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1 Executive Summary

Introduction

Accurate measurements of force, pressure and torque are required by European industry to enable the development of higher-performance, internationally-competitive products. This research project has made a significant contribution to ensure that these quantities are measured correctly by supporting the National Metrology Institute (NMI) community to develop facilities for calibrating sensors under dynamic conditions traceable to national measurement standards. These methods and devices are being developed into NMI calibration services for the European industry, and are being used to define new international standards.

The Problem

Measurements of force, pressure, and torque are important in a range of European industries, including aerospace, manufacturing, wind power, and the automotive industry. To ensure accurate measurements, the sensors (transducers) used to make these measurements must be calibrated against measurement standards with traceability to national standards. However, these transducers are only 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. There is therefore great concern within industry that dynamic measurements are not sufficiently accurate.

The Solution

To provide the metrological base for accurate dynamic measurements of force, pressure and torque, the participating institutes developed facilities and methods for calibrating sensors under dynamic conditions allowing dynamic measurements traceable to national measurement standards. The project set up new unique dynamic calibration facilities, developed the respective measurement methods for periodic and shock-like excitations and supplemented this experimental work with substantial mathematical modelling and data analysis including the necessary procedures for measurement uncertainty calculation.

Impact

The results of the project were disseminated with scientific and industrial end-users through 43 journal papers and 53 presentations to workshops and conferences. A web-based best practice guide provides practical information and advice for engineers and technicians in industry making dynamic measurements.

As an early impact, 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. Kistler Instrumente AG, a manufacturer of industrial sensors, was one of the first users of the NPL dynamic pressure calibration service, allowing them to document the performance of its pressure transducers under shock pressure conditions in the product specifications. HBM, a manufacturer of force and torque measurement equipment that was engaged throughout the project, used the results to modify its new bridge amplifier to ensure its suitability for making dynamic measurements. HBM's managers invited project members to a dedicated in-house workshop and have helped to disseminate project results themselves at an international metrology conference in Mexico, focussed on the Latin-American market.

A longer-term impact is the development of new international standards for dynamic measurement. 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", 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 to include draft standards on the dynamic calibration of force and pressure transducers. Two draft guidelines have been written for DKD, the German national calibration service, on the dynamic force transducer calibration and dynamic calibration of materials testing machines.

As a potential impact, the achieved progress in the NMI's research and calibration capabilities will provide the basis for traceable dynamic calibrations of industrial sensors to ultimately establish an infrastructure of accredited calibration labs with the respective traceable dynamic calibration capabilities. These advances in dynamic measurement will enable European industry to keep a leading position in the development of higher-performance, internationally-competitive products.

2 Project context, rationale and objectives

2.1 Project overview

The accurate measurement of the mechanical quantities force, torque and pressure is a key tool for the European industry, research and society to operate more efficiently, at lower cost; and to enable the development of higher-performance, internationally-competitive products.

To obtain accurate measurements, which also includes the knowledge of the associated measurement uncertainty, the sensors (transducers) used to make these measurements must be calibrated against measurement standards with traceability to national standards. However, these transducers are only calibrated under static conditions, i.e. with constant forces, pressures and torques, even when used for dynamic measurements. Up to date, calibrations capabilities and documentary standards for traceable dynamic calibrations are still lacking.

Yet, it was a well known and accepted fact that mechanical systems and accordingly, the sensors for mechanical quantities, may behave quite differently under dynamic load as opposed to static load. Under dynamic conditions, where the measurand varies through time, the measurement performance may be affected due to inertia loads and resonance in the transducers. Although transducers may be sufficiently accurate for static measurements, their behaviour and sensitivity may be compromised under dynamic conditions resulting in an increased measurement uncertainty. This means, accurate dynamic measurements require dynamic calibrations. To achieve traceability for the dynamic measurement of the mechanical quantities force, torque and pressure, new developments in calibration devices, modelling and in uncertainty analysis and propagation were required.

This research project addressed directly the metrological challenges concerning the lack of traceability for the dynamic measurement of mechanical quantities including traceability of the transducer response to dynamic stimuli, and traceability of the electrical part of the measuring chain to dynamic stimuli. The lack of traceability for dynamic measurements is identified explicitly in a number of standards and related documents.

- For instance, the ISO 6487 “Road Vehicles – Measurement techniques in impact tests – Instrumentation” which states that “no method for the evaluation of the dynamic response during calibration of data channels for forces and displacements is included in this international standard since no satisfactory method is known”.
- The EURAMET Technical Committee for Mass and Related Quantities in its March 2010 report entitled “Uncertainty of Force Measurements” points out that transducers calibrated under static conditions may be wrongly employed for dynamic measurements “due to the unavailability of dynamic standard facilities and/or calibration methods”.
- The Guide to the expression of uncertainty in measurement (GUM), which is the current standard for uncertainty evaluation in metrology, provides no specific advice on uncertainty evaluation for dynamic measurements. This unsatisfactory situation has been recognised by the Joint Committee for Guides in Metrology (JCGM) and the outputs from this project will assist the JCGM in future revisions of the GUM.
- The ISO/TC 108/SC 3 “Mechanical vibration and shock” has recognised that dynamic force calibration still is at an early stage where further developments are required preliminary to the establishment of an corresponding ISO standard. At the 2008 meeting of the TC 108/SC 2 this has led to the decision to leave the PWI 21691 “Dynamic force transducer calibration” at the preliminary stage.

A traceability network with international links via the BIPM was established for the static calibration of force, torque and pressure already decades ago. However, there was no primary dynamic calibration method, service or device available. The few dynamic calibration facilities available were without exception traceable to static primary realisations of the named quantities, only. Consequently, the establishment of primary dynamic calibration capabilities in the participating European NMIs was defined as the most prominent goal for this research project.

The motivation for a joint approach for the development of dynamic calibration capabilities for the mechanical quantities force, torque and pressure resulted from the knowledge of similarities in the metrology of the named quantities:

- The applied sensor principles for mechanical to electrical conversion are the same in all quantities, as there are piezo-electric (charge), strain-gage (resistive) and IEPE (voltage output) transducers.
- While the generation principles of dynamic mechanical calibration signals (force, torque, pressure) are different, the used waveforms are similar (sinusoidal, impulse, step), and therefore the methods of data analysis are similar, irrespective of the quantity.
- For all three quantities the sensor is complemented by a conditioning amplifier which by itself has a characteristic dynamic response which needs to be taken into account via appropriate calibration. Methods for such calibrations were only available for charge amplifiers, i.e. piezo-electric measuring chains.

Therefore, this research project could make use of synergies existing between the three different mechanical quantities. The project greatly benefited from the participation of the leading European NMIs which brought added value by pooling of know-how and infrastructure, joining and complementing their particular research areas, and ultimately allowing validations of the elaborated results.

