FINAL PUBLISHABLE REPORT

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1 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.

2 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.

3 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 neighbouring 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).

4 Results

4.1 <u>Objective 1</u>: 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 influence of continuous and dynamic force application.

This objective was met by a range of activities, the results of which all fed into the formulation of the required roadmap. These activities included:

- A review of commercially-available force-measuring devices and associated instrumentation, with the review covering both manufacturers' specifications and the results of additional practical test-work performed by a range of project partners (CEM, NPL, PTB, TUBITAK, VTT, and ZAG)
- A review of the existing force calibration infrastructure within each partner's (TUBITAK, NPL, PTB, VTT, CEM, INRIM, ZAG, Inmetro, RISE) country and, by further research, in other major industrialised countries (France, Japan, Netherlands, Romania, South Africa, Indonesia, Vietnam, China, India, Australia, USA)
- A review of the range of mechanical tests performed within accredited laboratories in partners' (TUBITAK, NPL, PTB, VTT, CEM, INRIM, and Inmetro) countries, together with the associated documented test protocols
- A review of the available documented force calibration methods and procedures in use both nationally and internationally
- Gap analysis looking at how testing machines used for the application of continuous and dynamic forces for accredited materials tests gain their traceability
- Interaction with stakeholders to discuss any issues associated with the existing force traceability hierarchy

Further details of this work are given in the following sections.

The **review of available equipment** looked at force transducers based on both strain gauge and piezoelectric measurement principles, together with the required instrumentation to energise and read from such devices, namely both AC and DC ratio meters for the strain gauge devices and charge amplifiers for the piezoelectric ones. Manufacturers' specifications were studied for all equipment and additional performance tests were carried out.

The following characteristics of the various measurement systems were investigated in detail:

- Repeatability
- Reproducibility
- Reversibility
- Interpolation
- Calibration uncertainty
- Long-term sensitivity drift
- Use of different instrumentation

The review of national **force calibration infrastructures** concluded that traceability for static force is well-established, with NMIs maintaining primary realisations of the newton and its multiples and sub-multiples via a range of deadweight force standard machines. Other force standard machines, based on principles such as lever or hydraulic amplification, strain-gauged columns, and reference transducers, are also used within NMIs to generate known forces. These forces are then disseminated out to end-users either by direct calibration of industrial transducers or via force machines in secondary calibration laboratories which obtain their traceability from the NMI's machines.

For non-static forces, the infrastructure is practically non-existent. Only one laboratory was found to be accredited for continuous force measurement (in accordance with DKD-R 3-9) and two laboratories for dynamic force measurements (in accordance with ASTM E467).

The **review of materials testing** currently performed within accredited laboratories identified a wide range of methods, virtually none of which employed static forces. These methods ranged from standard tensile testing, in which a specified strain rate needs to be applied, to hardness testing, in which large changes of force are required in short periods of time, to fatigue testing, in which the specified force needs to vary continuously.

The **review of existing documentation** identified a large number of calibration methods, for both transducers and machines, in the field of static force. There were also a number of documents related to dynamic force calibration, mainly in relation to fatigue testing, but very little related to continuous force calibration. The following Table 1 summarises the findings.

Table 1 Review of existing documentation on calibration methods

	Static Force		Continuous Force	Dynamic Force
Transducer Calibration	ABNT NBR 8197 ASTM E74 BS 8422 CEM ME-002	DIN 51308 DKD-R 3-3 ISO 376 VDI/VDE 2624-2.1	DKD-R 3-9	DKD-R 3-10(2)
Machine Calibration	ASTM E4 DIN 51302-2 EN 12390-4 ISO 7500-1 ISO 7500-2	ISO 4545-2 ISO 6506-2 ISO 6507-2 ISO 6508-2 ISO 14566 - Charpy		ASTM E467 DKD-R 3-10(3) ISO 4965-1 MIL-STD-1312B NASM 1312
General	DKD-R 3-10(1) EURAMET cg-4			

In addition to these force calibration documents, the review covered those documents related to force traceability for materials testing where the measured quantity is not a value of force, but another parameter whose measurement could affect the validity of the force measurement or test result. These documents are detailed in the Table 2.

Table 2 Review of existing documentation on force traceability for materials testing

	Static Force	Continuous Force	Dynamic Force
Acceleration			ISO 16063-1
Alignment	ASTM E1012 EN 12390-4 ISO 23788	ASTM E1012 ISO 23788	ASTM E1012 ISO 23788
Displacement / Speed	ASTM E2309 / ASTM E2658		
Extensometry	ASTM E83 ISO 9513		
Temperature			ISO/TS 21913
Voltage	ASTM E74 ISO 376		ASTM E1942 DKD-R 3-2 ISO 4965-2

The **stakeholder engagement exercise** took the views of three different user groups:

1. high quality accredited (for static force calibration only) laboratories;
2. materials testing laboratories, with modernised machines;
3. and other industrial end-users.

There were many criticisms of the existing situation, covering a wide range of topics, including: (i) traceability and uncertainty for fatigue testing; unclear alignment procedures; (ii) lack of procedures and uncertainty guidance for low frequency testing; (iii) lack of specifications relating to adaptors and clamping; (iv) effect of temperature on dynamic force measurement; (v) and lack of calibration procedures for piezoelectric transducers.

Based on this feedback, and the results of the other activities described, the following roadmap was prepared, see Figure 1.

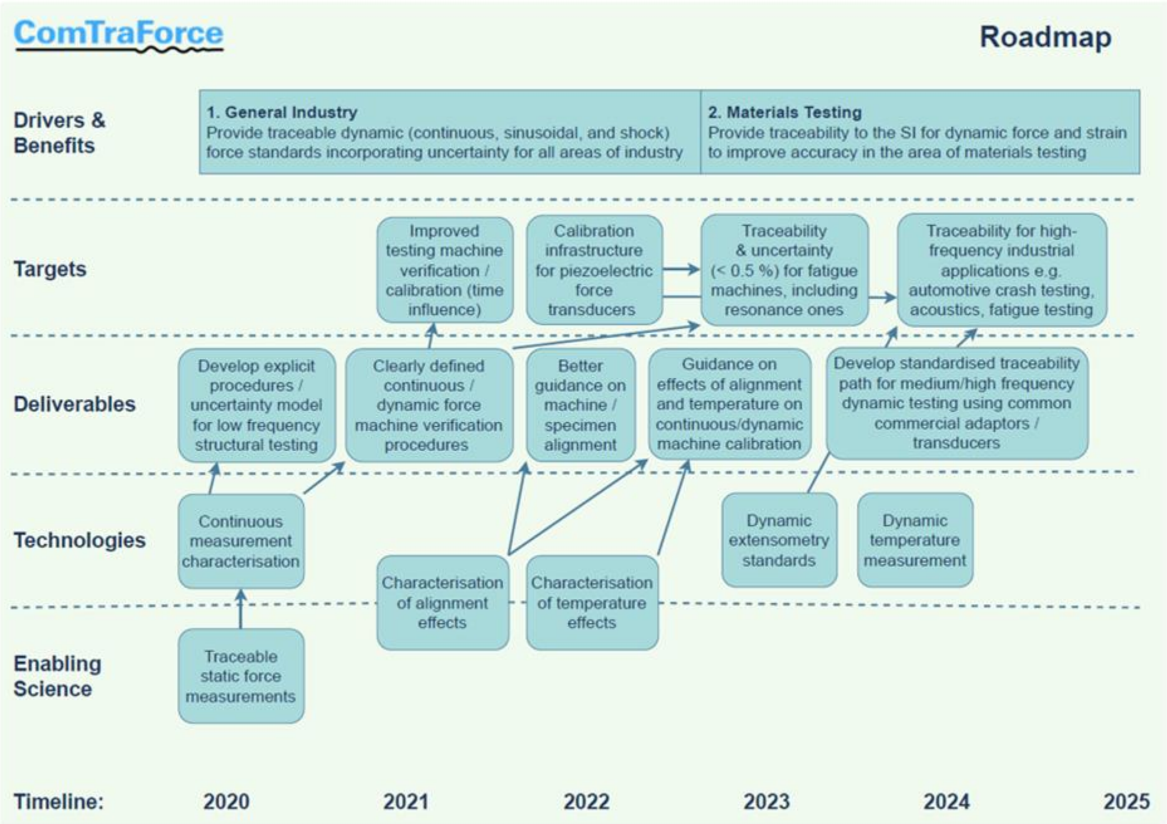

Figure 1 Roadmap detailing the future requirements for improved force transfer standards and associated calibration methods for force testing machines taking into account realistic uncertainties

Conclusions

The project met Objective 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.

The consortium used its 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 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 influence on dynamic testing.

4.2 *Objective 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 and 1000 Hz.*

In the scope of the project, three different approaches were selected to describe the relevant properties and the interference effects of force measuring devices adapted to the required accuracy for the respective area of application. These approaches were divided **into (i) static, quasi-static to continuous, (ii) dynamic and (iii) an FEM-based approach**.

The range below 1 Hz is referred to as from continuous, quasi-static to static. Here, the properties of force measuring devices can be determined with the help of dead-weight machines, which have a high level of accuracy (U<0.002 %), which is why the target uncertainty of even less than 0.1 % can be achieved for this range.

Various types of force transducers (**strain gauge** and **piezoelectric**) were examined with regard to their properties and their influenceing disturbance variables for static and continuous force measurements. As a first point of reference, **static calibrations** for the estimation of the **sensitivity** were carried out according to the established standard **ISO 376**.

