Final Publishable JRP Summary for IND09 Dynamic
Traceable Dynamic Measurement of Mechanical Quantities

Overview

Accurate measurements of force, pressure and torque are required by European industry to develop high-performance, internationally-competitive products. However, the sensors used to make these measurements are calibrated under static conditions, but are often used to make measurements in dynamic conditions. There is therefore concern within industry that dynamic measurements are not sufficiently accurate.
To address this, the project developed methods and devices for calibrating sensors under dynamic conditions to provide estimations of accuracy and uncertainty for dynamic measurements. These methods and devices are being developed into National Metrology Institute (NMI) calibration services available to European industry, and are being used to define new international standards.

Need for the project

Measurements of force, pressure, and torque are important in a range of European industries, including aerospace, manufacturing, wind power, and the automotive industry. Accurate measurements of these quantities allow European industry to operate more efficiently, at lower cost; and enable the development of higher-performance, internationally-competitive products.
To ensure these quantities are measured accurately, the sensors used to make these measurements (transducers) must be calibrated against measurement standards (traceability to standards). However, transducers are calibrated under static conditions, with constant forces, pressures and torques, but are often used under dynamic conditions, where force, pressure and torque vary through time, often dramatically. Such dynamic variations may cause inertia loads and resonance in the transducers, affecting their measurement performance, therefore, although transducers may be sufficiently accurate under static conditions, their behaviour and sensitivity may change under dynamic conditions, introducing inaccuracy and increased uncertainty.
For instance, an increase in fuel injection pressure in automobile engines will increase fuel efficiency and allow the development of cleaner cars. However, the pressure transducers used within engine development are calibrated against constant pressures. But, on engine ignition, pressures within engines may rise several hundred fold within a fraction of a second, and the transducers may not adequately record such a rapid pressure change.
European industry therefore needed the National Metrology Institute community to develop facilities for calibrating sensors under dynamic conditions, to allow dynamic measurements of force, pressure and torque traceable to national measurement standards.

Scientific and technical objectives

The goal of this project was to develop methods and devices within the European NMI community to calibrate dynamic measurement of force, pressure and torque. Objectives 1 to 5 developed methods for calibrating dynamic measurements against primary standards in NMIs (primary calibration). Objective 6 developed methods for transferring calibration from NMIs into industrial settings (secondary calibration). Objectives 7 to 9 developed analysis techniques for dynamic measurement results, including methods to estimate measurement uncertainties at each step of the calibration process.

Development of validated calibration devices:

1. Enable **primary calibration of force transducers** for traceable dynamic measurements of **periodic forces** with frequency ranges up to 1 kHz and amplitudes up to 10 kN.

2. Enable **primary calibration of force transducers** for traceable dynamic measurements of **shock forces** with amplitudes up to 250 kN.

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3. Enable **primary calibration of pressure transducers** for traceable dynamic measurements of **shock pressures** with amplitudes up to 500 MPa.

4. Enable **primary calibration of torque transducers** for traceable dynamic measurements of **periodic torque** with frequency ranges up to 1 kHz and amplitudes up 20 N·m.

5. Enable **traceable dynamic calibration of amplifiers** by development of suitable calibration procedures and bridge amplifier calibration standards with frequency ranges up to 10 kHz.

6. Enable traceable dynamic measurements of force, torque and pressure in industry by **provision of secondary calibration standards**.

Mathematical and statistical modelling at calibration and application level:

7. Reliable **characterisation of the dynamic behaviour of transducers** for force, pressure and torque, respectively, by establishment of dynamic models for the complete calibration measurement chain including the employed amplifiers.

8. Make traceability of the dynamic calibration measurement possible by the development of **procedures for uncertainty evaluation** in line with standard uncertainty evaluation for static measurements.

9. **Enable industry-level traceable dynamic measurements by design of appropriate deconvolution filters** utilising the models determined at the calibration level and by the development of procedures for the evaluation of uncertainties in line with standard uncertainty evaluation for static measurements.

Results

Development of validated calibration devices:

<u>1. Enable **primary calibration of force transducers** for traceable dynamic measurements of **periodic forces** with frequency ranges up to 1 kHz and amplitudes up to 10 kN.</u>

PTB, the German NMI has been active in this research field for many years but sought to improve the uncertainty of their measurements of sinusoidal forces (periodic rises and falls in force), and needed to validate such measurements against alternative methods. The creation of alternative periodic force calibration methods at CEM, the Spanish NMI, and LNE, the French NMI, was therefore an important goal of this project.