Traceability in (dynamic) measurement requires consistent modelling of the measurement system and a standardised evaluation of measurement uncertainty. Based on a mathematical model of the individual measurement chain components and a statistical model of the calibration measurement, the project aimed to establish primary calibration and traceability for dynamic force, pressure and torque by addressing the following scientific and technical objectives.

2.2 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.
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.

3 Research results

The scientific and technical objectives of the research project were classified into two thematic groups: “Development of validated calibration devices” (objectives 1 to 6), “Mathematical and statistical modelling at calibration and application level” (objectives 7 to 9).

3.1 Primary calibration of force transducers for traceable dynamic measurements of periodic forces

3.1.1 Summary of the key results

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.

3.1.2 Results in more detail

Force measurement plays a major role in industrial processes, statically as well as dynamically. In the past, a very versatile system of static force calibration was established which could be recognised by the many high-level force calibration laboratories and services around the globe. Nevertheless, most of the processes where force measurement is involved are dynamic by principle. However, traceability of the force transducers used in all applications leads back to static calibration, only. The deviations in measurement associated with this may rise to the order of several percent and, especially in the vicinity of mechanical resonances, up to 10 % to 100 %. It was the goal of this joint research project to develop the fundament for a European dynamic force calibration infrastructure in terms of methods, devices and knowledge.

The NMIs participating in dynamic force measurement with periodic force excitation were PTB, LNE and CEM. While PTB has been active in this research field for many years, CEM and LNE started their activity with this research project. Accordingly, the first step was the set up and commissioning of new calibration facilities for sinusoidal calibration in the laboratories of LNE and CEM.

The research on this topic was jointly worked on by metrologists from PTB, CEM, LNE including experimentalists and mathematicians. The cooperation included exchange of information about design principles of periodic force calibration devices, mutual visits for joined measurement campaigns, exchange of the measured data for the purpose of comparison, and joint publications. The theoretical support in terms of mathematical modelling and statistics was shared between PTB and LNE, where after a short introductory phase the LNE scientists were able to cover the field of sine forces while the PTB colleagues took care of the development of new methods in the field of shock force.

The principle of dynamic calibration is based on “model-based parameter identification” (MBPI), which means that the calibration results are supposed to be a model equation describing the sensor under calibration with a set of numeric values of the model parameters together with the associated uncertainties. With this principle the calibration result becomes independent of the applied calibration excitation and the used calibration device. Hence, it was the ultimate goal to compare the results between different laboratories for their consistency in the range of stated uncertainties.

For this purpose, three force transducers based on different principles were selected that could be calibrated in all available facilities. The set is depicted in figure 1.

Figure 1: Set of force transducers selected for the investigations in all force calibration devices, HBM U9B (1 kN), Interface 1610 (2.2 kN), Kistler 9175B (-8 kN to 30 kN) (left to right).

<u>Creation of an infrastructure for periodic force measurement at LNE, CEM and PTB</u>

The main aim to undertake this effort was to enable other NMIs then PTB to be able to perform dynamic calibrations of force transducers. Up to date, only PTB has a procedure for the dynamic calibration of force transducers based on a sinusoidal excitation which was anchored in its quality management system to provide a primary calibration service for the calibration of periodic forces.

The essential prerequisites for a primary sinusoidal force calibration are seen in figure 2. The periodical excitation of force transducers is realised with electrodynamic shaker systems. A shaker system providing forces up to 330 N was newly installed at LNE, and a shaker for forces up to 3 kN at CEM. Three electrodynamic shaker systems are available at PTB. A small one for forces up to 100 N ranging from 10 Hz to 2 kHz, a medium-sized shaker up to 800 N and 10 Hz to 3 kHz, and a large shaker providing forces up to 10 kN and frequencies from 10 Hz to 2 kHz. The type of excitation is determined by the chosen signal created by a function generator. This signal directly modulates the current signal of a power amplifier which drives the coil of the shaker armature.

The acceleration of the load mass can be measured in two different ways. CEM and PTB use a laser-Doppler vibrometers, while LNE performs an acceleration measurement with accelerometers. There are two types of laser heads available, one with a fixed beam (used at CEM) and the other with a scanning option (PTB). The scanning vibrometer is able to scan the surface motion in an angular region of ±4º in the x- and y- directions for objects which are roughly 20 cm in size placed at a distance of 1.5 m.

The measurement of the sensitivity of the force transducer is based on two signals, the force transducer signal and the acceleration signal defining the reference force exerted by the load mass. The force transducer signal is converted by a conditioning amplifier, a bridge amplifier for strain gauge sensors, or a charge amplifier for piezoelectric force transducers.

The data acquisition system (DAQ) at PTB is based on the Polytec software VibSoft which provides routines for the FFT analysis of the signals. The acceleration measured by the laser scanning vibrometer is traceable to the national acceleration standard of PTB. The measurement uses 50-80 scan points equally distributed over the upper surface of the load mass. The surface scan is repeated three times, and mean values and standard deviations are calculated.

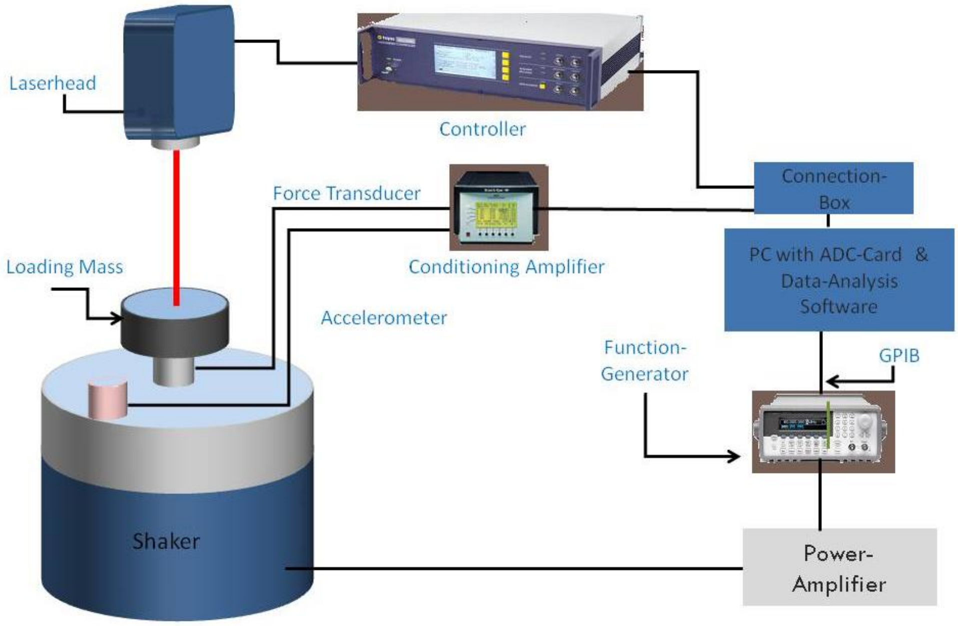


Figure 2: Schematic measurement set-up for the sinusoidal force calibration realised at LNE, CEM and PTB.