Figure 2 Investigation of a force transducer at different temperatures using a climate chamber

To investigate the **time-dependent behaviour**, knowlegde of which is essential for measuring continuous force, measurements were carried out according to **DKD-R 3-9 Annex A3.1 – A3.3**.

These include fast loading measurements in which, unlike static calibration, the load is applied in one step and the reading is taken immediately after stabilisation (approx. 1-3 s after the load was applied).

For further investigation, the signal behaviour was recorded at maximum load and after the subsequent unloading over a period of approx. 5 mins and the influence of different filter settings was examined.

Figure 3 Investigation of the influence of spurious side forces and bending moments using tilted plates

These investigations were carried out by PTB, TUBITAK, CEM, VTT, CMI and INRIM, and done in order to increase confidence in the later developed model, partly using the same force transducers as well as using their own force transducers in the respective calibration facilities. TUBITAK also examined piezoelectric force transducers.

Investigations regarding the **influence of temperature** on the sensitivity (PTB, CEM) and on time-dependent behaviour (PTB) were carried out (Figure 3). ZAG examined the influence of different loading times on the unloading behaviour of strain gauge force transducers and also carried out temperature tests by allowing the entire room to be heated to different temperatures. INRIM determined the **influence of spurious side forces and bending moments** on the sensitivity using special tilted plates (Figure 2). USTUTT and PTB used a self-developed strain gauge force transducerto test a **new method for identification of the model parameters and validating** a model-based correction of the time dependent behaviour.

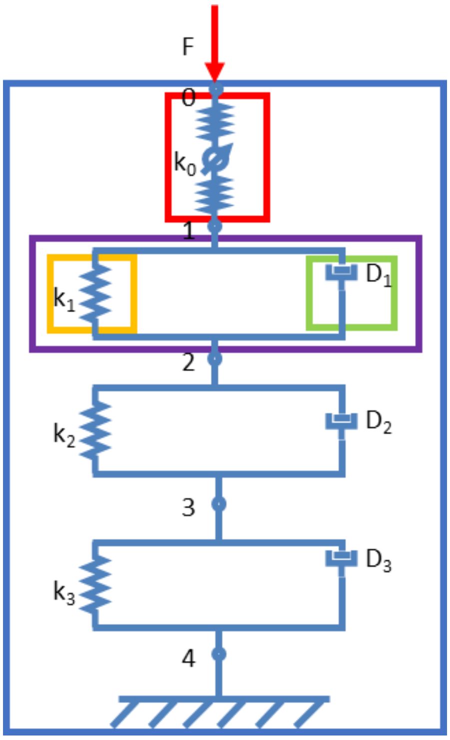

Figure 4 Extended generalized Kelvin Model: Red - Extended Hooke element; Yellow – Hooke element;. Green – Newton Element: Purple – Kelvin -Voigt element

For the range below 1 Hz, an **extended generalised Kelvin model** (**Error! Reference source not found.**) turned out to be suitable for describing force measuring devices.

This extended generalised Kelvin model consists of an extended Hooke element connected in series with up to three Kelvin-Voigt cells, which in turn consists of a Hooke element (spring) connected in parallel with a Newton element (damper).

The elongation of the elastic element of a force transducer after a step function can thus be described as:

$$\begin{aligned}\delta = (1 - d(F)) \cdot \frac{F}{k_0} + F \\ \cdot \left[\left(\frac{1}{k_1} - \frac{1}{k_1} \cdot e^{-\frac{k_1}{D_1}t} \right) + \left(\frac{1}{k_2} - \frac{1}{k_2} \cdot e^{-\frac{k_2}{D_2}t} \right) \right. \\ \left. + \left(\frac{1}{k_3} - \frac{1}{k_3} \cdot e^{-\frac{k_3}{D_3}t} \right) \right]\end{aligned} \tag{1}$$

However, since this ideal behaviour is disturbed by parasitic influences such as temperature, spurious side forces and bending moments, in practice, a **practical model** need to be found which is more suitable for the description of the force measurement.

This practical model uses a third-degree polynomial as a transfer function formed from the values determined from the fast loading or a continuous calibration.

$$F_{tra} = R' \cdot X^3 + S' \cdot X^2 + T' \cdot X \tag{2}$$

Then, correction factors are determined from the investigations carried out and combined in a product model.

$$\begin{gathered} F = F_{tra} \cdot \prod_{i=1}^{N} K_i \\ with \\ K_i = \left(1 + \frac{\delta x_i}{|x_i|} \right) \end{gathered} \tag{3}$$

An uncertainty must be specified for each correction and as well as for the influences which cannot be corrected. In the case of continuously calibrated force measuring devices, the influences shown in Figure **5** must be taken into account.

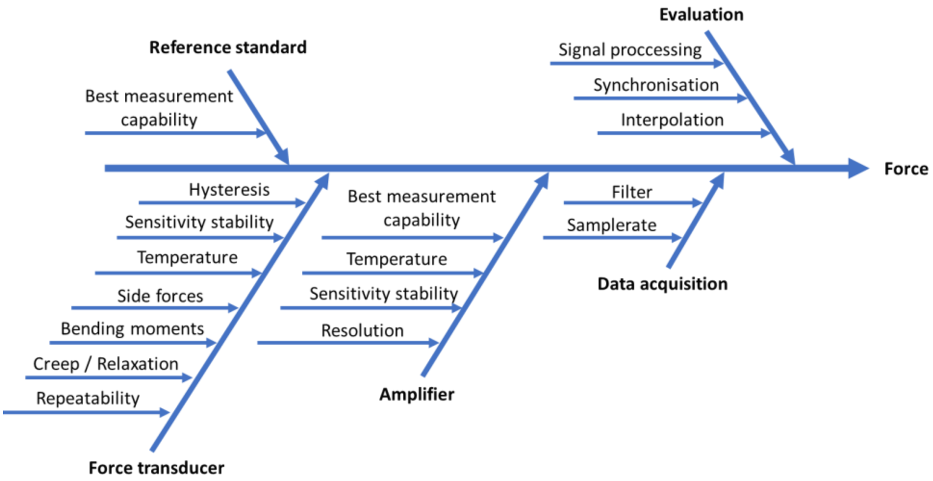

Figure 5 Ishikawa diagram of all influences on the indication of a force measuring device for continuous, quasi-static and static forces

The second part of objective 2 involved developing an advanced model for force transducers under **dynamic force conditions.** The strain gauge transducers selected in the project were measured using an electrodynamic shaker (see Figure 7) in the range from < **20 Hz to > 2 kHz.**

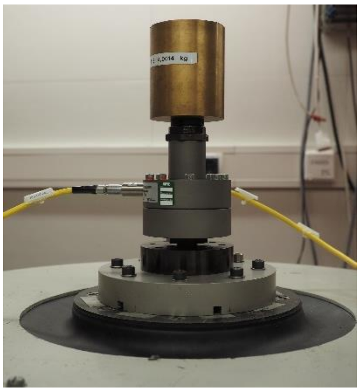

Figure 6 Force transducer mounted on the shaker

The force generation is performed by different top masses m_t.

The **dynamic sensitivity** of the force transducer as a function of frequency and model parameters were defined as part of the calibration process according to the guideline **DKD 3-10 sheet 2** which describes a force transducer as a head mass m_i connected to its base mass m_b by a spring of constant k_f and a damper b_f (see Figure 6)

$$S_f = \frac{U_f}{a_t(f).[(m_a + m_i) + (m_t.k_0)]} \tag{4}$$

In order to define model parameters, a **new measurement method** was suggested by PTB which provides a good understanding of the **rocking motions,** by using a scanning laser vibrometer to perform measurements at several points all around transducer at the bottom of the set-up (Figure 8).

This is an alternative approach to one-point acceleration measurement with the piezoelectric sensor which suffers from the lack of the rocking motion information as the main source of uncertainty in the acceleration measurement and hence force.

The latter (one-point acceleration measurement) was used by RISE as a proven method to verify PTB's new measurement method and to quantify measurement uncertainty.

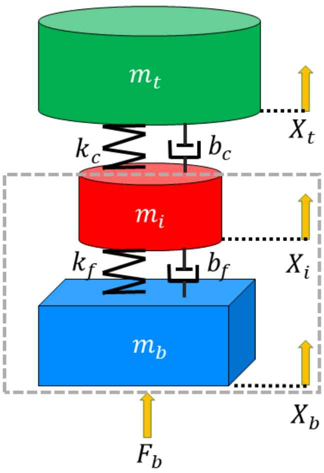

Figure 7 Schematic demonstration of the Kelvin-Voigt model

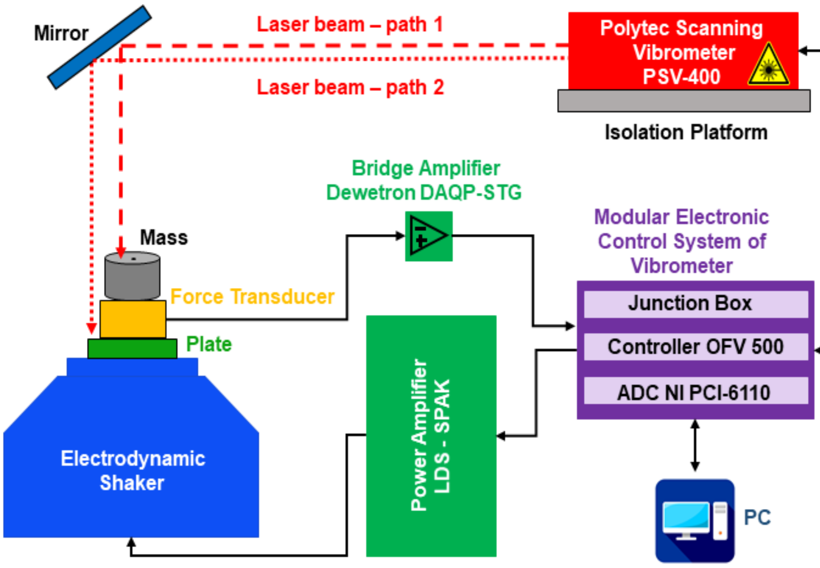

Figure 8 Dynamic force measurement set-up

In the new measurement method, a **periodic chirp** is selected to excite the shaker which allows **high-speed measurements** to be performed with **higher resolution** in comparison to sinusoidal excitation. It also provides a greater amount of measurement data which is important for the training of **artificial neural networks (ANN)**.

