a small scale. A use in BU systems in the MN-range is also possible.

A second way of improving transfer standards is the use of a hexapod-shaped multi-component system which can measure additional mechanical loads more precisely. These are caused by either multi-component loading or by imprecise loading. A prototype was developed and used for comparative measurements at several project partners facilities analysing possible effects of different FSMs.

Moreover, the effect of different loading scenarios on the force measurement was investigated by a group of participants. It was found that currently used force transducers mostly fulfil all requirements made for use in BU systems.

All aspects of the work have been carried out in a collective manner. Data or machines for investigations were provided by all partners in the consortium and the results have been discussed. Especially the analysis of time-loading effects profited from this collaboration as it needed a strong data base from different FSMs and force transducers to underline any conclusions.

3.3 Objective 3: Method for the determination of uncertainty of a build-up system

Within the project two different types of BU systems were investigated for which uncertainty calculations are presented in the following: standard BU systems with the two steps calibration (Section 3.3.1 – under supervision of PTB) and application (Section 3.3.2 – under supervision of PTB) as well as one hexapod-shaped BU system (Section 3.3.3 – under supervision of INRIM).

3.3.1 Calibration of a build-up system

For the proposed calibration procedure and the determination of the measurement uncertainty of a standard BU system, it is assumed that the single force transducers are precise enough for the intended use, i.e. they have sufficiently low creep and hysteresis and good reproducibility and repeatability. The BU system is set up and calibrated in a force standard machine (FSM) as shown in Figure 12. The calibration is performed according to the existing standards and guidelines preferably according to ISO 376: 2011. In addition, at least the following parameters must be determined as described below: reproducibility and indication deviation.

Reproducibility

The reproducibility b must be determined using the following procedure: a first measurement series is performed. The BU system is removed from the machine and completely dismounted. It is mounted again into the machine in the same set-up and mounting position. The possible variations of the geometry must be used. Another measurement series is performed. The deviation between the results of the two series is statistically evaluated and contributes to the measurement uncertainty of the BU system.

Indication deviation

The indication deviation must be determined from m consecutive measurement series in changed mounting positions. The result of each series j $(j = 1, \ldots, m)$ and calibration force F_{cal} is a sum $F_{\mathrm{S},j}$ of n forces $F_{i,j}$ $(i = 1, \ldots, n)$ calculated from the indications of the single force transducers using the corresponding regression functions. The relative indication deviations d_{L1} and d_{L2} can be calculated according to

$$d_{\mathrm{L1}} = \frac{1}{m}\sum_{j=1}^{m} d_{\mathrm{L1},j} = \frac{1}{m}\sum_{j=1}^{m} \frac{F_{\mathrm{S},j} - F_{\mathrm{LS}}}{F_{\mathrm{LS}}} \qquad d_{\mathrm{L2}} = \frac{1}{m}\sum_{j=1}^{m} d_{\mathrm{L2},j} = \frac{1}{m}\sum_{j=1}^{m} \frac{F_{\mathrm{S},j} - F_{\mathrm{cal}}}{F_{\mathrm{cal}}} \tag{2}$$

When the calibration force F_{cal} in the measurement series in changed mounting positions varies by more than its expanded uncertainty, then a suitable interpolation of the measured values should be applied. Note that in the case of a force standard machine, the calibration force F_{cal} and the nominal load step F_{LS} are identical. The indication deviation is treated as a typical parameter of the BU system.

Calibration result

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

$$F_{\mathrm{S}} = \frac{1}{m}\sum_{j=1}^{m} F_{\mathrm{S},j} = \frac{1}{m}\sum_{j=1}^{m}\sum_{i=1}^{n} F_{i,j} \tag{3}$$

$$u(F_{\mathrm{S}}) = \sqrt{\sum_{i=1}^{n} u^2\left(F_{\mathrm{T},i}\right)} \tag{4}$$

have to be calculated for each load step. For these values, a linear or cubic function describing the dependency of the sum force F_{S} on the acting calibration force F_{cal}

$$F_S(F_{cal}) = a_1 \cdot F_{cal} + a_2 \cdot F_{cal}^2 + a_3 \cdot F_{cal}^3 + a_0 \quad (5)$$

has to be determined by applying suitable regression methods (for example, the least-squares method) with an additional contribution to the uncertainty due to regression. In reasonable cases the constant value a_0 can be omitted. In the case of large hysteresis, two functions can be given, one for incremental forces and another one for decremental forces.

It must be mentioned that the calibration result contains the indication deviation.

The uncertainty $u(d_L)$ of the indication deviation d_L can be calculated from

$$u^2(d_{L1}) = \left(\frac{1}{m \cdot F_{LS}^2} \cdot \sum_{j=1}^{m}\sum_{i=1}^{n} F_{i,j}\right)^2 \cdot u^2(F_{LS}) + \left(\frac{1}{m \cdot F_{LS}}\right)^2 \cdot \sum_{j=1}^{m}\sum_{i=1}^{n} u^2(F_{i,j}) + u_{stab}^2$$

$$u^2(d_{L2}) = \left(\frac{1}{m \cdot F_{cal}^2} \cdot \sum_{j=1}^{m}\sum_{i=1}^{n} F_{i,j}\right)^2 \cdot u^2(F_{cal}) + \left(\frac{1}{m \cdot F_{cal}}\right)^2 \cdot \sum_{j=1}^{m}\sum_{i=1}^{n} u^2(F_{i,j}) + u_{stab}^2 \quad (6)$$

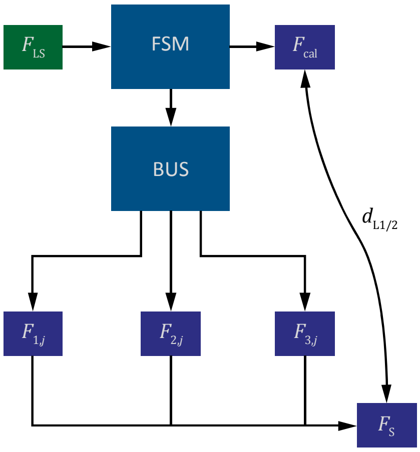

Figure 12: Scheme of BU system calibration, representation of involved quantities

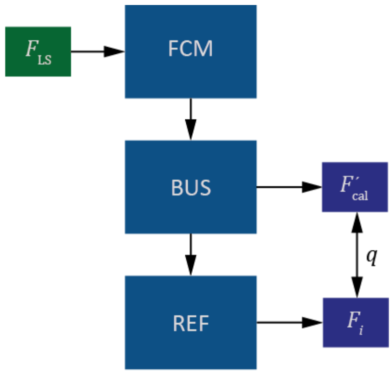

Figure 13: Scheme of BU system application in FCM, representation of involved quantities

3.3.2 Application of a build-up system

A BU system can be employed for the calibration of a force calibration machine (FCM) as shown in

Figure 13. In this case the BU system acts as the transfer standard providing a corrected force F'_{cal}, which is the reference force for the calibration. The deviation between this force and the indication of the machine F_i is the adjustment value q. If only load steps are to be measured where the BU system was calibrated, the calibration result without an uncertainty contribution due to regression can be used. If it is necessary to measure other load steps then an uncertainty contribution resulting from regression must be applied.

In the case that a force calibration machine with a measuring range exceeding that of the standard machine has to be calibrated, several steps are necessary. First of all, the machine has to be calibrated independently from the BU system in its partial range using another force transducer. It is assumed that a partial-range calibration result and an associated measurement uncertainty are available. All *n* force transducers need to be calibrated separately in the same range and with the same load steps like in the standard machine. Then the BU system has to be set up and calibrated in this range, which is a partial range of the BU system and the calibration machine. Next, the indication deviations d_{L2} and associated uncertainties $u(d_{L2})$ have to be calculated. A comparison of the two results d_{L1} and d_{L2} has to be performed using a suitable criterion (for example, the E_n value). If the criterion is fulfilled, the list of d_{L1} values that are known in the partial range can be extended to the full range d'_L under the assumption that these parameters stabilize asymptotically in the upper force range. With knowledge about the full-range indication deviations d'_L, it is possible to calculate the theoretical calibration result in the extended range.

In the case of application, the result is a linear or cubic function describing the dependency of the acting calibration force F'_{cal} on the sum force F'_S, which is the sum force indicated by the BU system during the calibration of the reference machine. In reasonable cases, the constant component of that function, referred to as b_0 can be omitted. In the case of large hysteresis, two functions can be given, one for incremental forces and another one for decremental forces. The measurement uncertainty associated with the calibration result must be determined taking into account the relevant written standards and guidelines.

The last step is the full-range calibration of the machine using the results with the corresponding measurement uncertainties. It must be mentioned that this calibration needs to be carried out in m mounting positions of the BU system. The machine to be calibrated can then be adjusted using the correlation with the indication deviation of the machine.

Expansion of the indication deviation

In the case of good agreement between the indication deviations of measurements in both machines, the indication deviation may be expanded into the rated load range, and is then called d'_L. If this is not the case Scheme A or B as described in Section 3.5.1 should be used and this uncertainty evaluation cannot be used.