At CEM, a LabView-based data analysis was developed. The measurement data is sampled with 40 kSamples/s and the data analysis applies a sine approximation method taking into account up to the third harmonic. The data acquisition is performed with an NI PXI 4462 card which measures the signals of the laser vibrometer, the force sensor and an additional accelerometer. The software determines the amplitude and the initial phase of the measured signals and calculates the magnitude and phase of the transducer sensitivity as a ratio of the force output and acceleration.

Comparison of force sensitivity measurements based on sinusoidal excitations

This work was undertaken to validate the quality of the sinusoidal force calibration at the three involved NMIs. The measurand of interest of this comparison was the frequency-dependent sensitivity of the selected force transducers.

Comparison measurements were performed mainly at PTB and CEM. Due to an unexpected lack of man power and additional technical problems with its shaker system, LNE had to focus its contribution on the measurements for the parameter identification, which are different from the sensitivity measurements.

For the comparison of the sensitivity, load masses of 1 kg, 2 kg, 4 kg, 6 kg and 11 kg were used for the dynamic force generation. Figure 3 shows the relative deviations of the measured sensitivities of three force transducers between CEM and PTB. The measurements were performed with load masses of 1 kg and 2 kg that were directly screwed onto the transducer under test. The figures present the first comparison of dynamic sensitivity measurements between different NMIs.

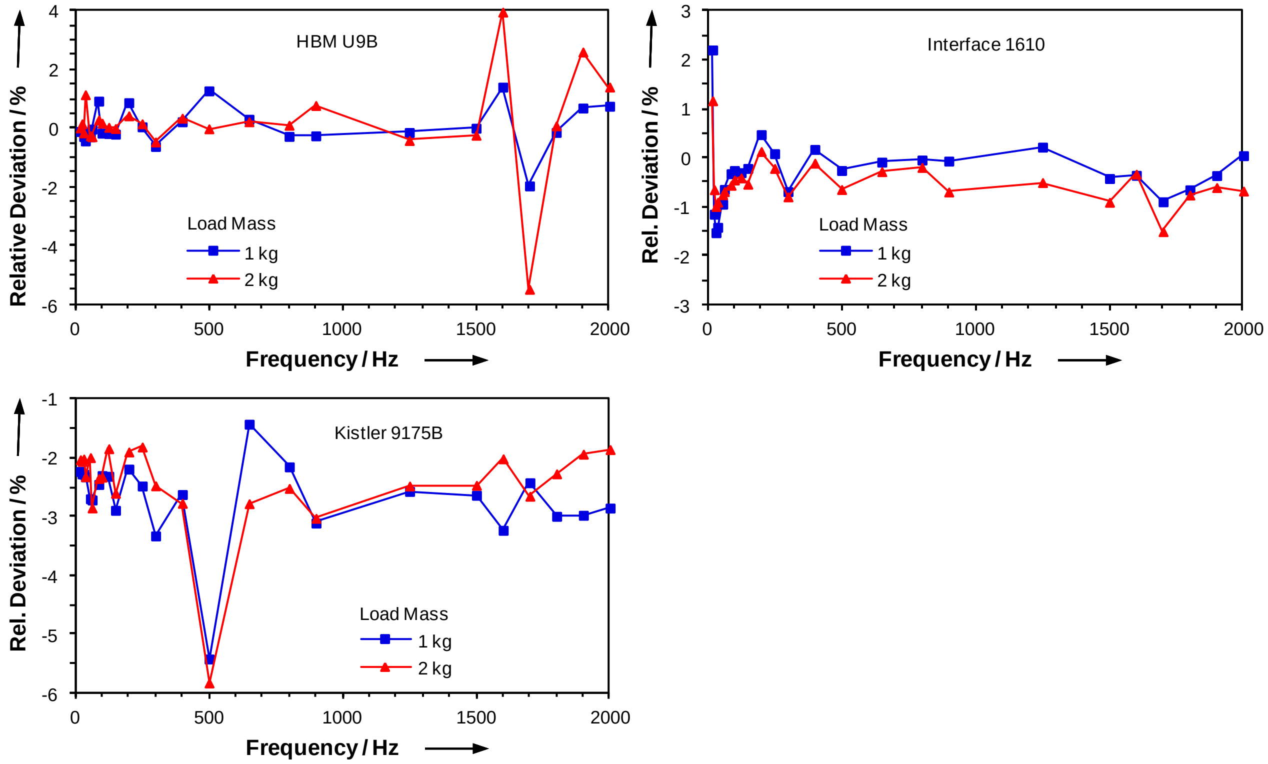


Figure 3: Relative deviation of the measured sensitivity between CEM and PTB for different force transducers: HBM U9B, Interface 1610, Kistler 9175B. In each case, the load masses of 1 kg and 2 kg were directly screwed onto the transducer.

Investigation of mechanical influences affecting a periodical force calibration

This task was designed to clarify the impact of different mechanical influences on the uncertainty of the sensitivity. This was investigated mainly at PTB. Three major influences had to be considered, which are the transverse and longitudinal acceleration distribution, and the mechanical coupling of the load mass to the transducer and the mounting conditions on the shaker table.

Investigations of the longitudinal acceleration distribution were made using a stepped pyramid-shaped load mass. The acceleration was optically measured at the pyramid's steps at several positions. As these steps are located at different distances from the pyramid's base, an acceleration gradient could be determined. The experimentally determined gradient could be reproduced in theory, which provides a simple formula to correct for the gradient. The formula is merely a function of the height of the mass block and depends otherwise only on material constants, like the young modulus and the density.

The transverse acceleration of the load mass during a sinusoidal excitation was measured using 4 triaxial accelerometers, which were mounted on a special plate, mounted on the top of the load mass. With this configuration, 8 transverse directions at each 45º could be measured. From these measurements, the amount of transverse acceleration as well as the symmetry behaviour of these motions could be determined. There is a quite good agreement between the measurements and FE calculations. Hence, FE simulations are a feasible tool to predict frequency intervals where complications due to rocking modes might be expected.

Last but not least, the reproducibility of the mounting conditions of the whole arrangement (force transducer and load mass) on the shaker table was investigated. It turned out that all mounting screws have to be fastened utilising a well-defined torque. Under this condition, the additional uncertainty component due to mounting conditions contributes to the total uncertainty budget with less than 0.5%.

Parameter identification of force transducers using sinusoidal excitation

This task was performed to improve the methodology for the parameter identification of force transducers. The knowledge of the parameters stiffness and damping of a force transducer is necessary for its proper use in a given dynamic applications. For those applications, complex models often have to be applied in which these parameters are an essential input. The studies in this task were made by LNE, PTB and CEM.

At LNE, dedicated software was developed which is not only able to obtain the force transducer's parameters, it can also determine the parameters of the load mass coupling.

