Publishable Summary for 18SIB08 ComTraForce
Comprehensive traceability for force metrology services

Overview

Internationally competitive high-tech products use highly efficient materials including carbon fibre, high strength steels and high strength concrete. Thus, European industry needs an improved scientific infrastructure, which covers a large range of different construction types, to measure their performance for safety and ecological use. Prior to the start of this project, calibration for material testing was done statically and did not only disregard time and frequency influences but also lacked traceability. This project developed methods and transfer standards for static, continuous, and dynamic force calibration traceable to the SI in the range of 1 N to 1 MN. In accordance with the requirements of industry 4.0, force measuring devices were also developed and described by extended theoretical models resulting in digital replicas. This software can be potentially implemented in calibration procedures and extended for use in manufacturing machines. Further to this, the outputs from the project were made available to force metrology services, such as accredited calibration laboratories, for use with their force transducers and testing machines in both quality control and science.

Need

Every year, societies and governments expect economic growth. But the resources are limited, as is the pollution load capacity of the environment. In order to grow future economies, whilst minimising negative impacts on the environment, it is vital that Europe ‘builds more by using less’. However, this requires new improved materials. The development of highly efficient materials has already had a beneficial impact on the environment, but material testing still needs better traceability to the SI units. Products from the automotive, aerospace, healthcare, and construction industries have a large impact on the life quality for many people and are important for European trade and infrastructure. Thus, improved force measurements in the continuous and dynamic regime are also socially important for improved product design.

In order to cover many different force measurement applications and to develop suitable calibration methods, for these applications, it was necessary for this project to review the state-of-the-art available machines, force measuring devices and standards. A roadmap detailing future requirements for improved force transfer standards and associated calibration methods for force testing machines which considers realistic uncertainties, was then developed during the project. In modern manufacturing, to meet the demands of industry 4.0 and the Factory of the Future, virtual tools which consider sources of uncertainty that can be directly implemented into calibration procedures are needed as well as testing machines. For an improved understanding, the time and frequency behaviour of the force measuring devices also needed to be investigated and described by suitable advanced models for continuous and dynamic force measurement. These models were used to form the core of a “digital twin”, which is the digital replica of the real force measuring devices.

Previous EMRP projects SIB63 Force and IND09 Dynamic, focused mainly on large forces and basic investigations of dynamic forces but did not consider (i) the need for their practical application, (ii)the implementation of a traceability chain for continuous and (iii) dynamic force measurements. For continuous forces, a calibration procedure for testing machines needed to be developed which extended the traceability chain from static to continuously changing load conditions. For dynamic forces a calibration procedure for the traceability chain in the frequency range from 0 Hz to 1000 Hz was required. There was also a need for suitable and practical validated methods and guidelines which can be applied by calibration laboratories for continuous and dynamic force calibrations. Due to the lack of above-mentioned methods, this project focused on the development of a traceable chain for continuous and dynamic force measurements.

Objectives

The overall aim of the project is to provide calibration services, in the field of mechanical and material testing, with the methods and guidelines needed for comprehensive traceability of static, continuous and dynamic force measurements. In more detail the objectives of the project are:

1. To review all types of mechanical and materials testing machine standards and force calibration methods and their traceability chain to national standards and to produce a roadmap for new extended calibration methods and innovative force transfer standards considering the static force calibration method as well as the continuous and dynamic force application.
2. To develop advanced models that accurately describe the influences in force measuring devices including the development of digital twins of force measuring devices according to the future requirements for digitisation and industry 4.0 with a target uncertainty of 1 % up to 100 Hz and 2 % between 100 Hz – 1000 Hz.
3. To develop a force traceability chain for metrological services by implementing new improved methods to consider static, continuous and dynamic force calibrations in a frequency range from 0 Hz to 1000 Hz and a force range from 1 N to 1 MN.
4. To develop guidelines for force calibration of testing machines under consideration of continuous and dynamic force applications and parasitic influences from multi-component forces and temperature effects and to develop a strategy for offering calibration services from the established facilities to their own and neighboring countries.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (e.g. National Metrology Institutes, National Accreditation Bodies), standards developing organisations (e.g. ISO, ASTM) and end users (e.g. testing machine manufacturers, test houses).