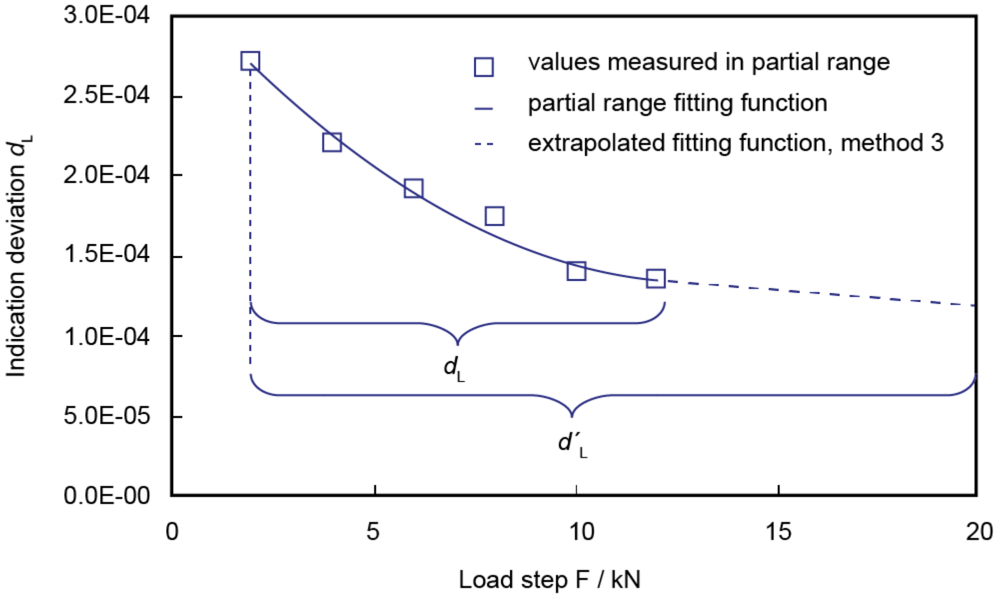

Figure 14: Extrapolation of indication deviation d_L

For the partial range the uncertainty of the indication deviation is computed according to eq. (3). The uncertainty in the extrapolated range is computed in accordance with the result of the extrapolation, which is described in Section 3.4. It is suggested to use method 2 for the extrapolation (see Section 3.4.1).

3.3.3 Uncertainty of a hexapod shaped build-up system

The 5 MN hexapod-shaped BU system is designed to work with a nominal force value of 5 MN, using 6 Uniaxial Force Transducers (UFTs) with a capacity of 1 MN. Since the UFTs have to work in tension and not in compression as normal in other BU systems, it was necessary to create an inversion frame, in order to put the UFTs in tension. The measurements of the force (F_x, F_y, F_z) and moment (M_x, M_y, M_z) vectors are obtained by combining the outputs (O_i) of each UFT in respect to the geometry of the HSM-BU system.

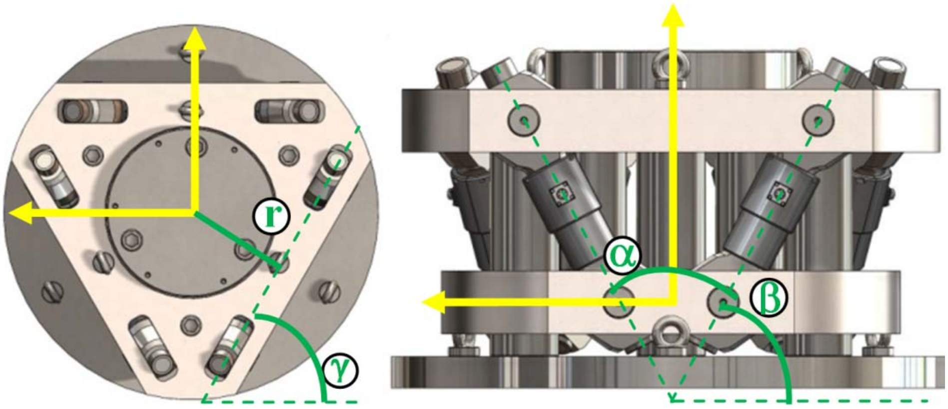

Figure 15: Geometrical variables in the hexapod structure

The applied force tensor is conveyed and subdivided into six different forces (F_1, …, F_6), each one acting and measured by each single UFT, as shown in equations (7) - (12). An overview of the geometrical components is shown in Figure 15.

$$F_X = [(F_6 - F_5) - (F_2 - F_1)]\cos\beta\cos\delta \tag{7}$$

$$F_y = -(F_4 - F_3)\cos\beta - (F_5 - F_6)\cos\beta\cos\gamma - (F_1 - F_2)\cos\beta\cos\gamma \tag{8}$$

$$F_z = (F_1 + F_2 + F_3 + F_4 + F_5 + F_6)\cos\frac{\alpha}{2} \tag{9}$$

$$M_x = [(F_1 + F_2) - (F_5 + F_6)]2r\cos\frac{\alpha}{2}\cos\delta \tag{10}$$

$$M_y = -(F_4 + F_3)r\cos\frac{\alpha}{2} + (F_1 + F_2)r\cos\frac{\alpha}{2}\sin\delta + (F_5 + F_6)r\cos\frac{\alpha}{2}\sin\delta \tag{11}$$

$$M_z = (F_1 - F_2 + F_3 - F_4 + F_5 - F_6)r\cos\beta \tag{12}$$

In the above formulas, α, β, γ and its complementary angle δ, are the nominal angles related to each UFT although different values will be evaluated in practice. As already seen, one of the most important features of the HSM-BU system, is that, as shown by eqs. (7) - (9), measurements of F_i can be directly related to the calibrated UFTs outputs O_i, from which the forces F_i are evaluated, and to the angles α, β, γ and δ. An a priori evaluation of the uncertainty can be made directly from the construction drawings, considering the geometrical tolerances. By taking eqs. (7) - (12) as mathematical models and considering the variabilities of all the independent variables, i.e. the geometry of the system and the forces measured by the UFTs, following the ISO GUM the expected uncertainty can be evaluated. Among the relevant angles, two of them, denoted α and β, can be obtained by the nominal dimensions on the technical drawings, and their variability from tolerances. In the 5 MN HSM-BU system the nominal values of the functional angles are 55.0° and 62.5° for α and β respectively. The mathematical model used to evaluate the contributions to the uncertainty of the functional angles takes into consideration the geometry of the hexapod. But, these calculations regard only variation in the XY plane, supposing that all the geometry would be parallel (or perpendicular) to the Z-axis. So, it is also necessary to investigate the effect of an undesired inclination, with respect to the Z-axis, due to the construction tolerances of the MFT. In addition, also the other two ideal geometrical elements have to be considered: the vertical distance between the two plates and the maximum misalignment of the face of the plates. They are obtained as the sum of the tolerances of the distances between the faces of the places and the centre in which passes the axis of symmetry of the HSM-BU system. The half widths of the functional angles (α and β) are calculated considering the geometry and are indicated as ρ. This means that, for the two functional angles α and β, the total contribution to the uncertainty u_{tot} is given by:

$$u_{\text{tot}} = \sqrt{(u_{\text{fa}})^2 + \frac{\rho^2}{3}} \tag{13}$$

To complete the contribution to the uncertainty of the HSM-BU system geometry, the other two complementary angles, γ and δ have to be analysed. The calibration of the single UFTs is one important contribution to the uncertainty budget of the HSM-BU system. With all the evaluated contributions to the uncertainty budget, it is now possible to estimate the budget of uncertainty of the signal output of the HSM-BU system. The uncertainty for each type of signal output (F_z, F_x, F_y, M_z, M_x, M_y) was considered, but for simplicity only the estimation of uncertainty of the axial force F_z is presented here.

From the first equations it can be seen that the axial force is obtained by:

$$\begin{aligned} F_z &= F_1 \cos\left(\frac{\alpha_1}{2}\right) + F_2 \cos\left(\frac{\alpha_2}{2}\right) + F_3 \cos\left(\frac{\alpha_3}{2}\right) + F_4 \cos\left(\frac{\alpha_4}{2}\right) + F_5 \cos\left(\frac{\alpha_5}{2}\right) + F_6 \cos\left(\frac{\alpha_6}{2}\right) \\ &\cong (F_1 + F_2 + F_3 + F_4 + F_5 + F_6) \cos\left(\frac{\bar{\alpha}}{2}\right) \end{aligned} \tag{14}$$

So, the only parameters that contribute to the relative standard uncertainty are F_i and α. The relative contribution of each parameter is used to calculate the sensitivity coefficient c_i due to the single parameter and, at the end, the contribution to the relative standard uncertainty. As an example, the contributions to the relevant standard uncertainty due to the forces measured by the single UFTs and due to the angles, are given in Table 2. Following this method, the relative extended uncertainties of each force and moment component have been evaluated and summarised in Table 3.