At PTB, the parameter identification was done via the analysis of the measured resonance peak, based on a spring-mass-damper model. Different fitting algorithms were investigated, including amplitude and phase fit as well as fits of the real and imaginary part of the transfer function. It turned out that a combined fit of the real and imaginary part of the transfer function leads to the lowest uncertainty; thereby a relative uncertainty of the stiffness of the force transducer below 1% can be achieved. The relative uncertainty of the damping factor is significantly larger, in the order of 10%.

At CEM, measurements concerning the stability of the resonance peak were performed. This confirmed that the manner of mounting is crucial for the reproducibility and the frequency stability of the measured resonance.

3.2 Primary calibration of force transducers for traceable dynamic measurements of shock forces

3.2.1 Summary of the key results

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

Existing shock force calibration devices at PTB, the German NMI, 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.

3.2.2 Results in more detail

To develop new methods in the field of shock force calibration, the research was performed at the two primary shock force calibration devices at PTB, which provide shock force amplitudes of up to 20 kN and 250 kN, respectively. The experimental work was supported in terms of modelling and statistics by PTB colleagues from the mathematical department.

Experimental investigations at the larger 250 kN shock force calibration device proved that shock-excited vibrations might not only result from the elasticity of the transducer's measuring spring element, but might be caused by the elastic coupling of the mounted transducer, too. These results were confirmed by finite element calculations of the modal vibrations of the mounted force transducer (see figure 4). Additional experiments further showed that the mounting conditions may have influence on the coupling stiffness. Figure 5 shows that the coupling resonance varies with different adapters and depends on mounting torque. This means that the coupling stiffness is a factor of great importance and that reproducible shock measurements require well defined mounting conditions.

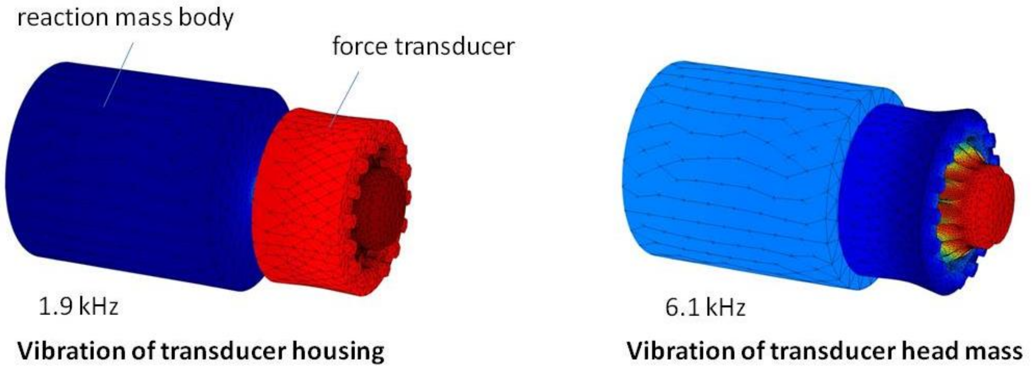


Figure 4: Finite element analysis of two axial vibration modes of a mounted 220 kN transducer: the figures visualise the colour-coded displacement and the deformed shape.

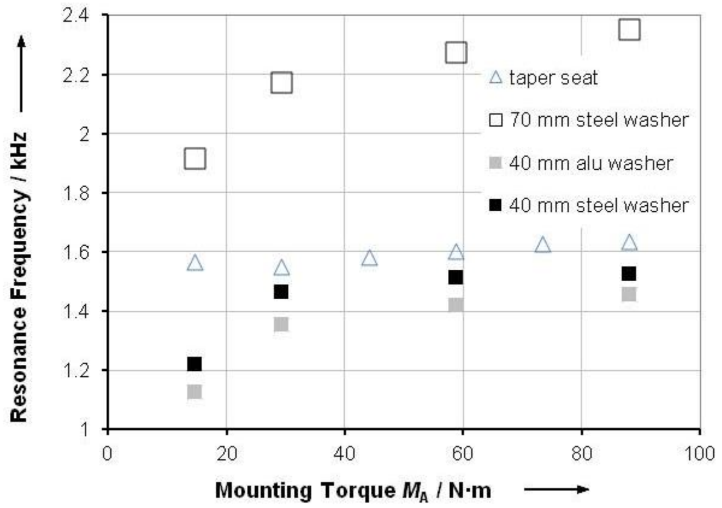


Figure 5: Dependency of mounting conditions on the transducer's resonance frequency.

Due to the limited force range of the devices for sinusoidal calibration, the transducers selected in this research project have comparably small capacities which allowed the testing at the smaller 20 kN shock calibration device.

At the beginning of the project, the 20 kN shock force calibration device (see figure 6) was modified in order to improve the quality of the two interferometer signals which provide traceability with primary methods. To probe both colliding mass bodies on their common axis of motion, the beam geometry of the laser interferometers was accordingly changed. Appropriate adapters were machined to mount the force transducers under test.

Numerous measurements were performed on the 20 kN shock force calibration device to investigate and validate the approach of a model-based dynamic calibration of force transducers by using shock excitations. The tests included several strain gauge force transducers of greatly differing structural design, size, weight and mechanical coupling. Physical models of the measurement set-up were investigated and data analysis procedures for the MBPI based on measured shock data were developed.

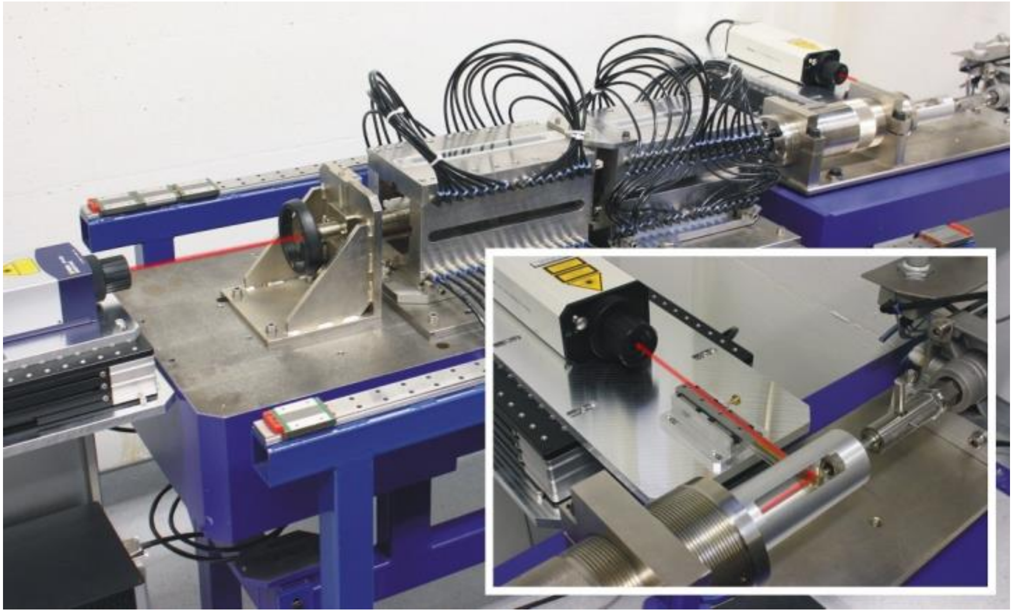


Figure 6: Modified 20 kN shock force calibration device.

