Final Publishable JRP Summary for SIB63 Force
Force traceability within the meganewton range

Overview

Large-scale industrial and civil engineering applications need to have confidence in the load bearing ability of structures such as aircraft wings and engine fixtures or cables supporting bridges. This involves mechanical testing of such structures in the force range they will experience during use. National Measurement Institutes (NMIs) can test materials and measure forces between 1 and 30 meganewton (MN) using a variety of techniques but measurement uncertainties increase drastically with increasing forces. Therefore engineering designers need to build in a safety margin that reflects this uncertainty. This project extended the range of primary force standards up to 30 MN with an uncertainty of 0.05 %, which reflects the requirements from industry. It also improved transfer standards to help disseminate the unit of force and increased the accuracy of force measurements in industry. Greater accuracy for the mechanical testing of engineering components means that more realistic estimations of measurement uncertainties can be made.

Need for the project

Force transducers are usually steel ‘deformation bodies' that are equipped with small gauges which measure the strain at a certain location under an applied force or load. If there are several loads on one transducer it can influence the force measurements. Force in the range 1 N to 15 MN is measured by NMIs very accurately. However, the very low uncertainties achieved in these high-end laboratories are not passed on directly to the industrial users such as material testers. Measurement uncertainties are further increased by laboratory influences such as temperature and humidity. The practical aspects of mounting and loading test pieces can also increases uncertainties, as the force transducer has to transmit additional mechanical loads such as bending, lateral forces and the varying rhythms of loading and test machine settling. These conditions are normally just accepted and the measurement uncertainty inflated appropriately. However to achieve very accurate measurements it is better to record the conditions and then correct measurements with this additional information.

Material testing in the range up to 10 MN is common in many laboratories but there is an increased demand from engineers for testing at forces up to 50 MN. Applications include the measurement of forces in bridges, steel and concrete materials used in civil engineering, wind turbines, aircraft structures and drilling platforms for gas and oil companies. Prior to this project there was only one NMI which could calibrate force transducers up to 30 MN (NPL) but this was with a measurement uncertainty of 0.15 %. A very easy way to extend the measurable range is to extrapolate the measured values of a force transducer above the maximum achieved force e.g. to calibrate a 20 MN transducer to 15 MN and then use mathematical methods to forecast its behaviour up to 20 MN. But this is only possible with very stable transducers, and the forecast of the measurement uncertainty for the extrapolated top force can be difficult. Another way to extend the force range is to use several force transducers in parallel meaning they are placed next to each other and are loaded at the same time. Setups like this are called build-up systems (BUS). In theory, every transducer within the BUS should receive the same portion of the overall force which makes the calculation of a measurement uncertainty easier than with an extrapolation. However, before this project there were no standards or best practice guidelines available for the use of BUS or for extrapolation methods.

Standardising measurement methods at loads to 50 MN will improve industrial measurement accuracy leading to lower uncertainties which has the potential to reduce construction and manufacturing costs without undermining component performance. Therefore this project aimed to improve force measurement accuracy under less controlled environmental conditions by providing guidelines on how to consider additional influences such as temperature, humidity and bending. Moreover, the project aimed to improve force measurements up to 30 MN and to extend the force range to 50 MN using extrapolation and/or BUS as well as to develop best practice guidelines on how they should be used.

Report Status: PU Public

EMRP
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Scientific and technical objectives

As the needs stated above and their solutions are quite diverse, the following scientific and technical objectives are defined to divide the approaches and address all needs:

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 0.05 % 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 due to negative effects and loading procedures different to the static calibration procedure will be evaluated.
3. To develop methods for the determination of uncertainty for a high force range BUS up to 50 MN.
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.

Results

1. Extension of the range of primary force standards to cover the range from 1 MN to 50 MN

A range of BUS were investigated using different force standards and force calibration machines, for example the new 30 MN BUS transfer standard was measured in the 30 MN force calibration machine at NPL, in the 25 MN force calibration at BAM and in the 16.5 MN force calibration at PTB. A 50 MN BUS was investigated at NPL and PTB on their respective 30 MN and 16.5 MN force calibration machines.