Table 2: Contributions to the relative standard uncertainty for F_z

Parameter	**$u(x_i)$**	**c_i**	**$u_i(F_z)$**
$F_{(1,2,3,4,5,6)}$	$5.64 \cdot 10^{-5}$	$8.87 \cdot 10^{-1}$	$5.00 \cdot 10^{-5}$
α	$3.59 \cdot 10^{-8}$	$-1.30 \cdot 10^{3}$	$4.25 \cdot 10^{-5}$

Table 3: Relative expanded uncertainty of the force and moment components

Component	**$U(y)$**
F_z	$2.56 \cdot 10^{-4}$
F_x	$5.09 \cdot 10^{-4}$
F_y	$6.52 \cdot 10^{-4}$
M_z	$1.46 \cdot 10^{-3}$
M_x	$1.96 \cdot 10^{-3}$
M_y	$5.92 \cdot 10^{-3}$

In this first approach, it was theorised that the application of the loads does not affect the geometry of the system. In the last part of our analysis, simulating the HSM-BU system under loads, the amplitude of these variations was verified in order to evaluate if they are significant or negligible. Using FEM analysis and after an experimental verification, the relation between the force application and the geometry deformation was determined. Since this deformation influences the functional angles α and β, the first order polynomial function that represents such variations was calculated using a least-square regression:

$$\Delta\alpha = a + b \cdot F \tag{15}$$

with the following parameters:

Table 4: Parameter of the correction Δα

Parameter	Value	$u(x_i)$
a	$-9.45 \cdot 10^{-3}$	$1.39 \cdot 10^{-5}$
b	$-1.20 \cdot 10^{-5}$	$4.94 \cdot 10^{-9}$

Now it has to be decided whether it is necessary to re-evaluate the uncertainty on the force and moment components, since there is a new contribution to take into account. As an example, the calculation on the expanded uncertainty of F_z is shown. This is obtained with the new equation:

$$F_z = (F_1 + F_2 + F_3 + F_4 + F_5 + F_6) \cos\left(\frac{\alpha + \Delta\alpha}{2}\right) \quad (16)$$

So, the contributions to the improved relative standard uncertainty became:

Table 5: Contributions to the improved relative standard uncertainty

Parameter	$u(x_i)$	c_i	$u_i(F_z)$
F_{output}	5.64×10^{-5}	8.87×10^{-1}	5.00×10^{-5}
a	2.78×10^{-9}	-2.27×10^{1}	6.30×10^{-8}
b	9.88×10^{-13}	-1.13×10^{5}	1.12×10^{-7}
F	4.78×10^{-8}	2.72×10^{-4}	1.30×10^{-11}
α	3.59×10^{-8}	-1.30×10^{3}	4.66×10^{-5}

As can be easily seen, the contributions to the uncertainty budget due to the correctional factor are much lower than others higher contributions, so it is possible to correct the effect on the variation of the geometry without increasing significantly the uncertainties.

Summary of objective 3:

Measurement uncertainty models for BU systems as well as hexapod-shaped BU systems have been developed. The results have been tested in the facilities of different project partners. This step is necessary as only comparison measurements between institutions can verify the results. As suitable FSMs in the MN range are rare, this comparison could only be conducted within a consortium.

The uncertainty model for standard BU systems and for their application as a transfer standard for a calibration machine are accessible on the project website. The investigation on the hexapod-shaped BU system has been published in the online journal "Metrologia" (see section 6 List of Publications).

3.4 Objective 4: Extrapolation and associated uncertainties

One objective of the project was to develop an extrapolation method and determine the associated uncertainties. In the following the measurements that were performed to establish an extrapolation method are described and several extrapolation methods are presented (Section 3.4.1). Moreover, the uncertainty of extrapolation is discussed (Section 3.4.2) and recommendations for the application of extrapolation methods are given (Section 3.4.3).

3.4.1 Measurements performed to establish a database for extrapolation

To determine the quality of different extrapolation methods and their associated uncertainty, a wide database of measurements had to be established. Therefore, all partners of the project, which were involved in this particular investigation, performed measurements with force transducers in partial and full range. The measurement procedure included several standard calibrations of the transducers according to ISO 376. As a minimum routine a calibration with about 40 % – 50 % of the nominal force and a subsequent calibration with nominal force were requested. Additional partial loads were possible and if possible requested. The calibration with the smallest load had to be the first followed by the other partial loads and the full load range in increasing order.

Based on the described measurement procedure, a database could be established. Altogether 23 transducers in several machines of the participants have been investigated. BAM, CEM, MG, INRIM, LNE and TUBITAK participated in this work under the supervision of PTB.

Additionally, the following different extrapolation methods were proposed and tested with the database (overview in In addition to the different listed extrapolation methods, also different fitting functions (linear, quadratic and cubic) were used. An evaluation tool was developed for this purpose based on MS Excel. The evaluation includes an analysis based on ISO 376, regression functions for the partial load calibrations using all extrapolation options as well as a comparison of these extrapolations with the full range calibrations. The deviation between extrapolation and real measurement is presented in several tables for comparison with each other as well as with the classifications of the interpolation error of ISO 376.

Using the results of all measured transducers, the following conclusions can be drawn:

- The precision of the extrapolation of the characteristic curve from the partial-range measurement increases with the maximum force of the partial-range measurement. The higher the range of the characteristic curve from the partial-load calibration which is used for the formation of the fitted function, the smaller the extrapolation deviations.
- Neglecting the lower range of the partial-load calibration leads to a fundamental improvement of the extrapolation deviations (extrapolation methods 2 and 4). This can be attributed to force introduction effects.
- The formation of the derivative of the fitted functions of the partial-range measurement at the maximum load of this measurement range for extrapolation is further improvement of the deviations from the real characteristic curve (linear extensions – extrapolation methods 3 and 4).
- The degree of the fitted function used has a decisive influence on the extrapolated characteristic curve. Generally, the linear fitted function is best suited.
- The extrapolation deviations depend in general on the linearity deviations of the transducer. Devices with a good linearity behaviour and small linearity deviations are more suitable for an extrapolation than those with high deviations. This is valid in particular if the extrapolation is performed by means of a linear function.

Table 6):

1) The fitting function found for the partial range is used in the full measuring range ("extension of full fit").
2) The second method takes into account that many transducers show a quite high nonlinear behaviour in the range of lowest forces. This range is not used for the calculation of the partial range fitting function. The fitting function is calculated for the results found between the minimum partial interpolation force $F_{PIR,min}$and the maximum partial measurement range $F_{PMR,max}$. This function is used in the full measuring range ("extension of partial fit").
3) The third method uses the fitting function found in method 1 with the difference that its extension to larger forces follows the tangent to the function in the end of the partial range ("linear extension of full fit").
4) This method uses the fitting function found in method 3 with the difference that its extension to larger forces follows the tangent to the function in the end point of the partial range ("linear extension of partial fit").

In addition to the different listed extrapolation methods, also different fitting functions (linear, quadratic and cubic) were used. An evaluation tool was developed for this purpose based on MS Excel. The evaluation includes an analysis based on ISO 376, regression functions for the partial load calibrations using all extrapolation options as well as a comparison of these extrapolations with the full range calibrations. The deviation between extrapolation and real measurement is presented in several tables for comparison with each other as well as with the classifications of the interpolation error of ISO 376.

Using the results of all measured transducers, the following conclusions can be drawn:

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- Neglecting the lower range of the partial-load calibration leads to a fundamental improvement of the extrapolation deviations (extrapolation methods 2 and 4). This can be attributed to force introduction effects.
- The formation of the derivative of the fitted functions of the partial-range measurement at the maximum load of this measurement range for extrapolation is further improvement of the deviations from the real characteristic curve (linear extensions – extrapolation methods 3 and 4).
- The degree of the fitted function used has a decisive influence on the extrapolated characteristic curve. Generally, the linear fitted function is best suited.
- The extrapolation deviations depend in general on the linearity deviations of the transducer. Devices with a good linearity behaviour and small linearity deviations are more suitable for an extrapolation than those with high deviations. This is valid in particular if the extrapolation is performed by means of a linear function.

Table 6: Overview of extrapolation methods

<table>
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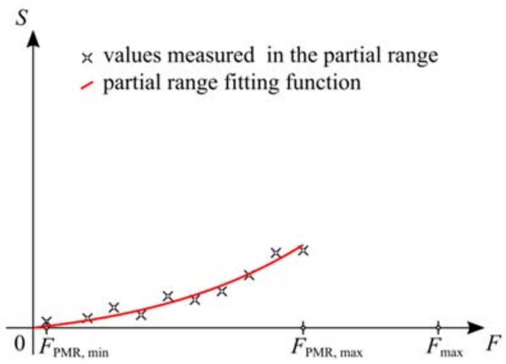
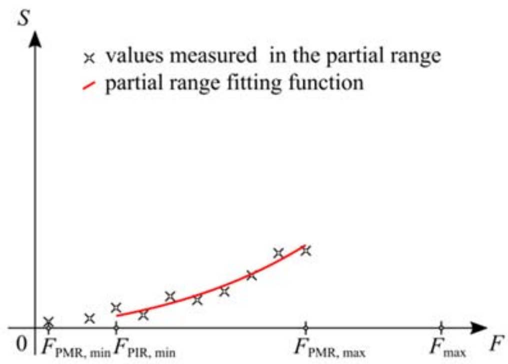
</td><td>Extension of partial fit
</td></tr>
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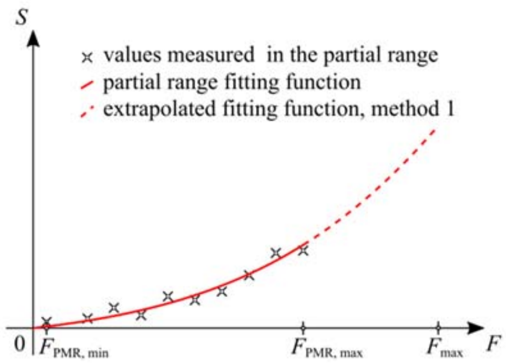
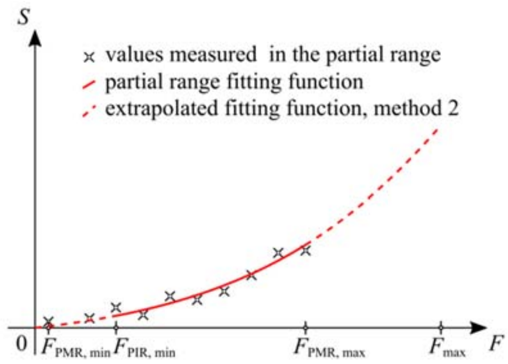
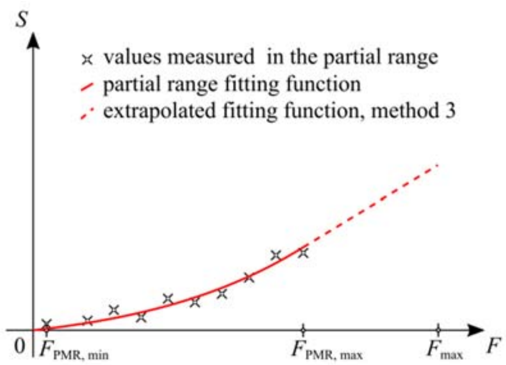
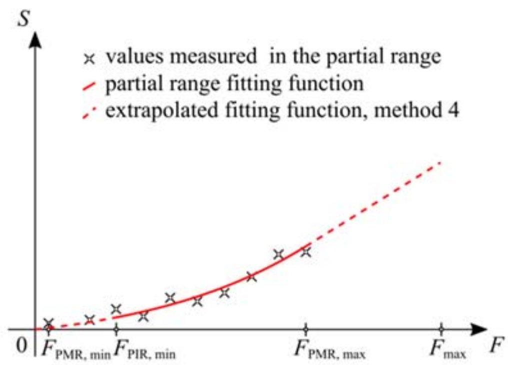
</td><td>Method 2
</td></tr>
<tr><td>Linear extension</td><td>Method 3
</td><td>Method 4
</td></tr>
</table>