These models are able to reproduce the dynamic response including the observed modal oscillations of various origins that limit the usable measurement bandwidth. Moreover, it was found that the modal oscillations may have an important role to give satisfying results of the parameter identification process.

Figure 7 shows models of the mechanical system, i.e. the calibration device with mounted force transducer, which are described by a one-dimensional multi-body system consisting of a linear series arrangement of lumped masses coupled by visco-elastic springs. The dynamic behaviour of a force transducer is characterised by four parameters. With at least four model masses, the elastic coupling of the transducer to the calibration device can be described.

The parameter identification of a transducer that responded with strong impact-excited ringing gave consistent results, with similar values obtained from the 4 and 5 mass model. However, the measured and calculated signals still show some deviations to be explained in future.

Initial trials on the parameter identification of transducers with smooth pulses of almost no ringing indicate that the excited modal oscillations presumably carry important information to unambiguously identify the model parameters of a multi-body system having more than one degree of freedom. In order to excite the resonances of the force transducer to a greater extent, two different methods were investigated.

For the first method, an auxiliary set-up was developed that replaces the original airborne impact mass body of 10 kg by a small pendulum mass. Figure 8 exemplarily compares three shock pulses obtained with different impact masses. The 10 kg impact mass generated a smooth pulse of 1.3 ms without ringing, whereas the small pendulum masses yield considerably shorter pulses, down to 0.1 ms with the pendulum of 7 g, followed by a pronounced ringing.

The second method uses small additional load masses that are mounted at the transducer's head mass in order to reduce the resonance frequency. Different load masses result in different shock responses which provide valuable information for the parameter identification and model validation. Figure 9 shows a DFT analysis of the ringing signal (the same transducer as in figure 8) for different load masses.

Ultimately, it proofed to be challenging to describe a simple method to identify the appropriate model and perform a calibration by MBPI. Further investigations and experience appears to be necessary to come up with a more universal procedure.

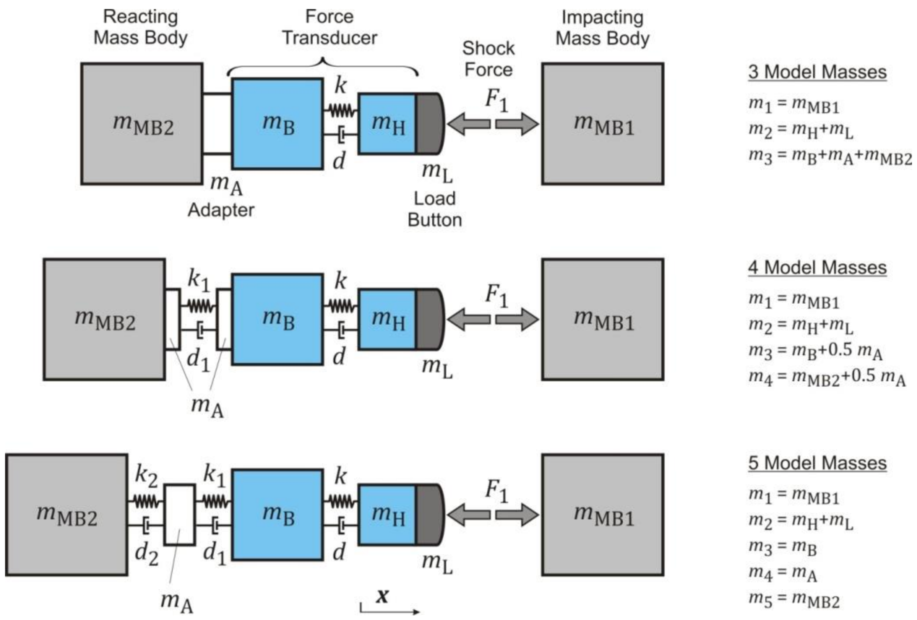


Figure 7: Models of the shock force calibration device with mounted transducer (blue components).

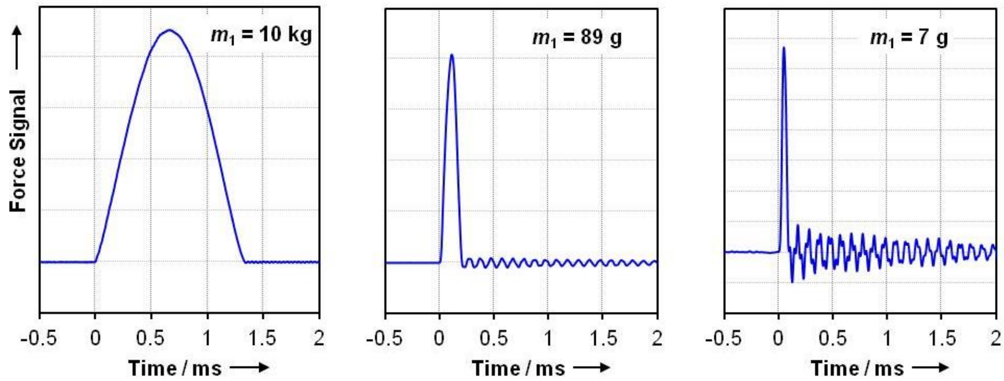


Figure 8: Shock pulses measured with impact bodies of differing mass (10 kg, 89 g, 7 g).

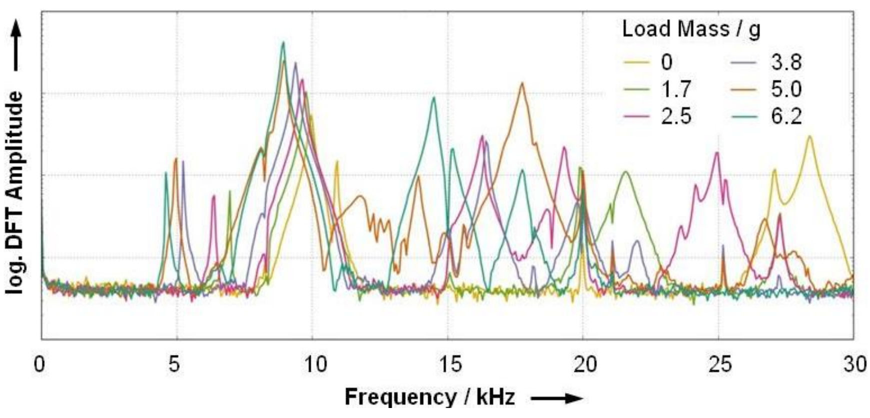


Figure 9: DFT analysis of the signal ringing for different additional load masses.