ANNs have outperformed other machine learning methods in several disciplines including metrology over the past years.

The investigations in the time and frequency domain reveal the complexity of the measuring and modelling of transducers under dynamic conditions with the shaker, where the traditional approaches come to their limits, and they may not meet the automation needs where much effort must be devoted to describing complex effects.

Therefore, we advocate using ANNs to eliminate the effect of the rocking motion of the calibration assembly due to the ability of ANNs to identify structure and non-linear patterns in a recorded signal and eliminating **parasitic effects**. This in turn should result in more stable and reliable model parameters, especially the damping coefficient

Figure **9** demonstrates the frequency response of the dynamic force calibration system as the ratio between measured acceleration on top mas and bottom as well as the fitted Lorentzian function. The stiffness and damping coefficient of the transducer can be calculated as follows:

$$K_f = (2\pi . f_0)^2 . [m_a + m_i + (m_t \cdot K_0)] \quad (5)$$

$$b_f = \frac{\Delta f}{f_0}\sqrt{k_f . [m_\mathrm{a} + m_\mathrm{i} + (m_\mathrm{t} \cdot K_0)]} = \frac{1}{Q}\sqrt{k_f . [m_\mathrm{a} + m_\mathrm{i} + (m_\mathrm{t} \cdot K_0)]} \quad (6)$$

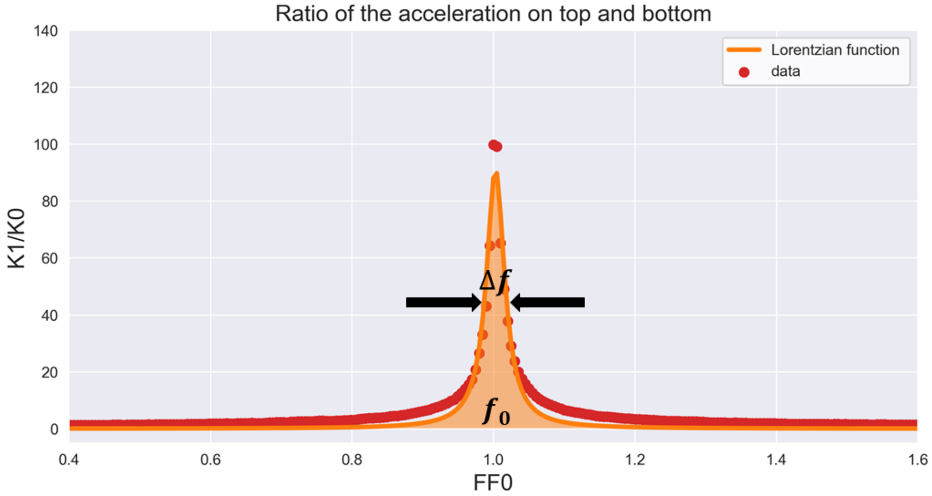

Figure 9 Resonance curve and Lorentzian function fit obtained after periodic chirp excitation to define model parameters

The **head mass** of the transducer is defined with two methods; (i) the method described DKD 3-10 sheet 2 and (ii) by rotating the transducer in the earth's gravitational field.

However, the latter method gives more reliable results.

Figure 10 demonstrates the dynamic sensitivity of the 20 kN GTM transducer for the measurements performed with head masses.

For frequencies below 800 Hz the head masses are in good agreement with the static sensitivity and reveal a **deviation of less than 1 %**.

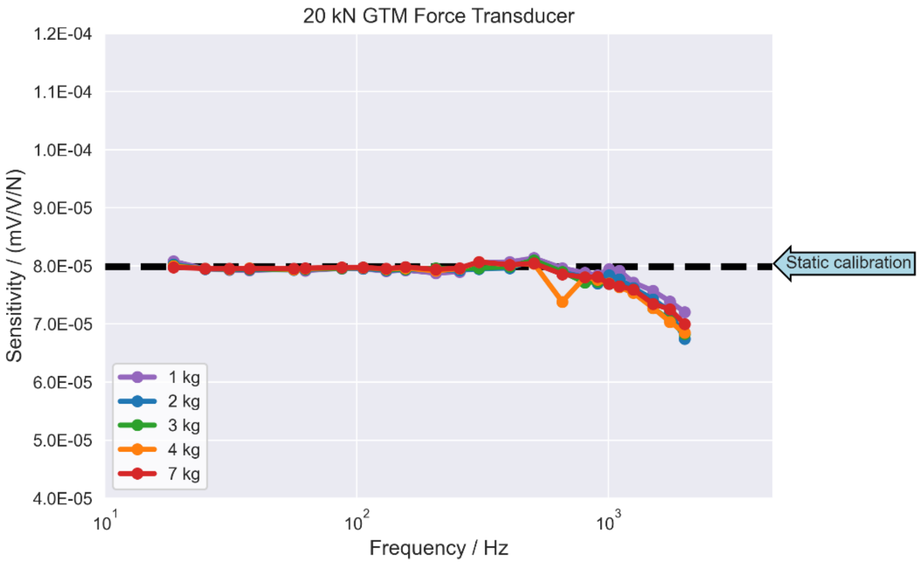

Figure 10 Dynamic sensitivity of 20kN GTM force transducers

It should be noted that the new measurement method developed by PTB is applicable to all types of set-up configurations where a laser scanning vibrometer is available. Furthermore, for the implementation of the **AI algorithms** an open-source python library, namely **Tensorflow** was chosen.

All suggested ANN architectures are available as build-in mathematical model in their simplest form which can be arbitrary customised. Thus, this could facilitate the validation of PTB's new method by other partners with their own generated data. The model definition also paved the way for the project's development of a **model-based digital twin**.

The third part of objective 2 was to develop a digital metrological twin of a force measuring device based on advanced models described above.

Firstly, the creep strain effect on the metrological performance of a force measuring device was investigated by CU and was found that the major source of creep is the carrier matrix of the strain gauge. Additionally, a digital metrological twin based on Larson-Miller equation was proposed that can indicate the safe use of the force cell. Following this, simplified geometrical models were used to perform analytical stress-strain analysis of the transducer developed within objective 3 and to determine creep strain rate of transducer materials. The analytical models were developed to validate subsequent more complex finite element analysis (FEA) models of the real force transducer used in static calibration. FEA static calibration models and the equivalent analytical solutions were in good agreement, but did not agree with the experimental results, which include additional error sources.

FEA model for continuous calibration was aimed at 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 the literature reported a dominant effect for the strain gauge relaxation behaviour, which has an opposite trend to the one associated with thermal creep of the load cell.

For dynamic force calibration, FEM modelling was used to evaluate the sensor behaviour under cyclical loading. The FEM simulations were able to reproduce the range of temperature variations previously reproduced experimentally, which were attributed to thermomechanical effects. However, the effectiveness of the simulations was hindered by the computational limitations of FEM.

At the same time, routines were developed to read a Digital Calibration Certificate (DCC) to enable the traceability to of the digital metrological twin information to the SI system.

Additional work covered the data storage in the current digital metrological twin concept, but not realised at this stage, and Python communication strategies that can be used in a digital metrological twin, see Figure 11.

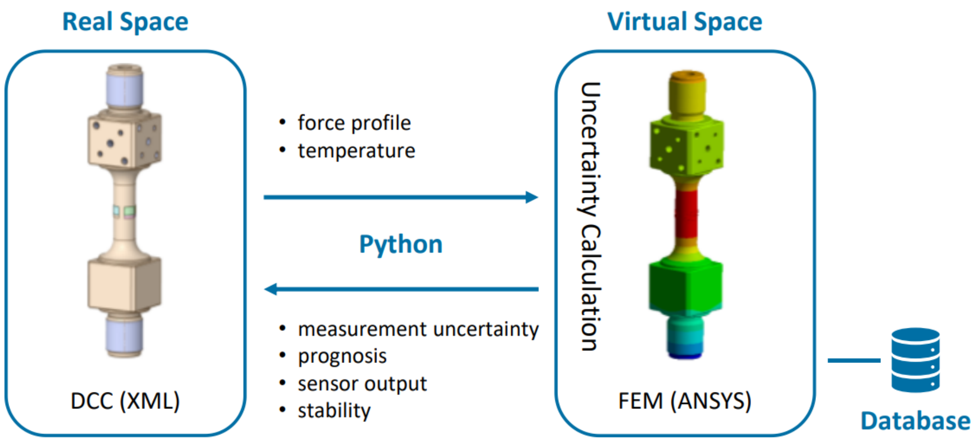

Figure 11 Concept of a Digital Metrological Twin of a force measurement device

A drawback of the current work is the lack of accurate FEA modelling of strain gauge behaviour. The main modelling efforts were concentrated on developing a comprehensive computational model of the entire device, which lead to a mismatch between the element size required to simulate the beam response and the accurate strain sensor response. Therefore, future modelling work should cover ‘real’ strain gauge behaviour.