3.4.2 Uncertainty evaluation of extrapolated ranges

It is quite difficult to estimate the behaviour of the uncertainties for force measurements in an extrapolated range. The deviation of the results for different transducers even of the same type is very large. Therefore, a general approach for an uncertainty evaluation based on the extrapolation of the absolute measurement uncertainties is proposed in the following. The Excel file used for the analysis was also updated to include the uncertainty evaluation.

The uncertainty for the extrapolated ranges can be determined with the following steps:

1) Based on the description in ISO 376 Appendix C (C.1.10.2) for the interpolation of measurement uncertainties, a regression function is determined for the smaller force range using the absolute

combined uncertainty. This function is $u_{\text{iso cal}} = f(F)$. Moreover, a function for the relative uncertainty is determined $w_{\text{iso cal}} = \frac{u_{\text{iso cal}}(F)}{F}$

2) A safety factor is used to apply $w_{\text{iso cal}}$ to the extrapolated range. This factor m is called *extrapolation uncertainty factor*:

$$w_{\text{extrapol}}(F_{\text{extrapol}}) = m \cdot w_{\text{iso cal}}\left(\frac{F_{\text{extrapol}}}{m}\right) \tag{17}$$

In the following, explanations and considerations for each step are given.

Regression function $u_{iso\ cal}$ and $w_{iso\ cal}$

In step 1) a regression function has to be determined. ISO 376 allows a free choice of the type of regression function. However, the type of the regression function determines the reliability of the uncertainty estimation for the extrapolated range. The distribution of the absolute uncertainty is often quite linear. This indicates the usage of a linear function or a second order polynomial function. From experience it can also be stated that the relative uncertainty follows a hyperbolic function in the lower range of force transducers and a linear to quadratic function in the larger range. Therefore, a third degree polynomial function is recommended for the determination of $u_{\text{iso cal}}$. This third degree polynomial is determined using a least squares method and the resulting function is shifted through the input data point with the largest positive deviation to obtain a conservative estimation. The corresponding function for the relative uncertainty can be determined by division by the respective force. In doing so, $w_{\text{iso cal}}$ can be determined with the addition of a hyperbolic function and a polynomial of second degree.

Extrapolation uncertainty factor m

During the analysis of the database it was noticed that the combined relative uncertainty in the extrapolated range is always smaller than the combined uncertainty of half of the value for the calibrated range: $w(F_{\text{extrapol}}) \leq w\left(\frac{F_{\text{extrapol}}}{2}\right)$. Based on this observation, equation (17) was established which also includes the extrapolation uncertainty factor m. This factor serves also as a safety factor.

The extrapolation uncertainty factor m should be determined for each individual transducer. As the determination would include a calibration up to the nominal force, this is not always possible. Using the database established for the extrapolation, the factor m was analysed for several transducers, m was chosen so that equation (17) results in a w_{extrapol} which is just bigger than the relative combined uncertainty determined in the calibration up to nominal force.

The analysis of the database clearly indicates that for partial loads larger than 50 % of the nominal load the factor m is well below 2.0. It can, therefore, be concluded, that a factor of $m = 2$ would be a safe estimation for the extrapolation uncertainty according to (17) for the transducer types investigated in this study.

Extrapolation deviation

In [2] it was proposed to additionally consider the extrapolation deviation $w_{\text{deviation}}$ in equation (17). This can only be done for transducers where a calibration up to the nominal force is possible or an additional extrapolation of the deviation has to be performed. However, for the investigated transducers it was found that $w_{\text{deviation}}$ is always some orders smaller than $m \cdot w_{\text{iso cal}}\left(\frac{F_{\text{extrapol}}}{m}\right)$. Because the latter one already includes a safety factor, $w_{\text{deviation}}$ can be neglected in these cases.

3.4.3 Recommendations for practical application

The presented uncertainty estimation in Section 3.4.2 is a suggestion and must be used only with careful respect to the named boundary conditions. In the following a few recommendations for the use of extrapolation methods are given.

Choice of transducer

In general, extrapolation entails a high risk. To reduce this risk, the transducer should have good measurement properties. It is recommended to use only transducers with the ISO 376 classification “00” and not to use the range of the partial calibration lower than 50 % of the nominal load. In all these cases, the described theories and assumptions fit perfectly with all investigated transducers.

Application cases

For practical use two cases can be distinguished:

1) The transducer was at least one time calibrated up to 100 % of its nominal load. The results were then compared with that of a partial range calibration. Thus, the best extrapolation method (see Section 3.4.1) and the factor *m* for the extrapolation of the uncertainties (see Section 3.4.2) can be determined. For future calibration, the transducer must not always be calibrated up to nominal load. This might be interesting for calibration labs owning a force reference machine with a smaller range than their highest transfer standard. The transducer can be recalibrated in the meantime between full load calibrations in their own smaller standard thus extending the time period between two calibrations up to nominal load.
2) If there is no possibility of a full range calibration, the transducer should be calibrated up to the possible maximum range. In addition, a second calibration in the partial range of the calibration facility should be done. These two calibrations can be used to determine the best method of extrapolation according to the 4 named cases (further explanation see *Choice of extrapolation method*). The factor m for the calculation of the uncertainties according to equation (17) should be chosen safely to be $m = 2$.

Choice of extrapolation method

For case 1) in the previous section, an extrapolation method can be determined using the calibration up to nominal load; for case 2) this is not possible. During the analysis, it was found that none of the 4 presented extrapolation method has a principal advantage. However, the best method can be reliably estimated from an extrapolation based on a calibration of circa 30 % of the nominal load and the subsequent comparison with a calibration of circa 50 % of the nominal load. In all investigated cases, the extrapolation from the 30 % range to 50 % range indicates the same optimal extrapolation method as the extrapolation from 50 % to 100 %.

Uncertainty estimation

The uncertainty can then be up scaled using equation (1). The factor m can be taken from a calibration up to nominal load in case 1) or presumed to be $m = 2$ for case 2. For the development of a calibration guideline for extrapolation, more transducers should certainly be analysed to evaluate the proposed procedures.

Summary of objective 4:

Extrapolation of measurement results is always a tricky problem. To optimise the basis for the development of a procedure, a large-scale calibration campaign was conducted using force transducers and FSMs of almost all participants of the project. Based on the large number of measurements within this task it was possible to evaluate different extrapolation methods and give an uncertainty for the extrapolated range based on the uncertainty of the measured range and a safety factor. An Excel-file with the necessary calculations for the extrapolation and the uncertainty can be found on the project website.

3.5 Objective 5: Procedures and technical guidelines on the use of high force measurement devices

In this section the two main calibration procedures that were established in this project are presented. The first one is aimed at the calibration of FCM (Section 3.5.1) and the second one deals with the calibration of multi-component force transducers (Section 3.5.2). Furthermore, an overview of the developed software is given (Section 3.5.3).

3.5.1 Calibration procedures using large scale build-up systems

Usually a BU system does not only incorporate the force transducers but also a base plate and a loading plate for the load distribution as well as force introduction parts. It is expected that all these additional parts influence the properties of the system and contribute to the uncertainty budget of the measurement. The underlying influences and their effects on the uncertainty have been considered during the investigations within the project. Figure 16 shows different schemes for the dissemination of the force unit (or traceability of force measurement) using BU systems.

The simplest **Scheme A** is just the use of a number of *n* calibrated single force transducers. This scheme can be directly applied to the calibration of a force calibration machine with a higher capacity of up to *n*-times of that of the standard machine. However, the influences of the additional parts cannot be determined and quantified because no calibration of the BU system is carried out. Therefore this scheme is not very reliable.