3.3 *Primary calibration of pressure transducers for traceable dynamic measurements of shock pressures*

3.3.1 Summary of the key results

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, the German NMI, 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 British 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.

3.3.2 Results in more detail

Despite the majority of industrial pressure measurement applications being – to a greater or lesser extent – dynamic in nature, the vast majority of transducer systems employed to make these measurements are calibrated only statically. This is due to the unavailability of dynamic pressure reference standards, and can have a significantly detrimental effect on the quality of the measurements made. The main aim of this objective was to develop dynamic pressure reference standards, traceable to the SI, in order to provide a set of internationally compatible facilities against which industrial pressure measurement systems could be calibrated.

The research work in this objective was partitioned by technology. It consisted of SP and NPL on the one hand, and PTB, MIKES and UME on the other hand. NPL and SP were working jointly on shock tube pressure calibration methods supported by the NPL math group in terms of modelling and data analysis. PTB and MIKES worked on the development of primary drop-weight high pressure calibration devices while UME complemented this work with results from their secondary high pressure calibration device. This work was supported by INRIM, the Italian NMI, in terms of modelling and data analysis. Since a major part of this work was the commissioning of the individual devices, the co-operational part developed more towards the end of the project when it came to comparison measurements.

Two different approaches were taken to generate SI-traceable dynamic pressures, namely drop weight systems and shock tubes. These two types of dynamic pressure standards, shock tube and drop weight system, generate very different dynamic pressure inputs, both in terms of magnitude and frequency content. The shock tubes generate steps of up to 1.4 MPa (14 bar) with useful durations of up to 0.2 ms of the acquired step-like waveform. In contrast, the drop weight systems generate half-sine pressure profiles with a maximum pressure value of up to 500 MPa (5000 bar) being reached approximately 1 ms after the initial impact. For this reason, the comparisons between the facilities were split into two separate exercises – a primary comparison between the two shock tubes and a separate primary comparison between the drop weight systems of PTB and MIKES. A comparison between the secondary systems of PTB and UME was also scheduled.

A report on the shock tube comparison has been drafted and demonstrates that, within the claimed uncertainty levels at the two NMIs, there is no evidence of any discrepancy in the magnitude of the generated pressure step. The analysis of the drop weight comparison exercises is still ongoing.

Prior to the comparison exercises being carried out, a great deal of work went into development of the various facilities, with much novel investigatory research required to ensure they were fit for purpose. In the area of shock tubes, studies into a wide range of possible influences, such as diaphragm material, thickness, and rupture mechanism, tube length and construction material, and side wall sensor location were carried out. Further tests to validate the applicability of the gas theory used to calculate the generated pressure step were also necessary, and involved varying the starting pressure and species of the gas in the driven section, as well as varying the pressure in the driver section prior to diaphragm rupture.

As an early impact, NPL has established a shock pressure calibration service now available for providing dynamic calibration for industrial users. Kistler Instrumente AG, a manufacturer of industrial sensors, was one of the first users of the NPL dynamic pressure calibration service, allowing them to document the performance of their pressure transducers under shock pressure conditions in the product specifications.

NPL also developed a secondary system during this project, based on a liquid-filled column receiving an impact at one end and transmitting a fast-moving pressure waveform to a set of pressure sensors mounted symmetrically at the tube's far end, to enable calibrations of industrial sensors against reference ones previously calibrated in a shock tube. Prior to this work, a study into possible acoustical techniques for providing traceable dynamic pressure standards had been carried out. An analysis of the effect of changing the fluid medium from liquid to gas on the performance of a specific type of piezoelectric transducer was also carried out to ensure the validity of this transfer from air to oil.

Drop-weight systems

PTB and MIKES have developed primary dynamic pressure standards in which a falling weight impacts on a piston, generating an increase in pressure within a liquid-filled cavity. The diaphragms of one or more pressure sensors are exposed to this pressure increase, and the relationship between the applied pressure and the output of the sensor system is used to calibrate it. Traceability for the applied pressure is realised by different methods at the two laboratories: the MIKES system derives the dynamic pressure from the piston area and the dynamic force required to decelerate the weight, whereas the PTB system determines the cavity pressure as a function of the liquid's refractive index measured by a laser interferometer.

For the high pressure range up to 800 MPa, MIKES, UME and PTB were involved in the development and investigation concerning drop weight impulse pressure calibration systems. While MIKES and PTB developed new primary systems, UME investigated properties and characteristics of a comparison device. Unfortunately the development and commissioning of the primary systems proved to be much more complex than expected, with the consequence that parts of the foreseen tasks could not be accomplished during the runtime of the project. For the primary realisation of the dynamic pressure measurement, MIKES and PTB employed different principles.

The MIKES device

The MIKES route to traceability was supposed to go via the displacement of the piston that is compressing the hydraulic liquid (figure 10). Since the piston is not easily accessible, its movement was determined indirectly by measuring the motion of the drop weight during impact. This could be done either by an accelerometer or in a more sophisticated approach by laser interferometry. In the further process the dynamic pressure was supposed to be calculated via a dynamic model of the compressible fluid. However, the complexity of the development of the generating and measuring system turned out to be prohibitive for further research within the runtime of the project. First measurements with the device showed that the measuring principle generally worked, whether the traceability approach is feasible is a matter of future research.