Progress beyond the state of the art

A wide range of different testing machines are used in all areas of technology, research and quality control systems. Due to the variety of technical applications, (e.g. in medical engineering, civil engineering, aviation industry or offshore technology), existing testing machines cover a wide range of different concepts of force generation, force introduction and systems for the measurement of the applied force. Material testing facilities often have a very low wear-out, and for this reason they have been in service for several decades. In addition, the capacity of the machines is often quite different, for example in the case of machines needed for bioengineering it is in the mN range, whereas for the machines in civil engineering it goes up to 100 MN.

Prior to the start of this project there was no single knowledge base on the individual requirements of different construction principles regarding the traceable dynamic calibration of the machines. Therefore, this project produced a roadmap with an overview of the measurement principles, technologies, and procedures that were currently used for force metrological services thus capturing a comprehensive description of the existing force calibration infrastructure for both physical and documentary standards (*Objective 1*). The roadmap also highlighted areas in which there were industrial force measurement applications where traceability needs were not being fully met. In the scope of this project, a new method of a traceable calibration procedure was developed that uses and extends the general idea of verification tests of ISO 4965-1 or ASTM E467-.

Prior to the start of this project existing systems for digital identification were already implemented in the latest generation of force measuring devices. However, the application area had not been specified and there was no digital twin especially for the field of metrology. Given that, digitalised data processes will heavily influence the field of material testing as well as force and torque measurement, the project went beyond the state-of-the-art by developing a digital twin which is able to deliver the output of a force measuring device as a function of the force spike (*Objective 2*). This included a detailed investigation of the instantaneous response of the material behaviour of the load cell's beam, which then gave rise to corresponding changes in the readings recorded by the sensors.
Moreover, the creep strain effect on the metrological performance of a force measuring device was investigated by the project and it was found that the major source of creep is the carrier matrix of the strain gauge. Additionally, the project developed a digital twin based on Larson-Miller equation that can guarantee the safe use of the force cell.

Before this project began, the force calibration of material testing machines was performed according to ISO 7500-1, which only considered the static axial calibration of the equipment. There were no European standards or recommendations available for such measurements nor CMC values available for non-static forces. This project contributed to improving the traceability of force measurement by implementing new validated and traceable methods for the calibration of material testing machines and test stands (*Objective 3*). In addition to static forces, traceable methods and procedures for continuous and dynamic forces were developed. So far, the project has produced traceability chains that use new types of transducers in the form of (i) specially adapted commercial products or (ii) a transducer developed from the verification samples of ISO 4965-1. Further to this, the project investigated the effects of multi-component force measurement for alignment influences, values of bending strain, associated percent bending, gripping and apparatus and the influences of temperature. By doing this, the project addressed aspects in the “Force” and “Dynamic” roadmaps of the EURAMET TC Mass and related quantities (TC-M).

ISO 7500-1 focuses on static procedures for calibrating the force indicator of a testing machine but does not consider the influence of dynamic effects. Therefore, this project prepared guidelines for the dissemination of force especially in the field of material testing (*Objective 4*). For continuous force calibration, a document describing improved calibration procedure was developed. The DKD-R 9-4 draft document was created with the detailed description of the dynamic calibration procedure including an additional template for calibration certificate. The aim was to develop a calibration routine from the verifications of different standards, suitable for real-time laboratory conditions, which can then be used for the revision of ISO 4695-1.

Results

Review of machines and standards used in force metrological services (Objective 1)

Due to the differing technical applications, existing testing machines cover a wide range of (i) different concepts of force generation, (ii) force introduction and (iii) systems for the measurement of the applied force. Therefore, the consortium used its extensive network of stakeholder contacts to develop an overview of the issues that need to be solved within the project. Using this information, the project created a roadmap which includes existing technologies in dynamic force applications and considers the current state of traceability in this field of metrology. The roadmap was also based on reports related to existing facilities, transfer-standards and normative documents. The project also identified industrial needs in a stakeholder’s report, which was prepared based on discussions with relevant experts. This report identified a number of issues that industry would like to be addressed which the project incorporated within the roadmap. The industrial issues included: (i) traceability and uncertainty for dynamic force standards; (ii) calibration procedures for piezoelectric transducers; (iii) a clearer definition of alignment protocols; and (iv) consideration of the influence of temperature on dynamic testing. The project used the roadmap and the stakeholder report to help define the work done in objectives 2, 3 & 4.