The more sophisticated **Scheme B** includes the calibration of the single force transducers as well as that of the whole BU system in the full range. This scheme can be used to investigate the properties of the BU system in comparison with the calibration results of the single transducers. The parameter describing the relative deviation between the sum of the forces indicated by the single force transducers and the calibration force is referred to as d_{L} (see Section 3.1.1). The knowledge about the influencing effects allows the uncertainty of BU systems to be determined more realistically. Nevertheless, Scheme B will usually not be the primary procedure for the calibration of a force calibration machine because this can be done faster and with less effort using a single force transducer with the capacity of the force standard machine. Therefore, this scheme cannot be used for the calibration of machines with higher capacity than the standard machine either.

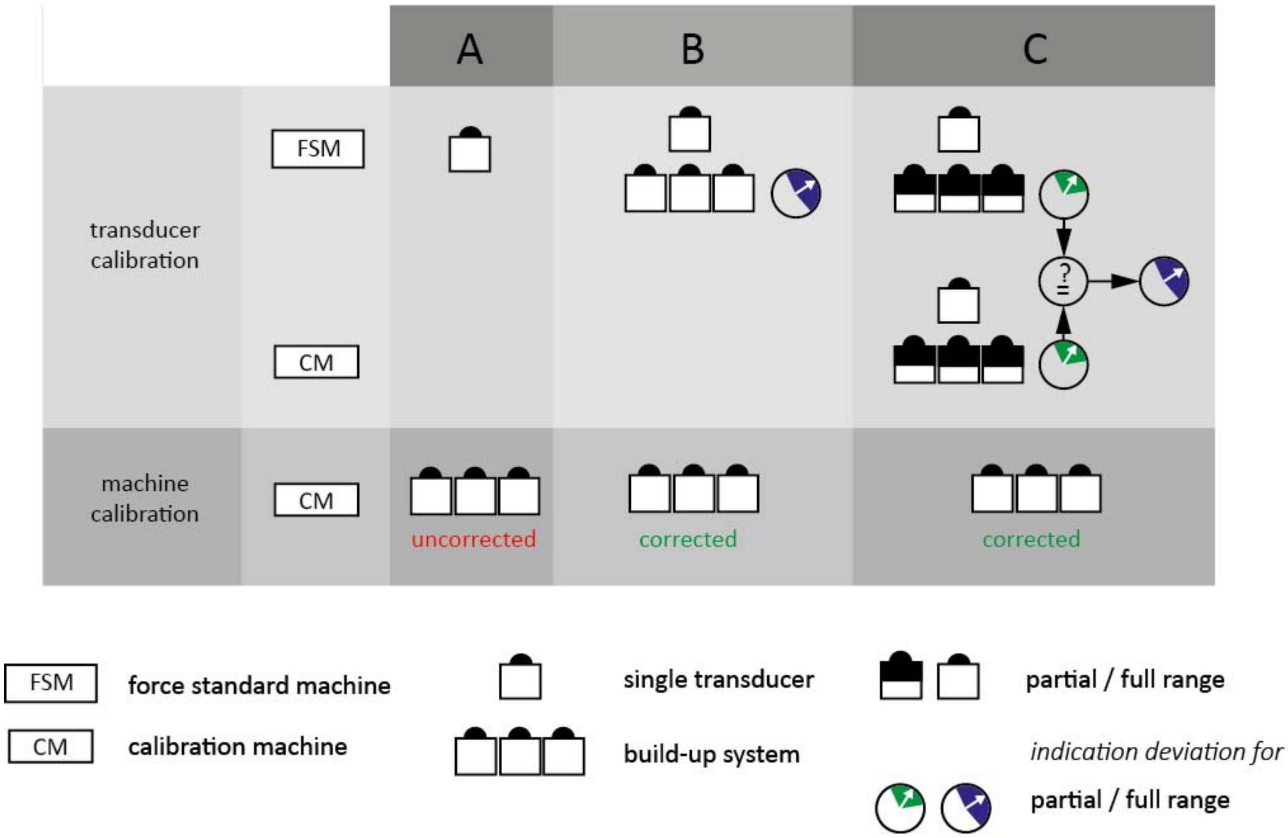


Figure 16: Different schemes of the calibration and application of force transducer BU systems without d_{L} (scheme A), using full range d_{L} (scheme B) or using partial range d_{L1} and d_{L2} (scheme C)

Scheme C consists of the full-range calibration of all *n* single force transducers supplemented by a partial-range calibration – up to the maximum capacity of the force standard machine – of the BU system. The indication deviation can be determined in the partial range of the BU system only, yielding d_{L1}. In a next step, all single force transducers as well as the BU system are calibrated in the partial range in the force calibration machine that is to be calibrated in its full range. The result of these calibrations is another value of the relative indication deviation d_{L2} for each force step. It is important to note that the machine must be traced back to the force standard machine in its partial range, corresponding to the full range of the standard machine. The additional calibrations of the transducers and the BU system in the partial range of the calibration machine is necessary to determine possible interactions between machine and transducers or BU system that have to be taken into account. If the agreement between d_{L1} and d_{L2} is sufficiently good, which has to be investigated further, the BU system can be loaded up to its maximum capacity. This allows the machine to be calibrated in the full range using the corrected forces indicated by the BU system. In order to reduce the effect of disturbing components, the calibration should be carried out in different mounting positions of the BU system. The deformation of the BU system should be monitored to avoid too large deviations of the force vectors acting on the single transducers from their axial direction. The transducers must have sufficiently small creep and hysteresis as well as a good reproducibility and repeatability.

Depending on the calibration requirements, Scheme A may be sufficient for machines with a low requirement for small uncertainties but due to the lack of information about the additional parts and their effect on the measurement this scheme is not investigated here. Scheme B can be considered as a subset of Scheme C, namely, when the measuring ranges of force standard and calibration machines are the same. Some of the measurements in the calibration machine can be omitted then.

3.5.2 Multi-component calibration procedure

The calibration of a multi-component force transducer (MFT, see Figure 17) represents a challenge in the Meganewton range, due to the lack of facilities able to perform this type of calibration. While to apply a moment, it could be enough to decentralise the transducer under the FSM, it could be more complex to break up the uniaxial force, since an FSM is only able to apply a uniaxial force to the MFT. In order to create an environment that could be used in every single FSM, a system of tilted plates was designed (see Figure 18). Rotating the MFT inside the plates and moving such a configuration to different positions from the axially centred position, it is possible to generate forces in the x-axis, y-axis, or both. In order to experimentally verify this kind of procedure, all the MFTs and FSMs available at INRIM, LNE and PTB have been surveyed and screened. At the end of this work, the INRIM 2 MN MFT was chosen; a system of tilted plates was designed and combined with displacements of the MFT in the FSM.

This method does not require any changes to the structure of the FSM and it is possible to combine force and moment vector components as desired, with the exception of the constant presence of the axial force F_z. Thus, the calibration procedure can be performed in any calibration laboratory. The main elements of the entire calibration system are the tilted plates. For this project, four pairs of tilted plates have been realised, with inclination angles α = 0°- 3°. This system permits inclination of the MFT inside an FSM and provides an orthogonal surface to the FSM to apply the force. Rotation through an angle ω of the MFT inside a couple of planes with an inclination of α, the axial force F of the FSM is decomposed in the three components as given by equations (18) - (20):

$$F_{\mathrm{z}} = F \cdot \cos\alpha \quad (18)$$

$$F_{\mathrm{x}} = F \cdot \sin\alpha \cdot \sin\omega \quad (19)$$

$$F_{\mathrm{y}} = F \cdot \sin\alpha \cdot \cos\omega \quad (20)$$

The application of a moment to the MFT is a little more complex. The moment is mainly due to the eccentricity ε of the system in respect to the centre of the central axis of the FSM and to the rotation angle ω, but also the inclination of the MFT leads to the creation of a moment, so it is described by the following equations:

$$M_x = F \cdot \left(\varepsilon \cdot \sin\omega - \frac{h}{2}\sin\alpha - h\sin\alpha\cos\omega\right) \quad (21)$$

$$M_y = F \cdot \left(\varepsilon \cdot \cos\omega - \frac{h}{2}\sin\alpha - h\sin\alpha\sin\omega\right) \quad (22)$$

where *h* is the height of the MFT. The calibration procedure of the MFT can be summarised as below (see also Figure 19):

- The MFT is aligned and centred with the single vertical force load (reference point 0).
- The MFT is still aligned with the single vertical force load but positioned with an eccentricity of 3 mm on the y-axis (point A);
- The MFT is displaced with a further eccentricity of 3 mm in the y-axis (point B);
- The MFT is displaced with a further eccentricity of 3 mm, but in the x-axis (point C);
- The eccentricity of the MFT in the y-axis is reduced to 3 mm (point D);

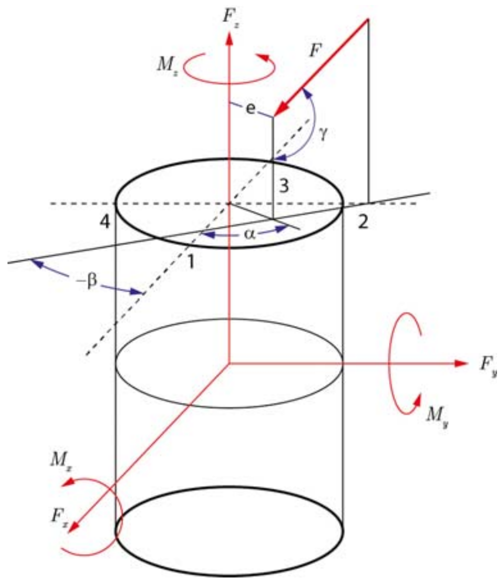


Figure 17: Reference system of the INRiM-2MN MFT

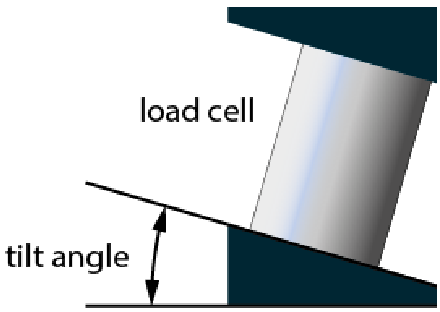


Figure 18: The MFT inside the a couple of tilted plates

For each step of the above described procedure, the MFT is to be rotated with an angle *ω* equal to 45° in order to complete a full turn; and these steps are repeated for each pair of planes.