The objective was achieved, as methods to calibrate sinusoidal forces were successfully developed at CEM and LNE, accurate over a frequency range of 1 kHz and force amplitudes up to 10 kN. These methods allowed for the first European comparison of periodic force measurements using three different types of force transducer, allowing the accuracy and performance of each method to be validated. PTB is now providing a primary calibration service for the calibration of periodic forces, whilst services are in development at CEM and LNE. Additionally, the periodic force methods were also used to identify the parameters required to model the dynamic behaviour of transducers. These parameters will be used to develop mathematical models required for further improving the accuracy and uncertainty of dynamic measurements.

<u>2. Enable **primary calibration of force transducers** for traceable dynamic measurements of **shock forces** with amplitudes up to 250 kN.</u>

In addition to calibrating periodic forces (objective 1), objective 2 developed devices for calibration with shock forces, rapid changes in force.

Existing shock force calibration devices at PTB were modified to improve their sensitivity at higher frequencies. The research focussed on the evaluation of calibration methods using impacting mass bodies, models describing the transducer's dynamic behaviour, and on parameter identification from shock force measurements. The devices were tested with substantially shorter shock pulses by using small pendulum impact masses. This testing revealed that the element of the transducers which connect to the mechanical component being tested can have a significant influence on dynamic measurements. The transducer may develop two resonances along its measurement axis which have to be corrected for by the dynamic models to provide accurate dynamic measurements. The objective was partially achieved, as the research revealed that the current transducers and mathematical models, although improved, do not yet provide sufficient accuracy. Research is continuing.

<u>3. Enable **primary calibration of pressure transducers** for traceable dynamic measurements of **shock pressures** with amplitudes up to 500 MPa.</u>

Shock pressures are rapid rises and falls in pressure, such as explosive pressure changes. Two approaches were investigated for measuring shock pressures, one using drop weight systems, the other using shock tubes. Drop weight systems were set up at PTB; MIKES, the Finnish NMI; and UME, the Turkish NMI. The objective was partially achieved with drop weights; the device at UME is currently used for secondary calibration, whilst the devices at PTB and MIKES have made progress in establishing traceability to primary standards and research is continuing at these NMIs.

Shock tube calibration devices were developed at NPL, the UK NMI; and SP, the Swedish NMI. The devices generated known, sharp pressure steps in gases, to assess the accuracy of pressure transducer measurements. Various aspects of the shock tubes were investigated, including different diaphragm designs, driven gas sections and gas species; the influence of the material onto which the sensor being calibrated is mounted; the modelling of the gas shock and the sensor; and the measurement of the reference signal by means of a laser vibrometer. The objective was partially achieved with shock tubes as the results showed that the devices were well suited for generating extremely rapid pressure steps suitable for the dynamic characterisation of pressure sensors, whilst validation measurements were still in progress at the end of the project and are continuing, with the intention of developing primary calibration services.

<u>4. Enable **primary calibration of torque transducers** for traceable dynamic measurements of **periodic torque** with frequency ranges up to 1 kHz and amplitudes up 20 N·m.</u>

A primary calibration device for torque transducers was set up and validated at PTB. The work focused on the investigation of methods and procedures for the calibration of sinusoidal torque. Similar to the procedures in dynamic force, the modelling of the dynamic torque measuring device and the torque transducer was performed with a corresponding rotational mass-spring-damper system. To determine the parameters of the various mechanical components which are included in this model, three dedicated devices were developed to measure the mass moment of inertia, rotational stiffness and damping. The objective was partially achieved, as a proof of principal was demonstrated for the measurement technique applying measurements at small torque levels. Work is continuing to achieve accurate measurements at higher excitation magnitudes.

<u>5. Enable **traceable dynamic calibration of amplifiers** by development of suitable calibration procedures and bridge amplifier calibration standards with frequency ranges up to 10 kHz.</u>

Amplifiers are used in conjunction with transducers to amplify the signal recorded to a measureable level. To ensure dynamic measurements can be reliably traced to measurement standards, the performance of amplifiers also needed to be validated under dynamic conditions to assess their contribution to inaccuracy and uncertainty, if any.