To obtain uncertainties of 0.05 % in the range up to 30 MN, different negative effects related to the BUS construction and the force introduction were investigated and these were accounted for using a correction factor which is called indication deviation. Thus, a measurement uncertainty of 0.05 % was achieved for the 30 MN BUS. For the 50 MN BUS, a measurement uncertainty of approximately 0.06 % was obtained at 30 MN, but measurements over 30 MN could not be performed.

In conclusion the project extended the upper limit of force measurements from 30 MM to 50 MN with associated uncertainties of 0.05 % and 0.06 %, respectively. A 50 MN BUS was calibrated and tested, and is now available to all NMIs to calibrate force calibration machines and material testing machines in order to provide more accurate force measurements.

2. Development of improved transfer standards for forces up to 50 MN:

As BUS are not as precise as a single transducer would be, they must be perfected to ensure a high precision for transfer measurements up to 50 MN. Furthermore, most very large force transducers which are used as transfer standards in the MN-range show different behaviour than the well-known transducers from the smaller force range. To improve force transfer standards in the MN-range, three different approaches were taken:

i. A BUS consists of several force transducers and the parts connecting them. The designs of these adaptation and load introduction parts were analysed by comparing different layouts of BUS up to 50 MN, constructing a small model and using finite element method (FEM) simulations. The aim of this step was to find the best layout of a BUS for the MN-range. Furthermore, the deformation of the load introduction plate was investigated, and from the results a new force introduction plate called the “bending neutral plate” has been developed and patented. Based on the results, it was also found that strain cylinders with additional bending moment measurement, to check the positioning, assembled on a very stiff base plate is the best set-up for a BUS.

ii. A 5 MN multi-component BUS was developed and tested, which can measure not only the direct force but other mechanical loads such as bending moments. The six force transducers used in the 5 MN BUS were not positioned in parallel but with a slight angle leading to a hexapod shape. This hexapod design enabled traceable measurement in the MN range with additional load components as found in force testing machines.

iii. Time-loading effects on force transducers using strain gauge technology were investigated. Such transducers are used in BUS but they have a small memory effect which leads to different results based on their treatment before use e.g. large forces, fast loading or even long-term storage. Therefore a method to correct for the effect of different loading scenarios which might occur in practical application was developed. For force transducers used in BUS the project's recommendation was to choose those with sufficiently small time-loading effects.

In conclusion, the effects on force transducers within a BUS up to 50 MN were investigated in detail and based on this a new adaptation part, the "bending neutral plate" was developed. Moreover, a multi-component 5 MN BUS that can measure not only the direct force but other mechanical loads, such as bending moments was constructed. Both can now be used by NMIs and industry as transfer standards to further improve their force measurements.

3. Development of methods for the determination of uncertainty of a high force range BUS:

A large number of different BUS were investigated in objectives 1 and 2 and from this an uncertainty calculation was proposed for the calibration of BUS and for their application as a transfer standard (as per objective 2). The uncertainty budget developed includes the uncertainty for each transducer in the BUS as well as the uncertainty of the indication deviation.

In addition, an uncertainty model for the hexapod-shaped multi-component 5 MN BUS (part of objective 2) based on the calibration of the six force transducers and the hexapod geometry was established.

Overall, a procedure to determine the measurement uncertainty of a BUS was developed, and using this the accuracy of extended force ranges up to 50 MN can be calculated and the improvement of the accuracy of measurements up to 30 MN (see objective 1) can be verified.

4. Extrapolation of calibration results for values higher than 15 MN:

The project tested a new method for the extrapolation of force calibration results which is less accurate but had much easier extrapolation methods. A large number of different force transfer standards and different nominal loads were investigated between 1 kilo Newton and 15 MN. Different extrapolation methods were then considered based on the slope of the calibration curve of the results. These extrapolation methods included the simple extension of the linear or cubic fit function used for the calibration results as well as the determination of a fit function for a partial range to minimise effects only shown in small force ranges (typically up to 20 % of the measured range). It was found that none of the different methods is superior to the others but a procedure to find the best method for each force transducer (within a BUS) was proposed. Moreover, an uncertainty estimation for the extrapolated values was developed.

This objective was fully achieved and a procedure to use extrapolation methods to extend the force range higher than 15 MN was established. This procedure is very important for end users who do not require very high accuracy of force measurements with BUS or users of tensile force transducers which cannot be put into a BUS. This happens for example in large test rigs for the oil or offshore industry which need tensile measurements of up to 30 MN but calibration is only possible up to 16.5 MN.