Modelling and development of digital twins for force measuring devices (Objective 2)

The project’s static investigations based on ISO 376 on selected strain gauges and piezoelectric force transducers have shown that the characteristic curve of both types of force transducers is best described with a third-degree polynomial. The long-term drift behavior of the charge amplifier, used for the piezoelectric force transducer, immediately after turning the device on was investigated and could be described with a function of two decaying exponential functions and a linear component. A drift correction with the linear component led to a reduction in the hysteresis in compression mode and an increase in tension mode. The project then conducted continuous investigations which confirmed the drift-corrected hysteresis values of the piezoelectric force transducer.

For the range below 1 Hz, an extended generalised Kelvin model turned out to be suitable for describing force measuring devices. This consisted of an extended Hooke element connected in series with up to three Kelvin-Voigt cells, which in turn consisted of a Hooke element (spring) connected in parallel with a Newton element (damper). However, in most cases, a more practical model was needed for the description of the force measurement. This is because the extended generalised Kelvin model gave ideal behaviour that was affected by parasitic influences such as temperature, spurious side forces and bending moments.

For the more practical model a third-degree polynomial was used to form a transfer function from the values determined from the fast loading or a continuous calibration. An uncertainty was specified for each correction as well as for the influences which could not be corrected for. In a separate set of measurements, INRIM investigated the effect of non-axial and side forces on the sensitivity of strain gauge transducers. This was done by rotating the sensor on different tilted plates. The sensitivities as function of the rotation angle showed a sinusoidal behaviour. Furthermore, at increasing side forces the sensitivities increased or decreased with respect to the reference mean sensitivity evaluated without tilted plates. Looking at the absolute relative deviations as function of the ratio between the side force and the applied reference force, it was found that they increase at increasing ratio.

A new measurement method and evaluation procedure was developed based on performing measurements with fast, leakage-free, and high-resolution periodic chirp signals for dynamic excitation of the shaker system. The developed method is applicable to all types of setup configurations where a laser scanning vibrometer is available. It also provides a good understanding of rocking motions by using a scanning laser vibrometer to perform measurements at several points all-around transducer at the bottom of the setup. This is an improved alternative method to existing one-point acceleration measurements with the piezoelectric sensor as these suffer from a lack of the rocking motion information as the main source of uncertainty in the acceleration measurement and hence force. The latter existing method was used by RISE to support the new method with a baseline and to quantify measurement uncertainty. It was also used for the implementation of the AI algorithms used for determining the model parameters with an open-source Python library Tensorflow.

A digital twin model was developed based on the transfer standard developed by USTUTT (Objective 3). To enhance measurement uncertainty models and validate future digital constructs, CU investigated the influence of creep in both the carrier matrix and spring element. CU also showed how temperature and strain gauges sensors are able to influence accuracy of the digital twin environment. A virtual load cell based on a finite element method (FEM) was developed, and the results were compared with the static calibration data recorded at PTB and with a simplified analytical model. An approach involving Python programming for data tie of a physical device including a Digital Calibration Certificate as a source of input data and its virtual model was developed. The FEM-model for continuous calibration was focussed on the thermal creep associated with the loading and unloading operations, and it was found to be in line with previous results. However, the creep data available in existing literature reported a dominant effect of the strain gauge relaxation behaviour, which has an opposite trend to the one associated with thermal creep of the load cell. The simulations provided useful outputs, but their effectiveness was limited by the computational limitations required by FEM.