Nevertheless, the methods of determining experimentally the creep behaviour contributed to a comprehensive force sensor surrogate measurement model. Given the variability in the sensors output, AI technologies could be used with experimental studies to predict strain gauges creep behaviour in the future.

The FEA models developed can be used to establish uncertainty information, means and standard deviations, associated with the effect of sensor position on the body of the dynamometer, bending moments, tilt and side forces to the transfer standard measurement output, and propagate them with an updated measurement model using the GUM S1 Monte Carlo approach. In this way, the digital metrological twin can be used to replace black-box calibration approaches and enable the prediction of the strain gauges output.

Conclusions

The project met Objective 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 and 1000 Hz.

The parameters of the models developed here for static to continuous forces can be determined with an uncertainty of less than 0.1 %. Measurements with a shaker system using a Kelvin-Voigt model up to 800 Hz showed a deviation of less than 1 % compared to the statically determined value. However, much effort was devoted to developing a sophisticated method for the measurement and the evaluation of the data to reach a better understanding of parasitic effects which previous studies have provided only partial insight into. This can in turn help to suppress the uncertainty below 2 % for frequencies up to 1000 Hz and even beyond that.

Development of digital constructs necessary for the digital metrological twin of a force transfer standard in relation to its static, continuous and dynamic behaviour based on FEA and analytical modelling were also discussed. A drawback of the current work is the lack of accurate FEA modelling of strain gauge behaviour as well as high required computational effort. However, the FEA models developed can be used to establish uncertainty information, means and standard deviations as well as used a basis for further development of digital metrological twin.

4.3 *__Objective 3__: To develop a force traceability chain for metrological services by implementing new improved methods to consider static, continuous and dynamic force calibrations across a frequency range of 0 Hz to 1000 Hz in a force range from 1 N to 1 MN.*

The work aimed to developing force traceability for continuous force application testing requirements. A prime example of this is the standard ambient temperature tensile test, as detailed in ISO 6892-1, in which the rate of change of strain applied to the testpiece is defined by the standard, resulting in a continuously increasing force throughout the material's elastic regime during a period that may last for only a small number of seconds.

Figure **12** shows force against time profiles for four different steel testpieces, and profiles for the calibrations of the machine (to ISO 7500-1) and the load cell (to ISO 376) used to calibrate the machine.

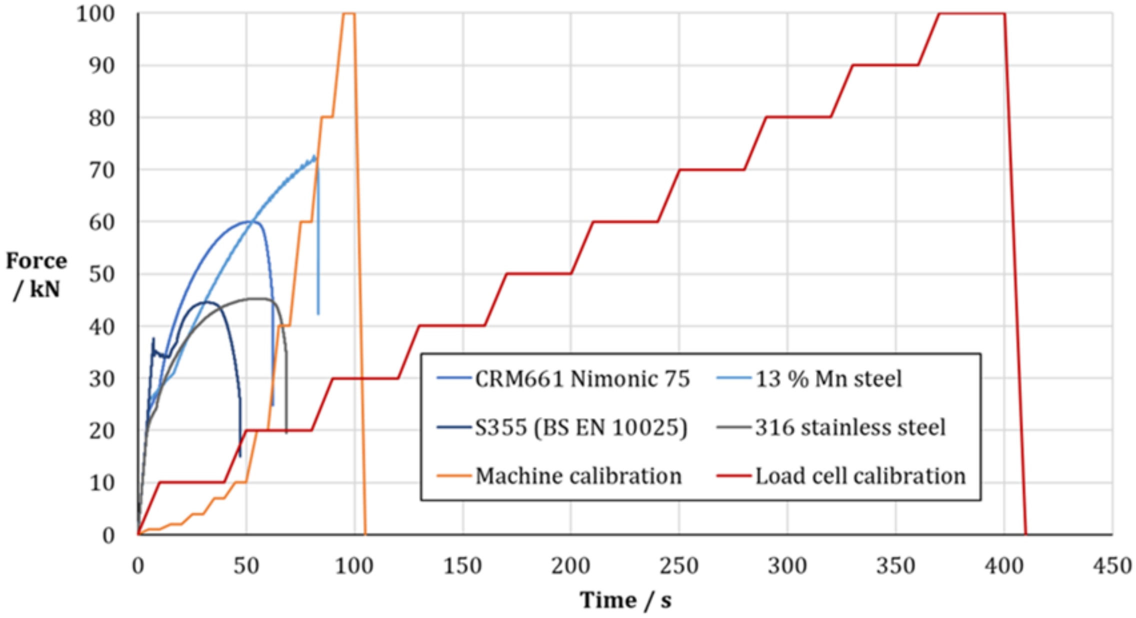

Figure 12 Diagram demonstrating force against time profiles for four different steel testpieces

In Figure 12, all four elastic regimes last for no longer than 7 s, while the time taken to reach these force limits during both calibration exercises is an order of magnitude greater. Thus, if there are any significant time-related force measurement sensitivities in either the machine or the load cell used to calibrate it, there could be a significant error in the magnitude of the force values recorded during the test. For this reason, a methodology to calibrate the machine following a force-time profile similar to that used during actual testing is needed and was developed by this project.

As well as the development of this methodology, the project also looked at four other aspects of force measurement related to continuous traceability:

1. potential influence factors which may affect the machine's force-measuring system, including short-term creep, hysteresis, temperature, data synchronisation, and instrumentation;
2. the effect of alignment and non-axial force application;
3. an uncertainty model for ISO 6892-1 test results;
4. and traceability for multicomponent force and moment measurements.

The results of this work are summarised in the following sections.

The work to investigate **potential influence factors** was carried out independently by partners GUM, Inmetro, NPL, PTB, TUBITAK, and ZAG, resulting in a comprehensive report covering all five of the identified parameters (i.e. short-term creep, hysteresis, temperature, data synchronisation, and instrumentation). The results of this work were used both to inform the data synchronisation procedures within the continuous calibration protocol and to derive sensitivity coefficients for use within uncertainty budgets.

Partners NPL, INRIM, TUBITAK, VTT, and ZAG, carried out work investigating the **effect of non-axial alignment** during testing, using both modelling and practical testing techniques. These tests covered a range of materials, dimensions, misalignments, and test parameters, including yield strength, tensile strength, Young's modulus, fatigue life. Again, the results of this work provided sensitivity coefficients for use within uncertainty budgets, enabling the effect of possible misalignments to be incorporated in the uncertainty derived for a given material parameter.

An **ISO 6892-1 uncertainty model** has also been developed. This incorporates uncertainty contributions resulting from three stages of the force traceability process:

- calibration of the force-proving instrument in accordance with ISO 376;
- calibration of the testing machine to ISO 7500-1 using the force-proving instrument;
- and the subsequent use of the machine to perform the tensile test.

The ISO 376 uncertainty calculations are based on Annex C.1 of ISO 376, with the ISO 7500-1 uncertainty calculations based partly on Annex C of ISO 7500-1, partly on Annex C.2 of ISO 376 (Uncertainty during the force-proving instrument's subsequent use), and partly on other identified potential uncertainty contributions. 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 proving instrument calibration) with other identified uncertainty contributions.

The work on **traceability for multicomponent force and moment measurements** was performed independently by partners INRIM, TUBITAK, USTUTT, VTT, and ZAG, and resulted in a final 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 led to the definition of a comprehensive model for uncertainty assessment of forces and moments in industrial applications.

The project developed methodology for producing a **traceability path for continuous force measurements**. The work can be split into three major areas:

1. Validation of a continuous force reference standard
2. Calibration of force-proving instrument against this reference standard
3. Calibration of testing machine against this force-proving instrument

The main characteristics required for a **continuous force reference standard** are that it gives an accurate force value over short time periods and that this value is in a format capable of being recorded for post-processing purposes.

The first of these criteria can be satisfied by specifying that it needs to meet the Class 00 requirements when statically calibrated to ISO 376 and that it exhibits low levels of short-term creep. This creep requirement can be demonstrated by subjecting the device to a creep unloading test, as the relative magnitudes of creep and creep recovery are, while not likely to be identical, normally of similar values. In addition, unlike a creep test in which it can be difficult to stabilise the magnitude of the applied force within a fraction of a second, a rapid removal of force to zero is more easily accomplished. If the device has had the maximum calibration force applied for at least five minutes, it is suggested that a variation in output of no greater than 0.02 % of the deflection at maximum force in a time period of 10 mins after it is clear that the force has been fully removed would be a sufficient limit on the capability of the device.

The **calibration of the force-proving instrument** against the reference standard should be carried out with the two rigidly attached to each other on the central axis of the force machine used. It may be that a standard testing machine is the optimum machine for this purpose, as the force application rate should be easier to set and control e.g. as opposed to a deadweight force standard machine.