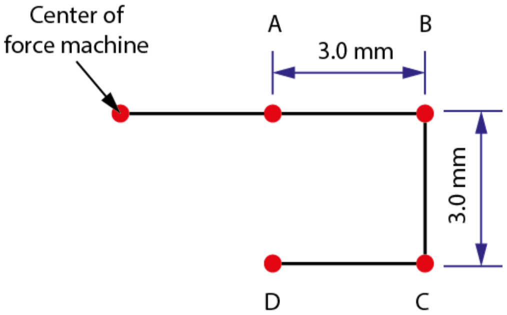


Table 7: *Set of values*

Parameter	Values
α	0°, 1°, 2°, 3°
ω	from 0° to 360°, each 45°
ε_x	0 mm. 3 mm
ε_y	0 mm, 3 mm, 6 mm
F_z	(500 - 1000 - 2000) kN

Figure 19: MFT position under the FSM

From the above listed equations (18) - (22) it is clear, that is possible to obtain all the desired correlation between components of the force and moment vectors only with the combination on the inclination angle *α*, the angle of rotation *ω* and the eccentricity *ε*. Every combination of these three parameters leads to the creation of a different set of forces and moments and the set of values for each parameter is listed in Table 7. This set of experiments can be represented in the experimental planes (Figure 20 & Figure 21).

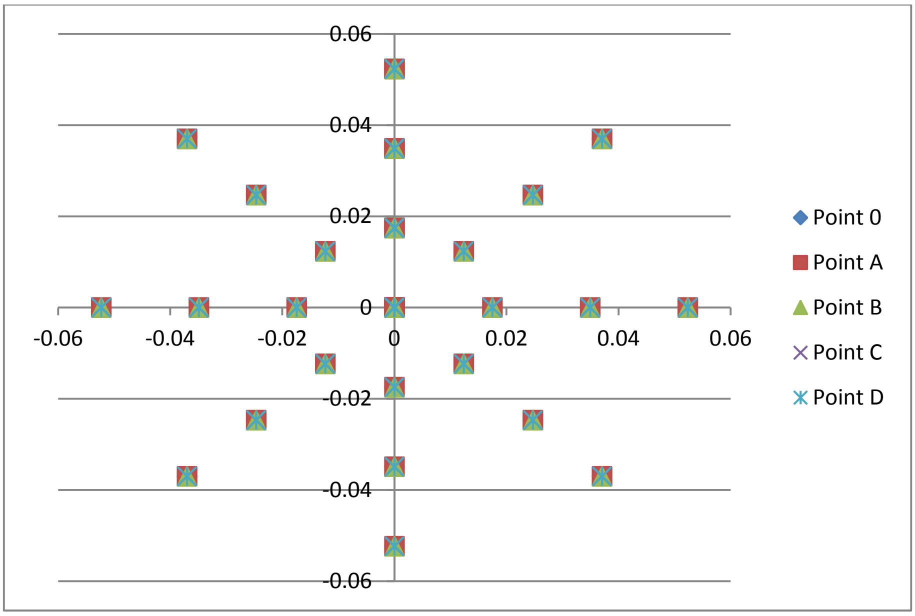


Figure 20: Experimental plane F_x vs. F_y

These experimental planes are fundamental because they immediately show if the chosen set points are sufficient to cover a large number of correlations between two different components or if redundant points are present that can be cut out. Regarding the experimental plane shown in Figure 20, the 5 displacements represent redundant points, because the transversal forces are independent from the eccentricity of the MFT under the FSM, while in Figure 21, the 5 displacement points cover a large set of the area in the experimental plane, with only a few redundant points. Both experimental planes shown above are related to each value of force applied. The ideal MFT has no correlations between the different components of force and moment vectors. This condition can be easily analysed with the use of the matrix of the coefficients, also called exploitation matrix. For an ideal MFT, the exploitation matrix is a diagonal matrix that means there is no correlation between different components of force and moment vectors. Since this is the condition that a MFT should point, the parameter I_1 as a performance indicator can be useful, as it numerically represents how much the exploitation matrix differs from the ideal one (for which I_1 is zero). But this parameter is not enough, because it is not able to discriminate if the total variation is due to single values or if it is due to a general variation of the coefficients from the zero value. For this reason, it is necessary to also analyse the parameter I_2, complementary to I_1. It represents the maximum deviation of the out-of-diagonal coefficients of the matrix. These two parameters are equal to zero for an ideal MFT. Both parameters are limited to zero as a minimum value while there is no upper limit.

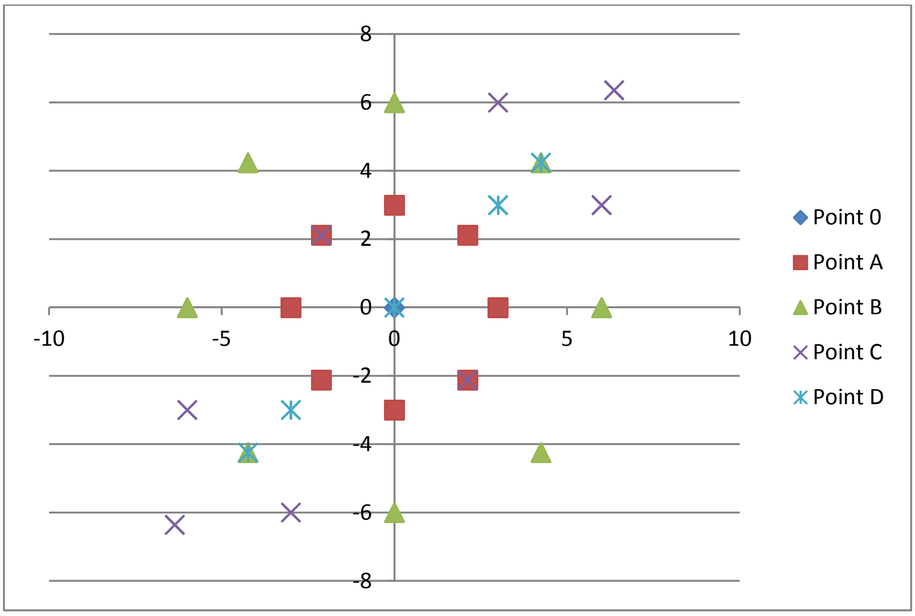


Figure 21: Experimental plane M_x vs. M_y

3.5.3 Software tools

Web-based tools

One aim of the project was to develop procedures, methods and tools for the calculation of uncertainties in the measurement of forces in the MN range. These methods are neither limited to this measuring range nor to the force quantity. But in the context of this framework they should enable the users of calibrated force measuring instruments (force transducers, BU systems, amplifiers) to obtain better results by applying corrections for known influencing quantities and to get more realistic measurement uncertainties, thus improving the dissemination of the force in the MN range.

The work started with a survey where the stakeholders were asked under which application conditions they use their force measuring devices. The different influences were grouped into Geometrical conditions, Mechanical loads, Temporal conditions and Environmental conditions. Several procedures and methods were developed to describe effects on measurements in the meganewton range. For procedures that do not require highly sophisticated calculations and special software, the corresponding calculations were made available to users with online tools and with spreadsheet templates which can be downloaded for offline use. A number of nine influencing effects and models were considered:

- Eccentricity effect on characteristic value
- Lateral force effect on characteristic value
- Storage effect on characteristic value
- Storage effect on zero signal
- Excitation voltage effect on characteristic value
- Excitation voltage effect on zero signal
- Temperature effect on characteristic value
- Humidity effect on characteristic value
- Pressure effect on zero signal

A description and a calculated text example are available on the project website for each of these models. The (online) software tool is available for the following effects:

- Eccentricity effect on characteristic value
- Lateral force effect on characteristic value
- Storage effect on characteristic value

- Excitation voltage effect on characteristic value
- Temperature effect on characteristic value
- Humidity effect on characteristic value

In the spreadsheet tool for offline use the

- Storage effect on zero signal

is additionally included.

The online and offline tools are offered for free download and use but without guarantee for the correctness of the results generated by the user.