Traceability chain for static and continuous and dynamic force (Objective 3)
Six of the project partners (GUM, Inmetro, NPL, PTB, TUBITAK, and ZAG) independently investigated potential influence factors on carefully selected force transducers, resulting in a comprehensive report covering all five of the identified parameters (Objectives 1 & 2) which were short-term creep, hysteresis, temperature, data synchronisation, and instrumentation.

Further to this, an investigation of the effect of non-axial alignment during testing, using both modelling (Objective 2) and practical testing techniques, enabled the effect of possible misalignments to be incorporated in the uncertainty derived for a given material parameter. An ISO 6892-1 uncertainty model was also developed from the results. The uncertainty budget for the force applied during the tensile test combines the uncertainty associated with the machine calibration (which itself includes the uncertainty of the instrument calibration) with other identified uncertainty contributions. The results of this work were used both to inform the data synchronisation procedures required within a continuous calibration protocol as well as to derive sensitivity coefficients for use within uncertainty budgets.

Three independent partners (i.e. INRIM, TUBITAK, Inmetro) investigated the traceability for multicomponent force and moment measurements. The results were used to produce a report describing a method for the static calibration of multicomponent force and moment transducers and multicomponent testing machines together with the evaluation of the associated uncertainties. This was in turn used to define a comprehensive model for uncertainty assessment of forces and moments in industrial applications. The methodology developed for traceable continuous force measurements covers three major areas: (i) validation of a continuous force reference standard; (ii) calibration of force-proving instrument against this reference standard; and (iii) calibration of testing machine against this force-proving instrument.

The project developed a traceability chain for metrological services in the dynamic calibration of material testing systems. Two commercial force transducers were selected and equipped with PT 100 temperature sensors, which were directly connected to the strain gauge measuring bridges for investigations of a temperature influence. The aim was to investigate adiabatic and cliometrics effects in dynamic applications and to be able to take their influence into account in the measurement results. Additionally, a special transducer was developed (called Dynamometer), which was as similar as possible to the test probe used in material testing in the testing facility and which extends the measurement capabilities of the transducers described in existing standards (i.e. ISO 4965-1, ASTM E467 and DKD-R 3-10, Sheet 3).

The project focussed on building a calibration set-up which allowed the quantification of parasitical influences, such as temperature, bending, stiffness and uncompensated masses. Investigations on temperature, mass and bending were done using resonance and servo-hydraulic machines (i.e. a resonance machine with a specific frequency of approx. 100 Hz, was used to investigate the impact of additional masses and bending strains on dynamic force measurement). An increase of force deviation was found with an increase of uncompensated masses as well as bending strains. From the results, a procedure for dynamic force calibration of material testing machines was developed, which includes a path for SI-traceability.

Recommendations and guidelines for force metrological services (Objective 4)
The focus of this objective was the development of calibration guidelines for the continuous and dynamic calibration of testing machines and how they can be effectively used by already established metrological infrastructures. In particular, the influence of temperature and parasitic side forces as well as bending moments (Objective 3) were examined and corresponding recommendations with measurement uncertainty specification were issued.
Measurements were carried out on a servo-hydraulic test stand at PTB and, with the help of temperature sensors on the load train and inside the transfer standard, precise statements were made for temperature during continuous calibration. The investigations with tilted plates were carried out at INRIM and provided valuable insights into the influence of spurious side forces and bending moments. Based on this, recommendations including uncertainty calculations for the continuous calibration of testing machines were derived.

The traceability chain developed in Objective 3 for the continuous calibration of material testing machines was found to be very well suited for integration into existing traceability chains for static calibration (i.e. the suitability test of a reference standard was attached to the existing ISO 376 as an annex (Annex E). The continuous calibration of a transfer standard can also be implemented an additional annex (Annex D) to ISO 376. An important factor is that the traceability by specifying classes can be retained, which will increase understanding and acceptance in industry.

The continuous calibration of the testing machine can then be implemented by using an annex (Annex D) to the existing ISO 7500-1. The uptake of these new Annexes was implemented in the modernisation of PTB´s 5 MN Force Standard Machine and provided the ability to realise traceable continuously force ramps up to 5 MN. PTB’s 1 MN and 200 kN Force Standards Machine are also planned to be updated.