Electrical calibration devices were developed, validated and documented for the dynamic calibration of different types of measuring amplifiers. The work focused on the dynamic characterisation of (i) bridge amplifiers for resistive sensors like strain gauges, (ii) charge amplifiers for piezoelectric sensors, (iii) voltage amplifiers and (iv) IEPE amplifiers for piezoelectric sensors with integrated electronics. For each amplifier type, a comparison of different commercially available amplifiers was carried out in terms of measurements of their frequency-dependent magnitude and phase responses. A major, and unexpected, result of this project was the finding that amplifiers could introduce substantial measurement uncertainty in dynamic conditions, and therefore needed to be calibrated alongside the transducers.

For the dynamic calibration of bridge amplifiers, both NPL and PTB developed their own dynamic calibration standard that is able to provide an adequate reference input signal. The methodology was introduced into a German DKD guideline and an international ISO draft standard, and the technology of the developed dynamic bridge standard at PTB was offered to industry as a licence product.

<u>6. Enable traceable dynamic measurements of force, torque and pressure in industry by provision of secondary calibration standards.</u>

Whilst the main goal of this research was to develop methods for NMIs to provide primary calibration of dynamic measurements, methods were also investigated for providing secondary calibration – to transfer traceability from NMIs to calibration laboratories.

Secondary standards were investigated by comparing a sensor under test to a reference sensor, at PTB for dynamic force calibration and at NPL for dynamic pressure calibration. At PTB, secondary calibration devices for sinusoidal forces were set up using an electrodynamic shaker or a hydraulic drive. At NPL, methods to establish standards in acoustics, in both air and water, were examined and considered for the development of dynamic pressure standards. MIKES and PTB performed a secondary calibration comparison of pressure transducers using their existing drop weight calibration devices. The evaluation of the measurement data was performed by the maths group of INRIM, the Italian NMI. The project made significant steps towards establishing secondary calibration, and work is continuing in these NMIs.

Mathematical and statistical modelling at calibration and application level:

7. Reliable **characterisation of the dynamic behaviour of transducers** for force, pressure and torque, respectively, by establishment of dynamic models for the complete calibration measurement chain including the employed amplifiers.

A model-based calibration approach was developed for the dynamic calibration of transducers for force, pressure, and torque. The approach modelled the complete measurement chain, from measurement to primary calibration, as well as the mechanical environment of the calibration device. The parameters of the model were identified from dynamic measurement data, applying a parameter fit in the time or frequency domain. For example, in the case of dynamic calibration of torque transducers, this model consists of a series arrangement of spring-coupled lumped mass moments of inertia, where the transducer's dynamic properties are characterised by its model parameters that denote the transducer`s stiffness, damping and structural distribution of mass. This objective was achieved as dynamic models were established for dynamic force, pressure and torque.

8. Make traceability of the dynamic calibration measurement possible by the development of **procedures for uncertainty evaluation** in line with standard uncertainty evaluation for static measurements.

To ensure that dynamic measurements can be traced to measurement standards, methods are needed to calculate measurement uncertainty at each step of the calibration process, from primary standard to the end user. As the quantity being measured in dynamic conditions can vary dramatically, new approaches are needed for uncertainty estimation above those used for uncertainty estimation under static conditions.

A Monte Carlo method was successfully developed, in accordance with Supplement 1 of the Guide to the Expression of Uncertainty in Measurement (GUM), which allowed for the evaluation of uncertainties. Furthermore, applicability of recently proposed methods for the implementation of the GUM "law of propagation of uncertainties" has been assessed. The results obtained for the transducers considered in the project successfully demonstrated the applicability of the GUM uncertainty framework for dynamic measurements.

9. **Enable industry-level traceable dynamic measurements by design of appropriate deconvolution filters** utilising the models determined at the calibration level and by the development of procedures for the evaluation of uncertainties in line with standard uncertainty evaluation for static measurements.

For many dynamic measurement systems, there is a need to correct the measured data for systematic errors introduced by the measurement system itself. The mathematical process for doing so is described as deconvolution. The project aimed to develop new deconvolution techniques and mathematical methods to allow these corrections to be made, in a robust manner, with reliable uncertainty estimation as part of the process.