Both instruments should use similar instrumentation with nominally-identical settings such as filter type and frequency and synchronous acquisition of data. The calibration should be carried out over a range of different loading rates, with the results analysed as follows:

- Check that nominally-synchronised data is synchronised – this can be done by repeating one test with the transducers and instrumentation modules switched, with the channel time offset determined by the shift in time data required to achieve the same results in the two runs
- For each pair of data points, calculate the force-proving instrument sensitivity by dividing its deflection by the applied force, calculated from the reference standard deflection and its static calibration coefficients
- For each run, determine a best-fit equation for the force-proving instrument sensitivity as a function of applied force, then determine the fitted sensitivity values at each calibration force of interest
- Determine the spread in the force-proving instrument sensitivity at the different loading rates at each calibration force
- Base the force-proving instrument calibration classification on the magnitudes of these spreads and on the results of its static calibration to ISO 376

The **calibration of the testing machine** has some similarity to the calibration of the force-proving instrument (e.g. similar range of loading rates) but there are significant other effects/complications that need to be considered and taken into account.

The first of these effects is that the two sets of data are likely to be taken using two independent data acquisition systems. Both systems will provide data giving output against time, but there is no guarantee that the clocks will be running at exactly the same speed in the two systems. For this reason, an additional test run should be included which incorporates a number of step force changes – the first phase of the analysis is to compare these traces and adjust the time-base of one set of data such that the two traces will overlay each other.

The second complication is that the data is not likely to be acquired synchronously, leading to a need for interpolation between values, using either a simpler approach or, for noisier data, one based on localised linear interpolation, as per the following two examples, see Figure 13, where the error at a machine reading of 600 N is determined:

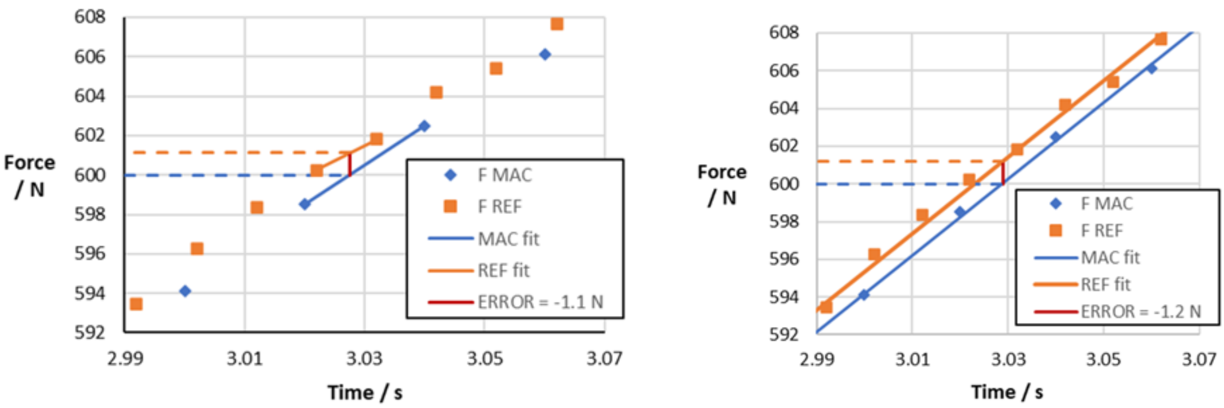

Figure 13 Examples of various interpolation approaches of measured data and resulting errors

Once the time-bases have been correctly adjusted and the data traces roughly synchronised, a plot of machine error against applied force can be generated, see Figure 14.

However, if not perfectly synchronised, this is likely to show significantly different errors for incremental and decremental errors, even near maximum force. Therefore, one way to optimise the synchronisation is to adjust it until the errors near the maximum force (e.g. 95 % of maximum force) are equal, as in Figure 14, in which the offset has been optimised from the original 3.000 s to 2.983 s:

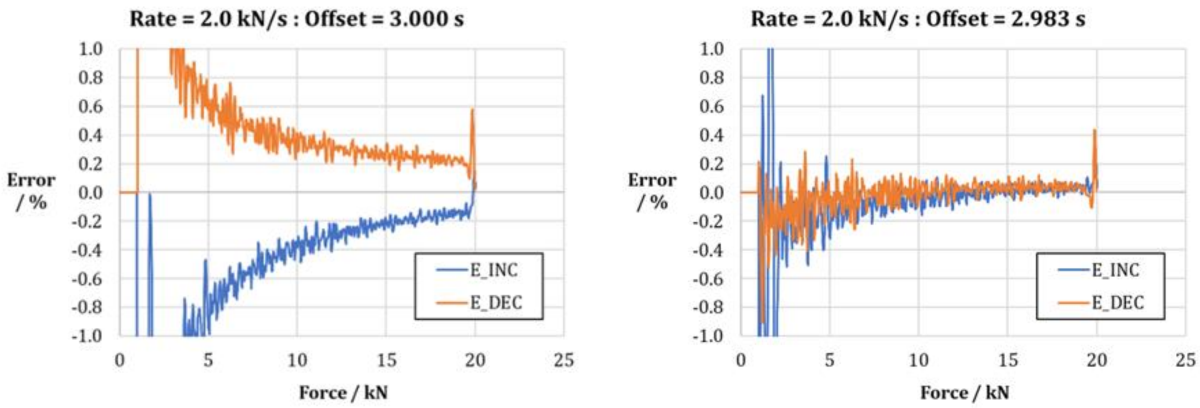

Figure 14 Diagram showing machine error against applied force using incremental and decremental errors

Once synchronisation has been optimised, the errors at calibration forces of interest can be derived from fits to these error traces, for each force application rate.

However, the uncertainty associated with these results will need to take into account components relating to the error estimation and data synchronisation, as well as the uncertainty of the proving instrument. As can be seen in Figure 14, these are likely to be major components so care should be taken in estimating them correctly.

For the development of a traceability chain for metrological services in the dynamic calibration of material testing systems it was decided to develop an optimised design with additional sensors. This was decided while reviewing the existing dynamic force calibration technology in Objective 1.

In parallel, metrological methods for dynamic traceability were debated.

Finally, two commercial force transducers were selected and equipped with PT 100 temperature sensors, which are directly connected to the strain gauge measuring bridges for investigations of a temperature influence.

A special transducer was also developed, called dynamometer, which is as similar as possible to the test probe used in material testing and which extends the measurement capabilities of the transducers described in existing standards, such as ISO 4965-1, ASTM E467 and DKD-R 3-10, Sheet 3.

The goal was to build a calibration set-up which allows the quantification of parasitical influences, such as temperature, bending, stiffness and uncompensated masses. Therefore, the dynamometer was equipped with two more planes of strain gages to measure bending strains and temperature in addition to the force measuring plane. To simulate stiffness and uncompensated masses of the real test set-up, special adapters were developed, which can be mounted to the dynamometer and to the commercial force transfer standards. The masses can be equipped with acceleration sensors to derive their inertial force.

Besides the durability of the dynamometer, the fatigue and operation behaviour of the new developed stiffness adapter and mass adapter were investigated. A model and a manufactured calibration set-up are shown in

Figure **15**.

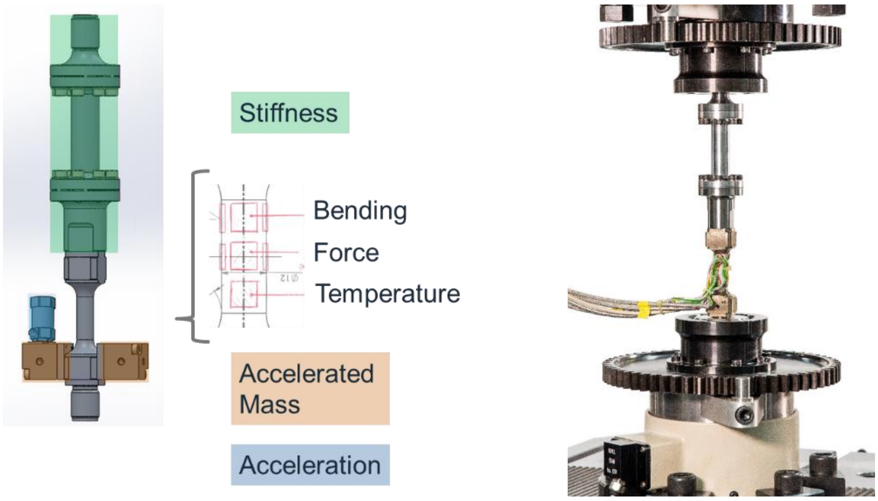

Figure 15: Set-up designed for dynamic machine calibration, with revised stiffness adapter; left: model; right: manufactured set-up applied to a 50 kN Rumul resonance testing system during approval

Investigations on temperature, mass and bending influences were done on resonance and servo-hydraulic machines. On a resonance machine with a specific frequency of approx.100 Hz, the impact of additional masses and bending strains on dynamic force measurement was studied. An increase of force deviation was found with an increase of uncompensated masses as well as bending strains (Figure 16, 17 &Figure **18**).

A full traceability chain for dynamic force calibration of material testing machines was developed, and consists of five main parts:

1. Introduction with definitions, purpose, scope, basic principle and set-up;
2. Preliminary work with requirements, e.g. static calibrations of machine and transfer standard, alignment verification, dynamic calibration of transfer standard, parameter matrix;
3. Dynamic calibration with details to parameter sets, cyclic loading and data evaluation;
4. Uncertainty estimation;
5. Appendices with informal content as well as mandatory information, e.g. calibration certificate and handling recommendations.