While the dynamic calibration of the transfer standard is already addressed in the existing DKD-R 3-10 a new guideline document for the calibration procedure for the dynamic calibration of material testing machines was produced. The DKD board was chosen to be in line with the DKD-R 9 series, which addresses the calibration of testing machines, as DKD-R 9-4.

Impact

The project has produced 12 open access publications in peer reviewed journals such as Acta IMEKO and Measurement: Sensors. As well as being presented 23 times at conferences such as IMEKO TC6 and TC3, the XXIII World Congress of the International Measurement Confederation and (SMSI) Sensor and Measurement Science International. In addition, 5 Masters or PhD thesis were part of this project. Further to this, the project has been promoted on via its website and social platforms such as LinkedIn https://www.linkedin.com/company/18159728 and Instagram https://www.instagram.com/p/CqZ0AHBAeSr/

Impact on industrial and other user communities

The 2 guidelines (Objective 4) developed in this project on (i) recommendations and standards for force calibration of testing machines under continuous applications taking into account parasitic influences from multi-component forces and temperature effects and (ii) recommendations and standards for force calibration of testing machines under dynamic applications taking into account parasitic influences from multi-component forces and temperature effects are available on the project website for stakeholders such as calibration laboratories and industry to access. The guides will provide national and accredited laboratories in Europe with support for improved capabilities and consistency of measurement capabilities. Indeed, PTB intends to introduce traceability chains for continuous and dynamic force calibration into its calibration services for end users (Objectives 3 & 4).

Of particular interest to industrial users, the website also contains 2 videos on how to perform continuous and dynamic force calibrations. The videos explain the new procedures in a practical way and give an impression of the effort required to carry them out, the measurement chain structure and the advantages for the end users.

The project included input and feedback from industrial companies and laboratories as part of its Stakeholder Committee, which included organisations such as ISO/TC 164 SC4 WG 4, DKD FA Material Testing Machines, DIN Material Testing Machines, DKD FA Force & Acceleration, Fujan Metrology Institute, INTI, calibration laboratories, material testing institutes and leading manufacturers of testing machines. Close interaction with the project's Stakeholder Committee, was established in the first months of the project, and ensured that the project was aligned with industry needs.

Stakeholders were also involvement by the project in an interlaboratory comparison between three stakeholders and PTB using special piezo transducers for dynamic measurements (Objective 2 & 3).

In addition, the project's final Stakeholder Workshop was held on 24th of February 2023 as a virtual event. Aspects discussed in the workshop included: (i) advanced practical model for describing force measuring devices used for the measurement of static, continuous, and dynamic forces, (ii) development of Digital Twin concept for force measurement device, and (iii) a traceability chain for metrological services by implementing new improved methods to consider static, continuous and dynamic force calibrations. Registration was via the project website and 42 stakeholders participated in the virtual event. The workshop also included a Q&A session at the end of workshop, which was used to discuss stakeholders needs and the routes for uptake of the project results.

Impact on the metrology and scientific communities

In terms of metrological services, the project developed new calibration methods and guidelines for continuous and dynamic force calibration which are traceable to the SI. As stated above PTB intends to introduce traceability chains for continuous and dynamic force calibration into its calibration services (Objectives 3 & 4). USTUTT also plans to be the first lab to adapt the guidelines (on recommendations and standards for force calibration of testing machines under dynamic applications) in their quality management systems.

Several types of transducers were established during the project (Objectives 2 &3) and used in 3 traceability chains for static, continuous and dynamic force calibration. The traceability chains included 4 transducers of 2 different types of strain gauge transducer and piezoelectric transducers. The traceability chain using piezo transducers was verified for dynamic measurements according to ISO 17025:2018 in an interlaboratory comparison.

The project developed a special transfer standard using high quality acceleration sensors which can be dismounted and used for traceable calibration of dynamic force measurements (Objective 3). A prototype of this transducer (called dynamometer) was manufactured by USTUTT and, provides high quality calibration not currently available using existing commercial transfer standards.