5. Development of new procedures and EURAMET technical guides for users in industrial calibration laboratories and testing laboratories:

The effects of application conditions for force transducers were investigated and mathematical models as well as an uncertainty budget for these effects were developed and are available for end users on the project website. Operators of calibration or testing laboratories can use these to correct influences on their force measurements.

Furthermore, new calibration procedures including a calculation of the measurement uncertainty for BUS and for multi-component transducers were developed using the results from objectives 1 and 2. These results were communicated to EURAMET Technical Committee of Mass and Related Quantities (TC-M) in order that they could include them into a technical guide. End-users which measure or calibrate forces in the MN-range can use the procedures to calibrate their facilities with a traceability to national or international standards and a determined measurement uncertainty.

The main outcomes of this objective are calculation tools and guidance notes on how to consider effects in laboratories or in industrial use of transducers that do not occur at most NMIs. The consideration of these effects is based on additional measurements of environmental (temperature, humidity), mechanical (bending moments, lateral forces) or other influences (magnetic fields, positioning). The results can be used directly by end-users but can also be included in official guidelines.

Actual and potential impact

The project has improved the calibration and measurement techniques for high forces. By improving material testing, the safety of structures which have to withstand high forces will be improved. Better testing in the research and development stages can decrease the requirement for large financial investments caused by unnecessarily large safety factors used to compensate for a lack of knowledge about materials. Moreover, the project will have an impact on standards and guidelines which include force measurements for testing.

The project covered a wide range of research on the topic of MN force and also had a variety of outputs, including three force transfer standards: a 30 MN BUS, a 50 MN BUS (from objective 1) and a 5 MN multi-component BUS (from objective 2). All transfer standards have been characterised, tested and are now available for use by NMIs, calibration laboratories or industry users. The two standards i.e. 30 and 50 MN BUS can be used to calibrate force calibration machines in the two-digit MN-range. The multi-component 5 MN BUS has a smaller force range but can also measure additional mechanical loads.

Furthermore, best practice guidance on the use of BUS and on the measurement uncertainty of BUS have been developed (objective 5) and are available on the project website. These include the calibration of the force transducers and the calibration of the whole BUS in a partial force range (part of objective 3). From these an uncertainty for the BUS can be given. Using this result, a procedure and calculation for the calibration of a machine with a BUS has been developed.

The extrapolation method from objective 4 is part of an Excel calculation file which includes guidance notes. It covers the calibration of a force transducer in several partial ranges and the extrapolation of the measurement values as well as the calculation of the measurement uncertainty for the extrapolated range.

A new load introduction part for BUS was designed in objective 2. It is called “bending neutral plate” and it has been patented (patent number DE 10 2015 114386.0 “Lastverteilerelement”). The invention improves the accuracy of BUS by perfecting the load introduction to the force transducers within the BUS.

The investigation of the time-loading effects (from objective 2) was incorporated into a software analysis tool. It calculates the hysteresis of a data set from a force calibration. Furthermore, it is possible to use differential equations to approximate the behaviour, and has the potential to be used for forecasting of how the transducer will behave under varying time-loading conditions.

The consideration of different laboratory influences (objective 5) was incorporated into web-based calculations. It covers influences that are of geometrical, mechanical, temporal, electrical and environmental behaviour. The calculations can be used by calibration laboratories as well as industrial users to improve the accuracy of their force measurements. There is also an Excel-version of the calculations to be used for offline calculations. The web-based calculations and the Excel-file can be found on http://www.ptb.de/emrp/2388.html.

Dissemination activities

The project generated eight high impact publications in key conference proceedings and papers, and two in the professional press. Most of the results were also presented directly at the conferences including IMEKO 2014 (World Congress and TC3), Sensor & Test and International Conference on Computational and Experimental Science and Engineering.

Eight exhibitions were attended including Sensor and Test, Control, 31st Danubia-Adria Symposium in Advances in Experimental Mechanics and InnoTesting to publicise the results to a predominantly industrial audience.

A stakeholder group, formed of 32 organisations, provided advice and feedback on the project as it progressed. The organisations represented included producers of force transducers, calibration laboratories and owners of material testing facilities. Three stakeholders workshops were organised during the life time of the project. One at the beginning of the project to determine the interests of stakeholders. A second workshop at IMEKO 2014 to discuss intermediate project results, and a final workshop including a training session on the project’s final results. The training course on evaluation methods for force measuring techniques was attended by 18 attendees from other NMIs, transducer manufacturers and material testing facilities.