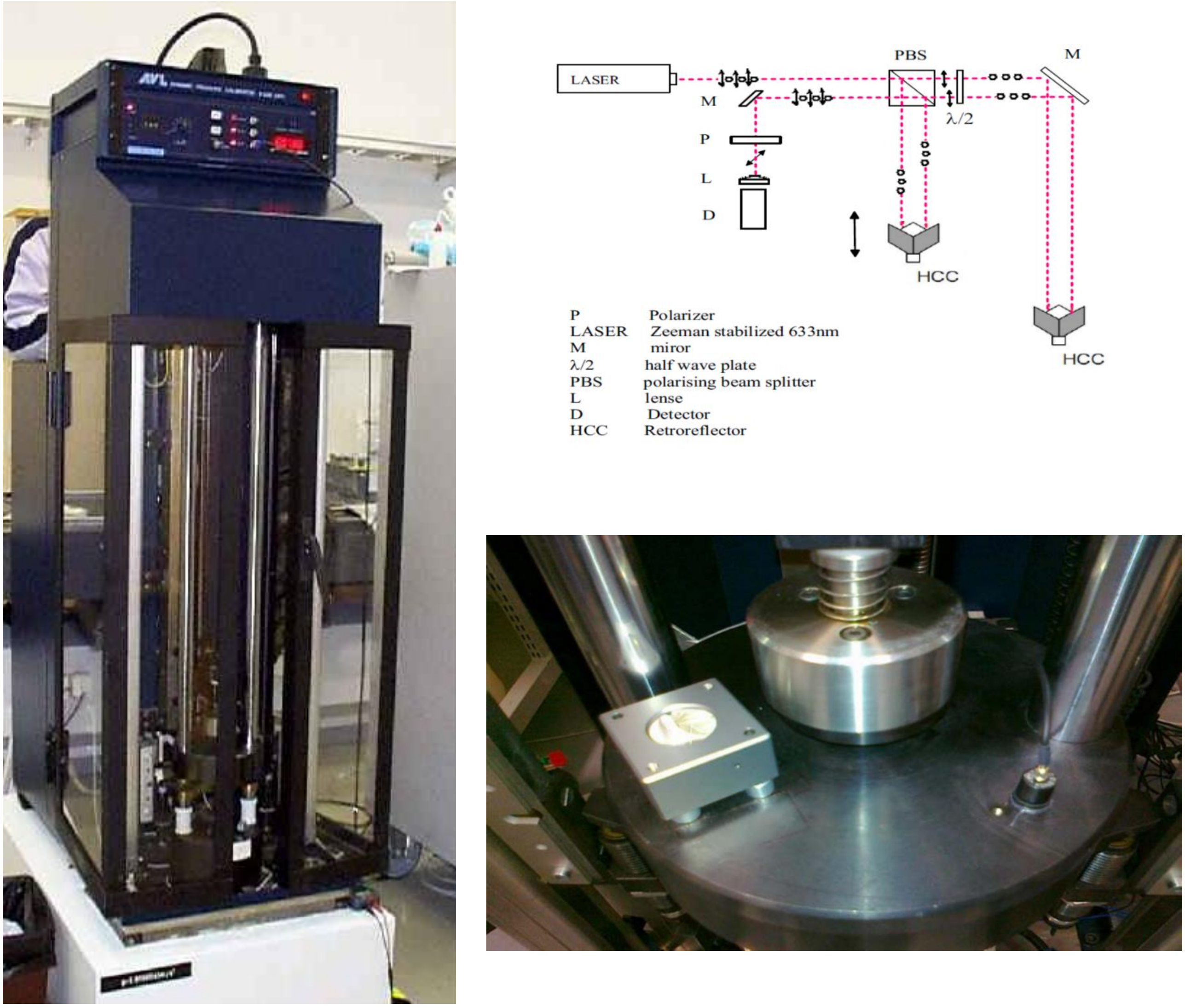


Figure 10: Drop weight devices at MIKES, with acceleration measurement of the drop mass either by accelerometer or by laser interferometer.

The PTB device

PTB's approach to gain traceability for dynamic pressure for the drop weight facility employed refractive index measurements by laser-Doppler interferometry. In a first step the feasibility of this approach was shown for stepwise pressure in a simplified set-up (figure 11). This proof of concept was successful in so far as the signal intensity and quality of the optical measurement was very good. It was possible to measure the pressure-dependent change in the optical path length with high accuracy and good reproducibility testing different hydraulic media (figure 12). The test set-up also helped to detect some potential pitfalls, which led to new requirements for optical windows and seals with high stiffness for the pressure vessel of PTB's drop weight device. This new critical requirement led to a redesign of the pressure vessel of the drop weight device which in turn delayed the work substantially. First laser-interferometric impact pressure measurements were possible only towards the end of the runtime of the project (figure 13). Nevertheless, these measurements confirmed the expectations put into this new method.

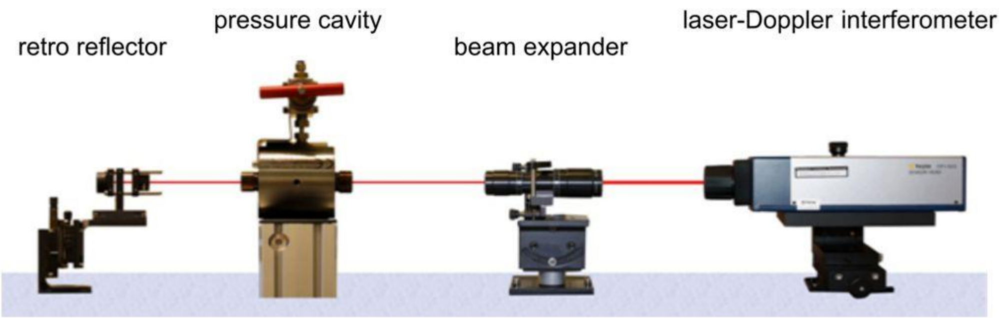


Figure 11: (Simplified) set-up for preliminary investigations of the laser-interferometric measurement of dynamic pressure.

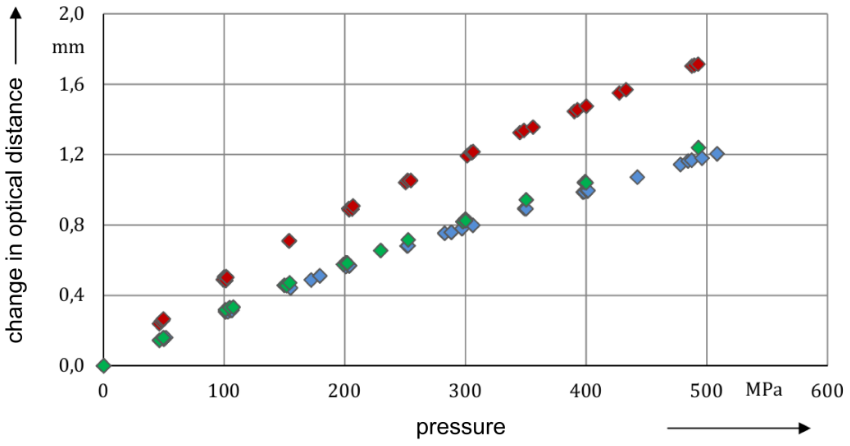


Figure 12: Pressure dependence of the measured maximum displacement (change in optical distance) for three hydraulic media: sebacate (red), glycerol (green), water (blue).