Hysteresis modelling software

In Section 3.2.3, a method to correct preload, creep and reversibility effects related to the loading time during a calibration of a force transducer was presented. The first step of the method is to determine the hysteresis, which then gives the possibility to determine other parameters such as the sensitivity, the offset and the nonlinearity. Software was developed in which the model of Bouc-Wen, Dahl, Lugre Maxwell-slip or Ramberg-Osgood can be selected. It can extract the parameters related to the models using the Levenberg-Marquardt algorithm. Once these parameters are determined, the software is able to solve the nonlinear differential equations of the hysteresis models by the backward-Euler method or by the ordinary differential equation method (ODE). The backward-Euler method consists in calculating the root of the equations at each temporal point of the signal by means of different methods: bisection, chord, secant, regalsi, Newton or Brent as proposed by the software. For the solution by ODE, the software offers Runge-Kutta algorithms explicit of order 2-3 and 4-5 or implicit method of order 2-3. Numerical differentiation formulas based on an implicit method of order 2-3 are also used.

Before calculating the model, a rough value of the hysteresis from measurements of the reference value $x(t)$ and the corresponding transducer's response $y(x,t)$ are determined. To achieve this, the linearity deviation $dy(x,t)$ is calculated with a least-squares 3rd degree polynomial fit of the curve through the points $x(t)$ and the average of increasing and decreasing values of $y(x,t)$. The hysteresis is the difference between the response of the transducer $y(x,t)$ and the linearity deviation d$y(x,t)$. The values t, x and dh are then implemented into the application to deduce the parameters of the hysteresis model. The hysteresis model can also be calculated using the solver. The results can be exported to the clipboard to be reused in other applications.

The final step is to recalculate the nonlinearity deviation by means of a 3rd degree least square polynomial fit of the curve through $\{x(t); y(t) - dh(x, y, sign\dot{x})\}$. From the non-linearity curve, the sensitivity s, offset y_0 and the straight line deviation $dy(x)$ are deduced to complete the model described in Section 3.2.3 (eq. (1)).

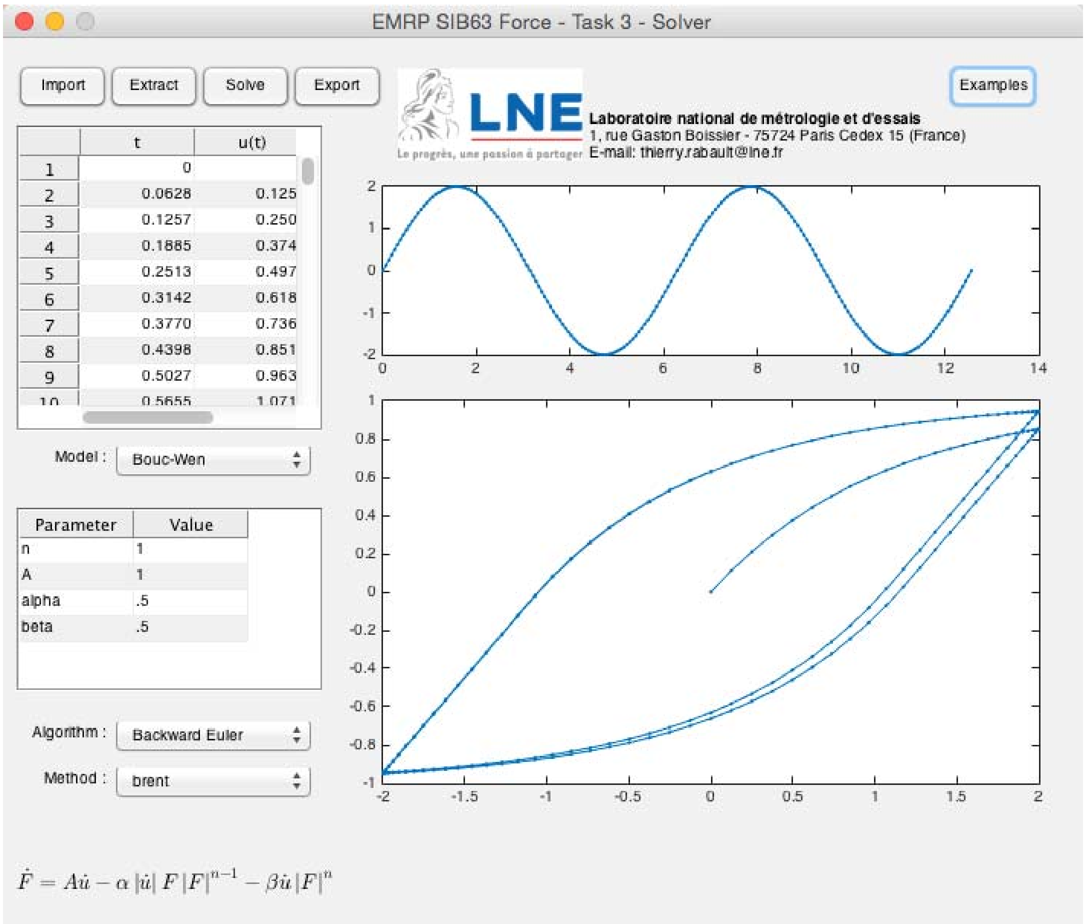


Figure 22: Hysteresis calculation software and parameter identification (provided by LNE)

Summary of objective 5:

A calibration procedure for force calibration machines using BU systems was developed. Furthermore, a routine to calibrate a multi-component force transducer was established. Moreover, several influences on measurements in industry and/or calibration laboratories were investigated within the project. A list of these influences as well as an online tool to calculate the associated measurement uncertainties was published on the project website. All partners contributed to this thorough investigation. Furthermore, the effects of temporal changes in the load application on hysteresis and creep have been summarised in an analysis tool for measurement results.

3.6 Summary of results

The project has successfully extended the traceable force measurements up to 50 MN by investigating effects in BU systems, setting up a calibration procedure for BU systems and proposing a procedure to calibrate force machines with such a BU system. Furthermore, multi-component BU systems have been developed and characterised within the project and a multi-component calibration procedure was established. As these procedures depend on highly evolved force transducers, a thorough investigation of effects on force measurements such as time-dependent loading, temperature or misalignment was made.

Many investigations within the project require a solid data base to verify approaches, procedures or evaluations. The large consortium provided not only the knowledge on many details of force measurements but also the facilities and sensors to accomplish these tasks.

The findings have been published in several papers. Moreover, publicly accessible Excel-files for some of the procedures and measurement uncertainty calculations are available on the project website. Other results are created as online tools directly on the website. The bending neutral plate, which is the result of FEM simulations to improve load introduction parts of BU systems, has been patented.

Further use of the calibration procedures is already planned. The results shall be used for a Calibration Guide for BU Systems after further investigation. A first verification is planned with a comparison between PTB and FJIM´s (China) 60 MN FSM using a 5x10 MN BU system.

4 Actual and potential impact

4.1 Metrological achievements

Concerning the capabilities for traceable calibration of the unit of force, the methods for the following objectives have been validated within this project:

- An extension of the traceability of the unit of force, beyond the state of the art, further into the MN range
    - Extension of the range of primary force standards to cover the range from 1 MN to 50 MN, with uncertainties of the order of 0.002 % up to 2 MN, 0.01 % up to 15 MN, 0.06 % (instead of 0.05 %) up to 30 MN and 0.1 % up to 50 MN
    - Improved transfer standards for forces up to 50 MN
- Guidelines and uncertainty budgets for the operation and use of BU systems
    - New methods for the determination of uncertainty for a high force range BU system
    - Methods of uncertainty calculation and on the improvements of the traceability of the unit force from primary standards to calibration services and testing laboratories
- New methods for the extrapolation of calibration results higher than 15 MN
    - Novel methods to extrapolate calibration results for values higher than 15 MN force, including evaluation of the associated uncertainties
- Investigation of additional effects on measurement accuracy and precision like multi-component loading and time-dependent effects.

Derived from the technical outcomes of the project several software routines, procedures and guidelines are in use for two different peer groups: end-users and manufacturers of force transducers, and NMIs. Moreover, the methods are described in scientific papers (see list in Chapter 6) which allow the user community to have access to them.

4.2 Dissemination activities

4.2.1 Scientific publications

The project has generated seven high impact publications in key journals and four more are in preparation. These publications are showing the significant scientific outputs of the project. A list of published papers is provided in Section 6. Additionally two articles were published in the professional press.

4.2.2 Conferences and relevant foreground

The work carried out in the project has already reached both the wider scientific audience in general conferences such as IMEKO (World Congress and TC3), Sensor & Test and the International Conference on Computational and Experimental Science and Engineering as well as targeted audiences in specialised meetings such as EURAMET TC Mass. In total, several invited lectures have been given by the coordinator, and ten oral presentations have been given by the partners during the life time of the project.

Additionally a wider community e.g. end-user and manufacturers of force transducers were addressed at eight exhibitions including Sensor and Test, Control, the Danubia-Adria Symposiums in Advances in Experimental Mechanics and InnoTesting. Positive reactions were received to all these contributions attracting discussions and comments.

4.2.3 Stakeholder Engagement and Standards

The stakeholders contacted during the project runtime and also potential additional stakeholders concerned with the results of this project are producers of force transducers, calibration laboratories and owners of material testing facilities. In total 32 stakeholders mainly from industry are in direct contact with the project and have been or will be provided with the relevant information.

End users are for example material testing facilities which are addressed via standardisation organisations or special working groups. Furthermore, transducer manufacturers and calibration laboratories are interested in the results. These are in a regular contact with the NMI in charge of their accreditation and (re)calibration. Moreover, any interested end user can use the results presented on the project website.