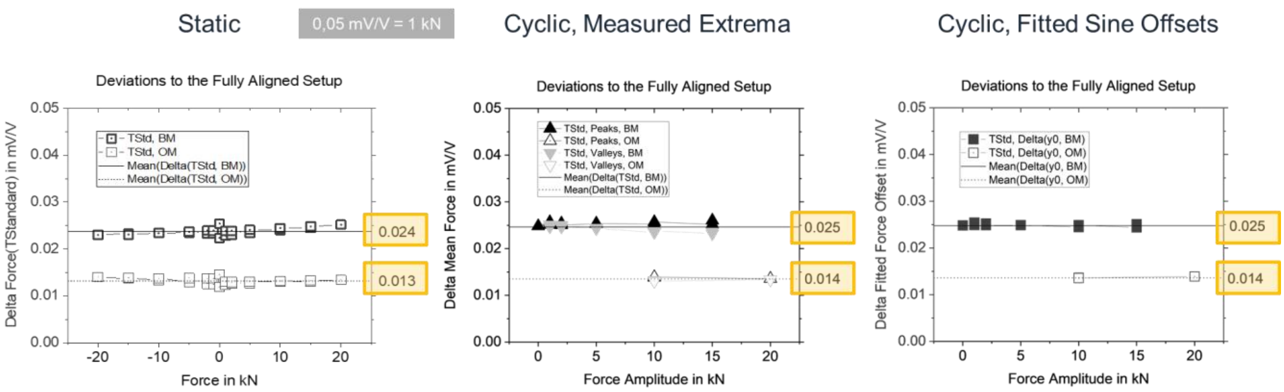

Figure 16: Force deviation due to bending strains, measurements at about 100 Hz on a 50 kN Rumul machine; left: static loadings; middle: cyclic loadings, extreme values evaluated, right: cyclic loadings, mean force y_0 evaluated

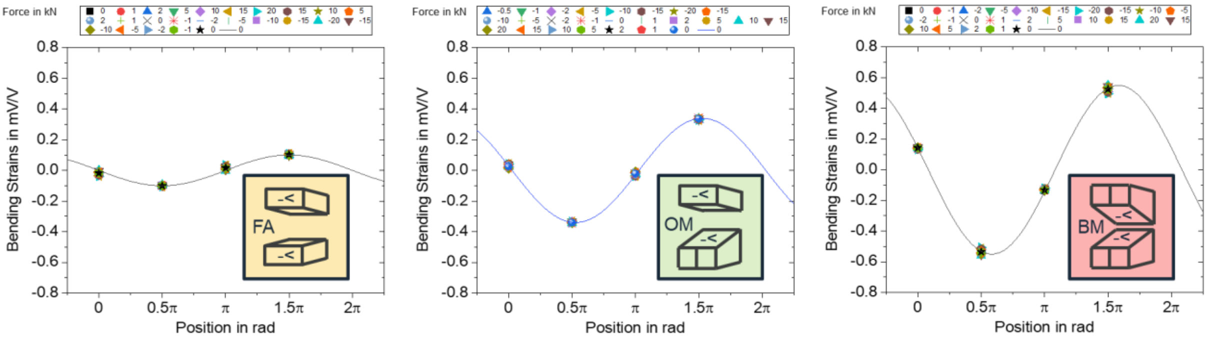

Figure 17: Calculated bending strains as a function of circumference under static loadings

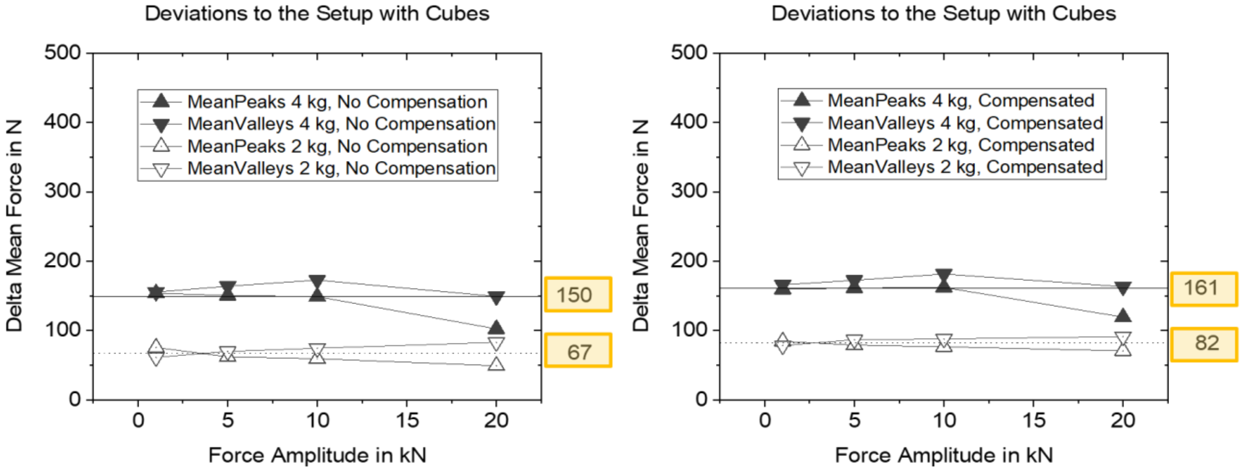

Figure 18: Force deviation due to additional masses, measurements at approx. 100 Hz on a 50 kN Rumul machine, where estimated masses to be compensated are: set-up with cubes (reference set-up): m≈13.7 kg, set-up named 2 kg: m≈18.7 kg, set-up named 4 kg: m≈20.7 kg; names of the set-ups, respectively the graphs in the charts are derived from mass elements excluding mounting elements; the differences between estimated masses and masses named are due to changes in mounting equipment needed to apply the masses; estimated masses are masses between sensing element of machine’s force transducer and force plane of the dynamometer; left: mass not compensated by the software of the testing system, right: mass compensated by the software of the testing system, the value of computational compensation was set to 18.7 kg in the cases of 2 and 4 kg measurement series and to 13.7 kg in case of reference measurement with cubes.

Conclusions

The project met Objective 3, to develop a force traceability chain for metrological services by implementing new improved methods to consider static, continuous and dynamic force calibrations across a frequency range of 0 Hz to 1000 Hz in a force range from 1 N to 1 MN.

The project developed a comprehensive methodology for producing a traceability path for continuous force measurements, based on three major verification activities which were described in detail: (i) validation of a continuous force reference standard; (ii) calibration of a force-proving instrument against this reference standard; and (iii) calibration of a testing machine against this force-proving instrument. An uncertainty budget related to the results of a tensile test in accordance with ISO 6892 1 was also developed, using the results of investigative tests to help define sensitivity coefficients. Furthermore, guidance on synchronisation of data from different force measurement sources was drafted.

In the case of dynamic force calibration services for material testing systems a chain was developed to ensure SI-traceability, which was published as the DKD guideline DKD-R 9-4. Connected to this a calibration set-up has been built to provide measurement capabilities for dynamic forces as well as parasitic influences such as bending strains and temperature and impacts by stiffness/frequency and uncompensated, accelerated masses.

4.4 *Objective 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 neighbouring countries.*

Internationally accepted guidelines increase confidence in calibration results and help to ensure comparability of measurement results. For these guidelines to be effective they must describe how a calibration should be carried out and which parasitic influences should be taken into account and how they should be taken into account in the measurement uncertainty budget. This work focussed on the development of calibration guidelines for the continuous and dynamic calibration of testing machines and how they can be efficiently implemented in already established metrological infrastructures. In particular, the influence of temperature and parasitic side forces as well as bending moments were examined and corresponding recommendations for measurement uncertainty budgets were developed.

Continuous calibration:

At PTB, measurements were carried out on a servo-hydraulic test stand and, with the help of temperature sensors on the load train and inside the transfer standard, accurate statements were derived on temperature during continuous calibration. In addition, thermographic pictures was produced of the temperature gradients caused by heat flows using thermography, see Figure 19.

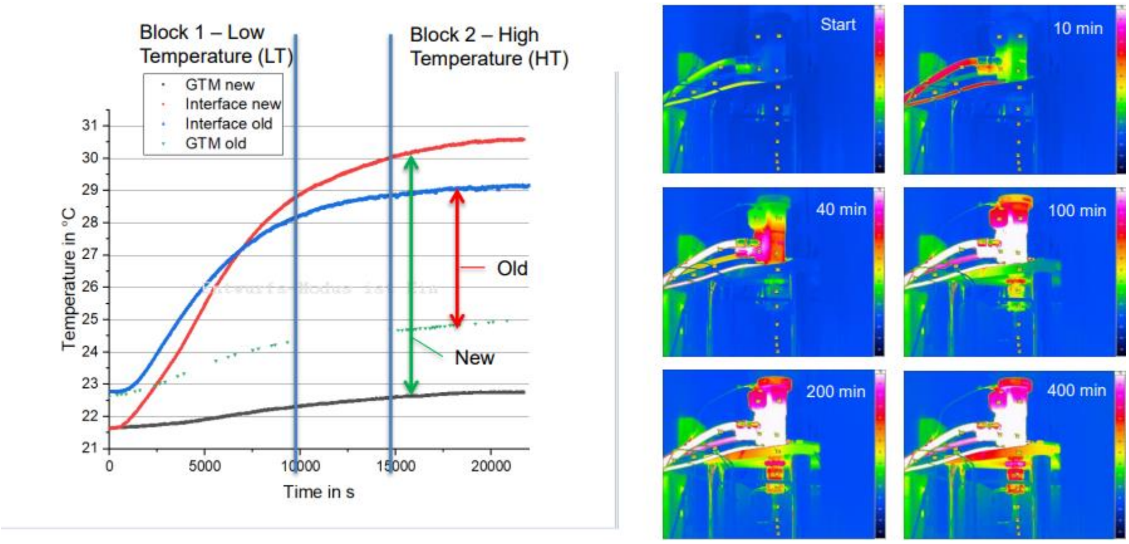

Figure 19 Left hand side shows the temperature increase during use of a servo-hydraulic machine and the influence of different adaptations between the two transducers. On the right hand side thermograph pictures for the identification of heat flows and resulting temperature gradients are shown.