Impact on standards

The project consortium presented the results of the project and attended 10 standards committee meetings e.g. EURAMET TC-M and ISO TC164 SC1. The most important standards for force metrology are:

- ISO 376 which describes a standard force transducer calibration, it is discussed in ISO TC164 SC1 meetings
- ISO 7500-1 which describes the calibration of calibration machines, it is also discussed in ISO TC164 SC1 meetings
- EURAMET calibration guide 4 (cg-4) which describes a force transducer calibration, it is discussed in EURAMET TC-M

None of these standards includes information on the use of BUS or on how to consider additional influences; topics were dealt with in this project .ISO 376 and EURAMET cg-4 are both in discussions for a revision of their standard and guide and are currently considering the project outcomes.

Examples of early impact

As the impact beyond the end of the project is mainly achieved by the cooperation with operators of 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.

A pilot test for the traceable calibration of a material testing machine with a BUS was performed at TU Braunschweig. Using the 30 MN BUS of PTB, the first tests of calibration procedures developed in this project were undertaken in 2013 using a 30 MN material testing machine at TU Braunschweig.

In 2015 further investigations with a 30 MN BUS at EMPA (the Swiss NMI) as well as additional tests with the PTB 30 MN BUS were performed. An estimation of the machine uncertainty was provided and has been used to calculate the uncertainty budget for the calibration performed using the TU Braunschweig material testing machine.

A patent for a bending angle plate was made by PTB, and there have been two confidential expressions of interest for commercialising the technology.

Potential impact

The project demonstrated, how material testing machines can be calibrated with BUS. This meets the demands from industry for more accurate force measurement in the MN-range. The material testing machine of TU Braunschweig tests structures or part of structures for the use in construction e.g. steel cables for cable-stayed bridges. Therefore, the lower uncertainties of the measurements have already impacted industry and it is envisioned that more material testing machines can be calibrated using the 3 force standards developed by this project.

This project will also have an impact on the new EMPIR project ‘14IND14 MNm Torque’ which started in September 2015. For torque measurements above 1.1 MN·m, there is currently no traceability and therefore, extrapolation methods have to be developed. It is therefore intended that the results obtained in this project can be applied to torque measurements.

List of publications

[1]. Jinhui, Y., Knott, A., Qingzhong, L., Hang, X., & Haigen, L. (2015). INTERCOMPARISON BETWEEN LARGE FORCE STANDARD MACHINES IN CHINA AND UK. In Proceedings of the XXI IMEKO World Congress “Measurement in Research and Industry.”

[2]. Kleckers, T., & Graef, M. (2014). High Capacity Reference Transducer For Tensile Forces. In Proceedings of IMEKO 22nd TC3, 15th TC5 and 3rd TC 22 International Conferences Proceedings.

[3]. Kumme, R., Tegtmeier, F., Röske, D., Bartel, A., Germak, A., & Averlant, P. (2014). Force Traceability within the Meganewton Range. In Proceedings of IMEKO 22nd TC3, 15th TC5 and 3rd TC 22 International Conferences (p. 2) Proceedings.

[4]. Palumbo, S., Germak, A., Mazzoleni, F., Desogus, S., & Barbato, G. (2016). Design and metrological evaluation of the new 5 MN hexapod-shaped multicomponent build-up system. Metrologia, 53.

[5]. Rabault, T., Averlant, P., & Boineau, F. (2015). Numerical modeling of hysteresis applied on force transducer. In Proceedings of the XXI IMEKO World Congress “Measurement in Research and Industry.” Proceedings.

[6]. Röske, D. (2014). Uncertainty Calculations Using Free CAS Software Maxima. In Proceedings of IMEKO 22nd TC3, 15th TC5 and 3rd TC 22 International Conferences Proceedings.

[7]. Tegtmeier, F., Wagner, M., & Kumme, R. (2015). 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.” Proceedings.

[8]. Wagner, M., & Tegtmeier, F. (2015). Processing and Evaluation of Build-Up System Measurement Data. In Proceedings of the XXI IMEKO World Congress “Measurement in Research and Industry.” proceedings.

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