Based on the dynamic models developed for the transducers and the measurement chain, appropriate digital deconvolution filters were developed, including procedures for uncertainty evaluation, allowing industry-level traceable dynamic measurements. These techniques are being put into the public domain in a follow-on project.

Actual and potential impact

Dissemination of results

To promote the uptake of the new NMI calibration facilities, and to share insights generated throughout the project, results were shared broadly with scientific and industrial end-users. Articles were published in scientific journals (10 peer-reviewed papers, 23 conference papers), 2 PhD theses were made, and 9 papers were published in a dedicated issue of PTB Mitteilungen. 53 presentations were made, including 16 contributions to two Workshops on Dynamic Measurements (presentations available online), 13 contributions to International Measurement Confederation (IMEKO) conferences and congresses, and other high-level measurement conferences and events, including an International Bureau of Weights and Measures (BIPM) workshop on traceable dynamic measurement. A web-based best practice guide, providing practical information and advice for engineers and technicians in industry making dynamic measurements, has also been produced on the project's website, found here.

Impact on standards

The results of this project will be central to the development of international standards for dynamic measurement, and were introduced to the standards community through presentations to national and international standards committees. Results are currently being used to develop a range of standards, including ISO TC 108/SC 3/WG 6 "Mechanical vibration and shock – calibration of vibration and shock transducers", and ISO TC 164/SC 5/WG 5 "Mechanical testing of metals – dynamic force calibration". ISO TC108 has accepted a draft standard on the dynamic calibration of conditioning amplifiers, and has accepted to include proposed draft standards for dynamic force transducer calibration, and dynamic pressure transducer calibration. Two draft guidelines have been written for the Deutscher Kalibrierdienst (DKD), the German national calibration service, concerning dynamic force transducer calibration and dynamic calibration of materials testing machines.

Early impact on industry

The project has identified a range of methods to trace dynamic measurements to primary standards for industrial users, including sensor manufacturers, sensor users, and calibration service providers. PTB, the German NMI, has established a sinusoidal force calibration service, and NPL, the UK NMI, has established a shock pressure calibration service, both now available for providing dynamic calibration for industrial users. Where the methods developed have not yet been established as NMI calibration services, detailed strategies have been put in place to do so, and project results have been made publically available, allowing end-users to set up their own secondary calibration services.

Kistler Instrumente AG, the German arm of the Kistler Group, a manufacturer of industrial sensors, was one of the first users of the NPL dynamic pressure calibration service. Kistler used the service in response to enquiries from customers about the dynamic response of their pressure sensors. The dynamic calibration service allowed Kistler to better understand and validate the performance of their pressure transducers under shock pressure conditions, allowing them to document this performance in their product specifications. Kistler pressure transducers have since been used in the development of more efficient, more environmentally friendly engines.

The project also engaged with industrial stakeholders, including automotive and transducer manufacturers, from the start of the research, to better understand prevailing industrial needs and to aid the dissemination and uptake of the project's developments. For instance, Hottinger Baldwin Messtechnik GmbH (HBM), a manufacturer of force and torque measurement equipment, was engaged throughout the project, and used results to modify their new bridge amplifier to ensure it is now suitable for making dynamic measurements. HBM's managers also invited project members to a dedicated *Challenges of Dynamic Metrology* workshop, and have helped disseminate project results themselves, at an international metrology conference in Mexico, focussed on the Latin-American market.

Potential future impact on industry

The new methods developed in this project have already led to the creation of two new dynamic calibration services in European NMIs, the facility for dynamic pressure calibration at NPL, and dynamic force calibration at PTB. The project has also laid the groundwork for the development of additional dynamic calibration facilities, which are currently being established. These dynamic calibration methods and facilities, and the formation of a network of cooperating measurement scientists, are first steps in the development of a new branch of measurement science, dynamic calibration. We anticipate that over the next decade these dynamic calibration methods will be further refined in NMIs, and will be adopted by commercial accredited calibration laboratories, to provide traceability for dynamic measurements to a wide range of industrial users. Ultimately, the development of dynamic calibration methods will allow European industry to accurately measure and control forces, pressures and torques, facilitating gains in production efficiency, and the development of higher-performance, more internationally-competitive products.

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