The investigations with tilted plates carried out at INRIM also provided insights into the influence of spurious side forces and bending moments. Based on these findings, recommendations including uncertainty calculations for the continuous calibration of testing machines were produced. Together with partners PTB, INRIM, INMETRO, TUBITAK and NPL the developed calibration procedure from Objective 3 was extended for continuous force calibration with additional recommendations and uncertainty calculations.

In order to test the developed calibration procedure for continuous force and give further guidance to end users, a video was created of a calibration according to the new procedure and then uploaded to the project website https://www.ptb.de/empir2019/comtraforce/home/.

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 the existing standard traceability chain for static calibration, see Figure 20.

For this purpose, the suitability test of a reference standard is 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. The traceability by specifying classes can be retained, which will increase understanding and acceptance by industrial end users. The continuous calibration of the testing machine can then be implemented using an annex (Annex D) to the existing ISO 7500-1.

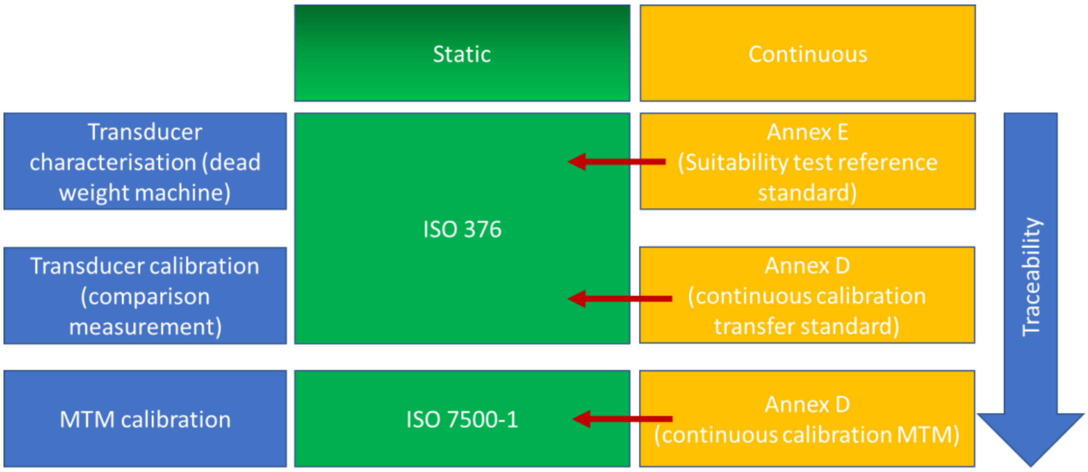

Figure 20 Proposed implementation of the new developed continuous calibration into the existing static normative traceability chain

It should be noted that ISO 7500-1 is not the only ISO standard that refers to ISO 376 for traceability to the force displayed by materials testing machines. For example, calibration standards for hardness testing machines such as ISO 6506-2 (Brinell hardness), ISO 6507-2 (Vickers hardness), and ISO 6508-2 (Rockwell hardness) all reference ISO 376. Thus, if the proposed changes to ISO 376 are accepted, it would be possible for these other standards to also take advantage of the availability of a calibration procedure that is more representative of the use of the machine during actual test work.

Dynamic calibration:

A self-resonance and a hydraulic testing machine were investigated, and the results showed the impact of harmonics, caused by different sources, see Figure 21. Such sources can include: (i) bending, (ii) torsion, (iii) side forces, (iv) side accelerations, (v) deformation and movement of the lower adaption, (vi) influences of the piston damping, (vii) mass and acceleration, (viii) machine frame dynamics, (ix) modal oscillations, and (x) misalignments. As both machines (i.e. self-resonance and a hydraulic testing) have different working principals and set-ups, both must be described and analysed differently.

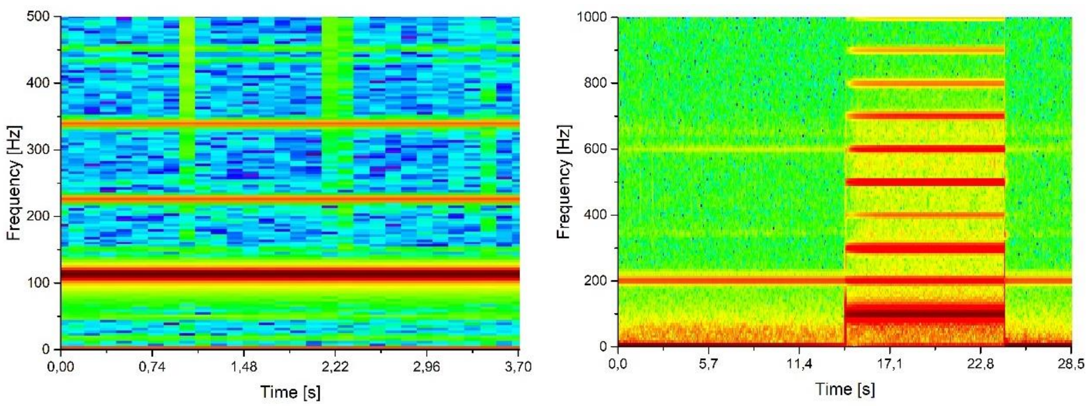

Figure 21 Impact of harmonics due to different sources on behaviour of a self-resonance and a hydraulic testing machine

The hydraulic testing machine uses, in contrast to the self-resonance machine, a control loop which not only adjusts the maximum amplitude but the whole form factor of the oscillation. Furthermore, the hydraulic testing machine applies an additional signal called a dithering signal. The dithering signal, which is added in order to avoid slip- stick effects of the valve-spool, is modulated onto the control signal of the valve. The dithering signal has a fixed amplitude and a fixed frequency of 200 Hz and creates a force on its own and interacts with other harmonics, see Figure **22**.

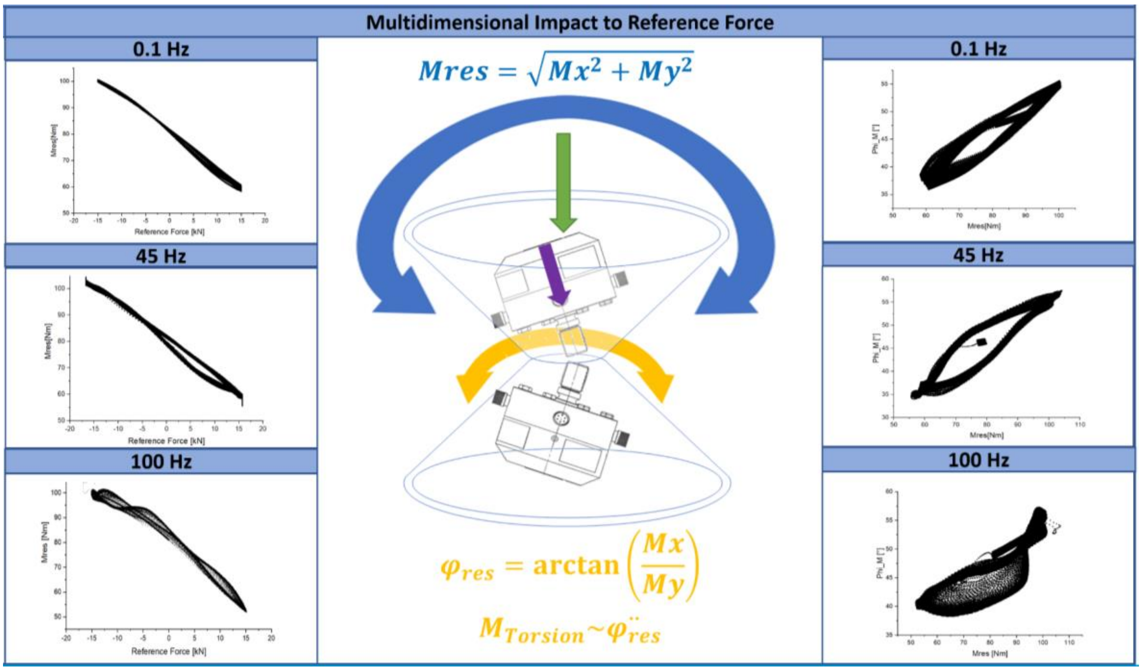

Figure 22 Frequency dependent and multidimensional impact to reference force. Left column: bending moment to force; center column: mechanical interactions; right column: bending angular to force

Non linearities and harmonics, (i.e. via interactions with other system behaviours as e.g. dithering signal or the control loop), can cause several effects. Effects in compression, tension or both can get weaker and disappear while other effects appear and get stronger with frequency. Therefore, an uncertainty budget would be different for tension and compression. This was found to not be caused by moving masses which used to be considered as the main impact on the transfer function. Instead, the odd and even harmonics are an indicator for non-symmetric non linearities.