Further to this, the project undertook the calibration of two dynamic transfer standards for the National Institute for Standards (NIS) Egypt.

The project's digital twin model (Objective 2) was developed for the project's transfer standards. The digital twin was used (i) to investigate the influence of creep in the carrier matrix and spring element and (ii) to demonstrate how temperature and strain gauges sensors are able to influence accuracy. The digital twin model is the first developed especially for the field of metrology and can be used by calibration laboratories, material testing enterprises as well as NMIs. The digital twin concept can be accessed via open access publications.

Finally, the 2 sets of guidelines produced by the project (Objective 4): one on the force calibration of testing machines under continuous forces and the other, for under dynamic forces, are to be submitted to EURAMET TC-M for publishing as a EURAMET calibration guide on dynamic force.

Impact on relevant standards

The project has provided input to relevant international standardisation and technical committees such as BSI ISE/101 - Test methods for metals, DIN NA 062-01-45 AA Fatigue testing, BIPM and CIPM CCM (Mass and Related Quantities), ISO TC 164 Mechanical testing of metals, DKD TC Torque, DIN NA 062-08-11 AA Materials testing machines, DAkkS Department 1 and EURAMET TC-M.

The project's new methods and guidelines for continuous force calibration are particularly relevant for ISO TC164/SC1 "Mechanical Testing – Uniaxial testing" and for dynamic force calibration for ISO TC164/SC4 "Fatigue Testing". The project's goal is for their implemented in future updates as Annexes (Objective 4) to ISO 376 and ISO 7500-1 to enable time continuous calibration procedures.

Standardised methods for periodic force measurements have also been described by the project in a DKD-procedure which can be added to the ISO standards. USTUTT is the chair of related DKD and DIN standards committees and has promoted the project's output on the dynamic calibration of a material testing system (DKD-R 9-4) to DKD committee Material Testing Systems and DIN committee Material Testing. Within DKD a workgroup "AG Dynamic Calibration (Dynamische Kalibrierung (DKD-FA WPM)" has been founded of members from material testing institutes from different German federal states.

Longer-term economic, social and environmental impacts

In the longer term, this project will support economic efficiency in future markets involved in force metrology, material testing and mechanical testing. This will be done through the project's development and support of traceable and harmonised methods and procedures needed for the calibration of testing machines and test stands for both continuous and dynamic forces. Long-term the project will enable test results to be more comparable and because of these new methods uncertainties for continuous and dynamic forces can finally be quantified. As a result, improvements in material science will be supported as well as the development of more reliable instruments, better future materials and improved quality control. Further to this, this project has supported advancements in both industry 4.0 and the IoT via the development of a digital twin of force measuring devices.

List of publications

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[3]. J. D. Fidelus, M. Kozuchowski: GUM's Rockwell hardness standard machines after modernization. Acta IMEKO 9 (2020) 5, 240-246, 10.21014/acta_imeko.v9i5.977

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[5]. H. Dizdar, B. Aydemir, C. Vatan: Establishment of continuous force calibration system at TUBITAK UME force laboratory in Turkey, Measurement: Sensors, Volume 18, December2021, https://doi.org/10.1016/j.measen.2021.100216

[6]. M. Hiti: Analysis of loading profile effect on testing machine calibration results, Measurement: Sensors, Volume 18, December2021, https://www.sciencedirect.com/science/article/pii/S2665917421000945

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 September 2019, 42 months	
Coordinator: Rolf Kumme, PTB Tel: +49 531 592 1200 E-mail: rolf.kumme@ptb.de Project website address: https://www.ptb.de/empir2019/comtraforce/home/		
Internal Funded Partners: 1. PTB, Germany 2. CEM, Spain 3. CMI, Czechia 4. INRIM, Italy 5. NPL, United Kingdom 6. RISE, Sweden 7. TUBITAK, Turkey 8. VTT, Finland	External Funded Partners: 9. CU, United Kingdom 10. USTUTT, Germany 11. ZAG, Slovenia	Unfunded Partners: 12. GUM, Poland 13. Inmetro, Brazil
RMG: -		