Stakeholders profit especially from the published work and the relevant tools which can be used on the project website. Six software routines are provided directly on the website for the application of corrections to measurement results to account for the influence of different quantities and for the estimation of uncertainties in force measurement. Additionally information for stakeholder and online guides are provided as well.

These can be used by stakeholders as e.g. calibration laboratories with different environmental conditions (lower temperature or humidity than in NMIs) to calculate a more exact force value during their calibrations and also to consider any correction in the measurement uncertainty.

Additionally Excel evaluation sheets and workbooks, software to extract hysteresis parameters, a knowledge base “BUS chronicle” and an interpolation and extrapolation file are provided for the project partners to be used for calibrations of force transducers.

The new principles for force and time-loading procedures are a good opportunity to gather experience valuable for standardisation purposes. The know-how was fed back into the relevant standardisation committees. A number of the project partners are members of standards and high-level metrology committees. The outcome of the project has also been discussed in the following international standards/committees. Overall, 10 standard meetings have been attended by members of the project consortium.

Table 8 Overview of attended standards/committees

Standards Committee / Technical Committee / WG	JRP-Participants involved	Likely area of impact / activities undertaken by JRP-Participants related to standard/committee
ISO TC 164	PTB, NPL, LNE, INRIM	Development of new standards for force measurement for forces up to highest values and for the consideration of parasitic components and time influences in the calibration and application.
ISO 376	LNE, PTB	Calibration of force-proving instruments used for the verification of uniaxial testing machines.
ISO 7500	PTB, NPL, LNE, INRIM	Verification of static uniaxial testing machines
EURAMET TC Mass and rel. Quantities	PTB, INRIM, LNE	Development of new guidelines for force measurement up to highest values and for the consideration of parasitic components and time influences in the calibration and application.
CCM Working Group Force	PTB, INRIM	Improvements in the traceability in the high force range.

4.2.4 Workshops

Three stakeholders workshop have been organised during the life time of the project. During the first one, held in Braunschweig in September 2013 in conjunction with the periodic meeting of the project, about 25 persons attended the meeting, including representatives of force transducers, academic groups and research laboratories in the field of force. The workshop was dedicated to document the stakeholders' needs and ideas to maximise the project impact.

The second stakeholder workshop was organised at the IMEKO TC3 conference in February 2014 in South Africa and was linked to the non-confidential part of the JRP meeting. The workshop presented the first project results.

A final workshop was held at the end of the project in June 2016 in Braunschweig. The final results of the project were presented. The presentations of the detailed technical results and the resulting foreground were attended by more than 30 persons, 19 amongst them from industry. At the afternoon session a training course was held to instruct industry and project partners in online and software tools, evaluation methods, force measuring techniques and time loading influence.

For all workshops, the delegates showed very positive interest about the outputs of the project, in particular emphasising the role of the NMIs in the development of new routines and software tools.

4.3 Effective cooperation between project partners

The European Metrology Research Programme (EMRP) is a metrology-focused European program of coordinated research and development (R&D) aimed at facilitating closer integration of national research programs and ensuring collaboration between National Measurement Institutes (NMIs), reducing duplication and increasing impact. Several tasks within the project have taken benefit from the collaboration between the partners, as demonstrated by the joint publications and presentations and the collaborative development of software routines, databases and guidelines. The material was offered to all partners and measurement data has been provided by several partners to be integrated in nearly every part of the project.

The participation of a large number of research groups from several countries shows the general interest of the topic and represents the first valuable impact created by the project. Many exchanges between the partners have taken place.

A large number of different BU systems were investigated in the project so that a more detailed knowledge about the build-up systems is available. In near future, this allows a reduction of the measurement uncertainty in the high force range in the dissemination of the force unit by using BU systems. In principle it will be possible to extend the force range in Europe to 50 MN by using large machines in combination with large BU systems up to 50 MN.

4.4 Examples of early impact

As the impact beyond the end of the project is mainly achieved by the cooperation with material testing machines, this impact is ensured by a constant contact either directly or via standardisation organisations and special working groups. The institutes with material testing machines are now able to use the results of the project and spread the impact to any industry relying on their machines. The same goes for calibration laboratories and their customers and transducer manufacturers and their clients.

<u>Standards and regulation:</u>

A large number of force measuring devices were investigated during the project according to the standard ISO 376 so that a large data base of measurement data and analysis is available which will be helpful for decisions in respect of a possible revision of ISO 376 which is a topic of the next ISO TC 164 SC1 meeting at the end of October 2016 in Tokyo, Japan. Therefore the working group ISO TC 164 SC1 WG 3 will meet to discuss a possible revision of ISO 376 and project partners like PTB, LNE, INRIM and NPL will participate in this meeting and will give input to this topic. For the calibration of large material testing machines the results of the project can be used to improve the force measurement in the upper range. This can give an input to ISO 7500-1.

Another topic is the EURAMET Calibration Guide No.4 "Uncertainty of Force Measurements". In case of a revision of EURAMET cg-4, project results can be added to this guide. In particular in respect to BU systems EURAMET cg-4 can be further improved by considering the project results. This guide is also related to ISO 376 and ISO 7500-1 and in case of a modification of the ISO standards EURAMET cg-4 will be updated.

User uptake:

During the project period one application for a patent on a ”neutral plate” as it is described in Section 3.2.1 and shown in Figure 3 on the right was made by PTB (patent number DE 10 2015 114386.0 “Lastverteilerelement”). This invention reduces the amount of parasitic forces on the force transducers in a BU system. Until now there is no licensee but there are two confidential expressions of interest.

A pilot test for the traceable calibration of a material testing machine with a BU system was performed at the Materialprüfanstalt (MPA) at the TU Braunschweig. Using the 3 x 10 MN BU system of PTB, first tests of calibration procedures in the MPA 30 MN material testing machine were undertaken already in 2013. In 2015 further investigations with a 3 x 10 MN BU system of EMPA (Eidgenössische Materialprüfungs- und Forschungsanstalt; NMI of Switzerland) as well as additional tests with the PTB BU system were performed. An estimation of the machine uncertainty was provided and already used for an uncertainty budget of a calibration performed in the MPA machine.

The eight software routines, guidelines and knowledge bases which are listed in the impact report as foreground are in use at all project partners institutes. Most of these tools are available for the stakeholder via the project website.

Scientific uptake and impact:

The EMRP Project “SIB63 Force” will also have an impact on the new EMPIR project “14IND14 MNm Torque” which has started in September 2015. For torque measurement above 1.1 MN·m, there is at the moment no traceability and therefore, extrapolation methods have to be developed. The results obtained in the “SIB63 Force” project can probably be applied to torque measurements. This assumption has to be validated in the new project. Additionally, the question of multi-component measurements with the main component being torque is related those measurements with the main component being axial force and it will be checked if results obtained in the “SIB63 Force” project can be applied to torque measurements which has to be further evaluated in the new project.

Moreover, the project results can be used as a basis for further research. The project findings are important because they are essential to determine more effects that occur in the use of force transducers. While the present project focused on the effects in calibration laboratories (temperature, humidity, small parasitic loads) the effects in material testing machines or other test stands also include the difference between static, continuous and dynamic conditions. These effects could be in the focus of a possible future project which will then be based on the results of the present project e.g. the data bases and software tools.

4.5 Potential impact

The impact of the project will mainly be improving innovation in mechanical and civil engineering by providing better measurements in the testing and optimisation phase of the development process. This impact itself can be transferred to different parts of everyday life:

- By improving material testing, infrastructure such as bridges and also other buildings and structures can be improved in their safety
- Intensive testing can also decrease financial investments caused by needlessly large safety factors used to compensate for the lack of knowledge about materials

Moreover, the project will have an impact on different standards and guidelines which include force measurements for testing of any kind.

5 Website address and contact details

http://www.ptb.de/emrp/forcemetrology.html

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6 List of publications

1. F. Tegtmeier, M. Wagner, and R. Kumme, “Investigation of Transfer Standards in the Highest Range up to 50 MN within EMRP Project SIB 63,” in Proceedings of the XXI IMEKO World Congress “Measurement in Research and Industry,” 2015.
2. T. Kleckers and M. Graef, “High Capacity Reference Transducer For Tensile Forces,” in Proceedings of IMEKO 22nd TC3, 15th TC5 and 3rd TC 22 International Conferences, 2014.
3. R. Kumme, “Force Traceability within the Meganewton Range,” in Proceedings of IMEKO 22nd TC3, 15th TC5 and 3rd TC 22 International Conferences, 2014, p. 2.
4. S. Palumbo, A. Germak, F. Mazzoleni, S. Desogus, and G. Barbato, “Design and metrological evaluation of the new 5 MN hexapod-shaped multicomponent build-up system,” Metrologia, vol. 53, 2016.
5. T. Rabault, P. Averlant, and F. Boineau, “Numerical modeling of hysteresis applied on force transducer,” in Proceedings of the XXI IMEKO World Congress “Measurement in Research and Industry,” 2015.
6. D. Röske, “Uncertainty Calculations Using Free CAS Software Maxima,” in Proceedings of IMEKO 22nd TC3, 15th TC5 and 3rd TC 22 International Conferences, 2014.
7. M. Wagner and F. Tegtmeier, “Processing and Evaluation of Build-Up System Measurement Data,” in Proceedings of the XXI IMEKO World Congress “Measurement in Research and Industry,” 2015.