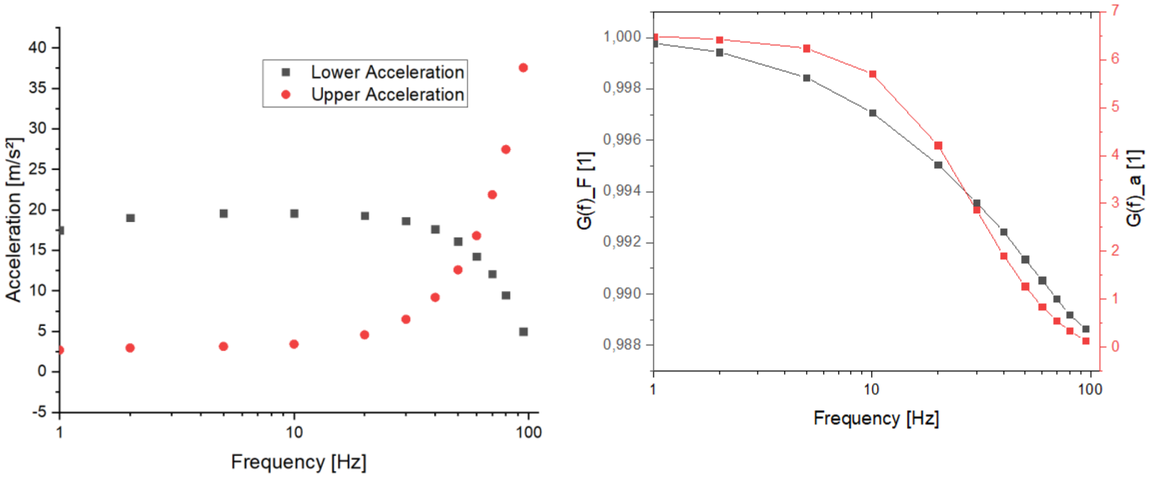

Figure 23 Left: Frequency response of the upper and lower acceleration measurement of the DUT transducer. Right: Transfer function of those accelerations and transfer function of the reference and DUT force measurements.

The impact of the moving masses of the (device under test) DUT transducer were investigated using their associated accelerations, see Figure 23. The lower mass of the DUT transducer also showed, compared to the upper mass, frequency dependent accelerations. The lower alignment adaption was not rigid as previously thought, and appropriate transfer functions were created from the data. The results demonstrate that the linear behaviour of the hydraulic machine is more complex than existing state of the art models imply.

Procedure

Components related to the calibration procedure strongly depend on the measured data and how its evaluation is performed. The procedure for dynamic calibration of testing machines developed in Objective 3 assumes the determination of a variety of parameters. These parameters can be divided into two groups depending on how they are determined.

- One group consists of parameters determined as a mean value of samples. These parameters include mean of span of force due to additional masses and mean difference between force spans of machine and transfer standard. For these parameters, a standard deviation of the estimated mean value can be considered as an uncertainty contribution due to the repeatability of calibration results.
- The second group are parameters determined from fitting procedure. A data stream obtained during the calibration can be fitted with a sine function, resulting in set of four parameters: (i) mean force, (ii) force amplitude, (iii) frequency, and (iv) phase. The statistical data used for the fitting (spread of results) can also be used for determining the uncertainty components associated with the fitting function parameters.

Uncertainty sources of dynamic force measurement during application, i.e. when calibrating a material testing machine dynamically, can be divided into four groups related to (i) the transfer standard (incl. force transducer, measuring amplifier and multi-channel data acquisition system), (ii) the machine, (iii) uncompensated masses, and (iv) the procedure. Figure **24** shows the division of individual sources into these four groups.

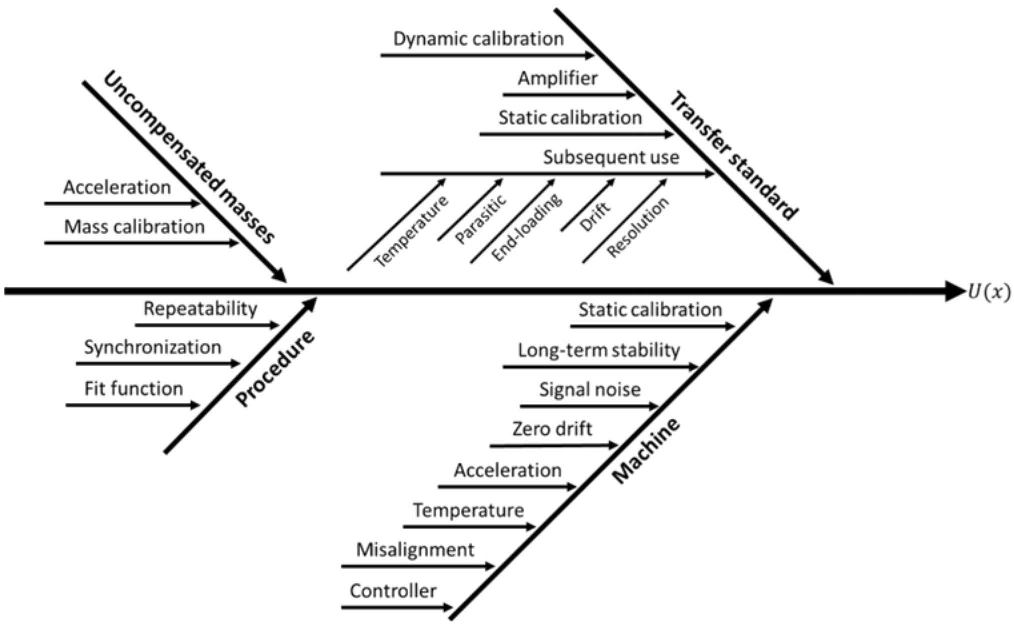

Figure 24: Sources of uncertainty attributed to the parameters determined during the evaluation of measurement data.

Some of the components are frequency dependent (e.g. uncertainty corresponding to the dynamic sensitivity of the transfer standard), which makes it necessary to derive the uncertainty value for the specific frequency level at that which the calibration was performed. The models of a variety of parameters determined during the evaluation were formulated as linear product models using relative measurement uncertainties.

The dynamic calibration of the transfer standard is addressed in the existing DKD-R 3-10, however a new guideline document for the calibration procedure for the dynamic calibration of material testing machines is needed and will be produced. For this standards body DKD board was chosen and the new guideline shall be aligned with the DKD-R 9 series, which addresses the calibration of testing machines, as DKD-R 9-4.

As a head of relevant standardisation committees USTUTT will promote the standard for dynamic calibration of a material testing system (DKD-R 9-4) through these committees, such as the DKD committee material testing machines and the DIN committee material testing (NMP 811). Within the DKD committee a new workgroup on dynamic calibration “AG Dynamische Kalibrierung (DKD-FA WPM)” was also founded, whose members are from material testing institutes from different German federal states. Between 70 % and 80 % of the laboratories accredited by the German Accreditation Body (DAkkS) regularly attend the meetings.

Conclusions

The project met Objective 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 neighbouring countries.

The traceability chains for continuous and dynamic forces developed in Objective 3 can be integrated into the existing static traceability chain (ISO 376 and ISO 7500-1) using additional annexes. In addition, for dynamic forces, an independent guideline (DKD-R 9-4) was developed. Further to this, recommendations for suspected parasitic temperature gradients and bending moments were developed and videos that describe the calibration processes as examples are available on the project website and will help to facilitate uptake by end users.

5 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.

6 List of publications

[1]. J. Fidelus, K. Cybul: Study on short-term creep effect and hysteresis for the HBM Z4A force transducer under compressive and tensile forces, Acta IMEKO 9 (2020) 5, 137-142, https://doi.org/10.21014/acta_imeko.v9i5.956

[2]. Dirk Röske: Linear regression analysis and the GUM: example of temperature influence on force transfer transducers, Acta IMEKO 9 (2020) 5, 407-413, 10.21014/acta_imeko.v9i5.1010

[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

[4]. L. Klaus: Static and dynamic bridge amplifier calibration according to ISO 4965-2, Acta IMEKO 9 (2020) 5, 200-204, 10.21014/acta_imeko.v9i5.969

[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

[7]. M. Hiti: Compensation of Synchronization Error Effect in Testing Machine Calibration, Measurement: Sensors, Volume 18, December2021, https://doi.org/10.1016/j.measen.2021.100132

[8]. J. Sander, R. Kumme: Comparison of force measuring devices with static and continuous loading, Measurement: Sensors, Volume 18, December2021, https://doi.org/10.1016/j.measen.2021.100241

[9]. Prato, D. Borgiattino, F. Mazzoleni, A. Facello, A. Germak: Theoretical insights on the influence of the experimental plan in the calibration of multicomponent force and moment transducers, Measurement: Sensors, Volume 18, December 2021, https://doi.org/10.1016/j.measen.2021.100209

[10]. H. Dizdar, B. Aydemir, C. Vatan: Investigation of the effect of load rate on creep and hysteresis errors in strain gauge and piezoelectric force transducer, Measurement: Sensors, Volume 22, August 2022, https://doi.org/10.1016/j.measen.2022.100374

[11]. Prato, D. Borgiattino, F. Mazzoleni, A. Facello, A. Germak: Calibration of multicomponent force and moment transducers using uniaxial force standard machines integrated with tilted plates, Measurement Science and Technology, Volume 33, July 2022. https://doi.org/10.1088/1361-6501/ac793c

[12]. O. Baer, C. Giusca, R. Kumme, A. Prato, J. Sander, D. Mirian, Frank Hauschild: Digital Twin concept of a force measuring device based on the finite element method, Acta IMEKO, March 2023, https://acta.imeko.org/index.php/acta-imeko/article/view/1404

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