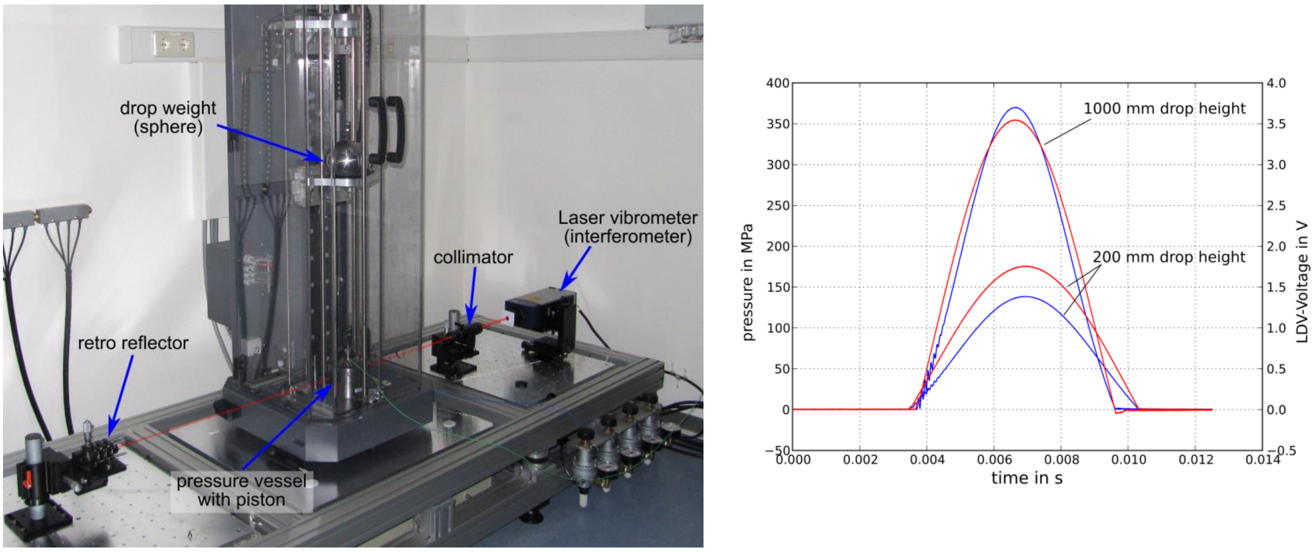


Figure 13: PTB's drop weight device (left) with laser-interferometric measurement of pressure and chart of two time series of measurements of different drop heights (pressure sensor in blue, laser interferometer in red).

Irrespective of the development of the calibration devices, UME and NPL investigated the influence of the pressurized medium on the dynamic sensitivity of pressure transducers. The background is that in force and torque metrology as well as acoustics it is a well-known fact that the mechanically coupled environment has some influence on the pressure transducer. For the investigated media it could be demonstrated that there is some influence on signal shape due to the mutual interaction, however, an influence on the transducer sensitivity was not detectable.

Finally some work on intercomparison measurements was started by the end of the research project between the three drop weight devices (UME, MIKES, PTB). However, due to delays this is still work in progress.

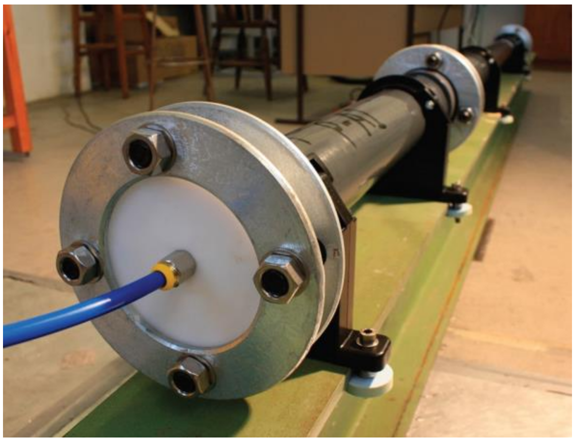
Shock tubes

NPL and SP have developed shock tube systems, in which a practically instantaneous pressure step can be applied to the diaphragm of a dynamic pressure sensor. The dynamic performance of the sensor system can be determined from its response to this pressure step, the magnitude of which can be calculated from the initial conditions of the shock tube and the velocity of the shock front.

As part of the project, SP has worked with the company Simea Optic to characterise the performance of a novel optical pressure sensor. This sensor was used in the comparison between the two shock tubes.

Various aspects of the shock tubes were theoretically and experimentally investigated at NPL using a 1.4 MPa (maximum pressure) shock tube made from PVC-U pressure tubing which provides a low-cost, light, and easily modifiable basis for establishing a method for determining the dynamic characteristics of pressure sensors (see figure 14).

These investigations included different diaphragm designs and driven gas sections (see figures 15a, 15b), gas species (see figures 15c, 15d); the influence of the material onto which the sensor being calibrated is mounted (see figure 15e); the modelling of the gas shock and the sensor; and the measurement of the reference signal by means of a laser vibrometer. The results showed that shock tubes were well suited for generating extremely rapid pressure steps suitable for the dynamic characterisation of pressure sensors. As pressure sensors may also be sensitive to acceleration, further work is required to eliminate any effect of acceleration of the sensor mounting block on the calibration result. It should be noted that the method of mounting the sensor in practical applications will be critical to its dynamic performance. Validation measurements were still in progress at the end of the project and are continuing, with the intention of developing primary dynamic pressure calibration services with traceability linked to the absolute pressure magnitude.



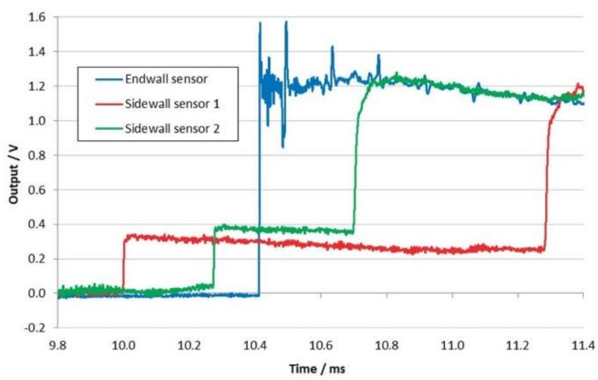
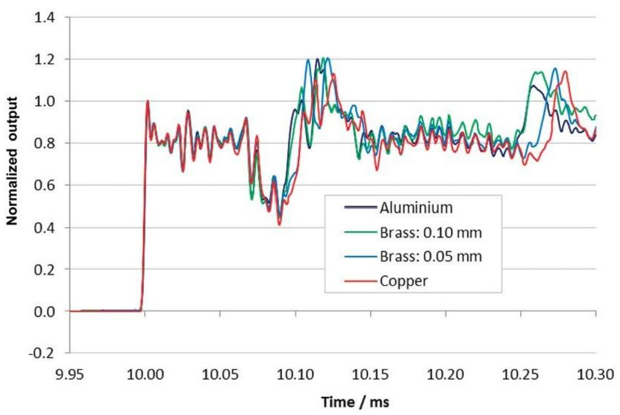
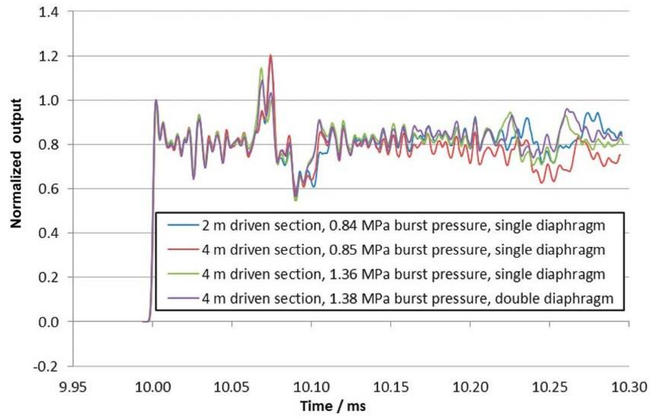


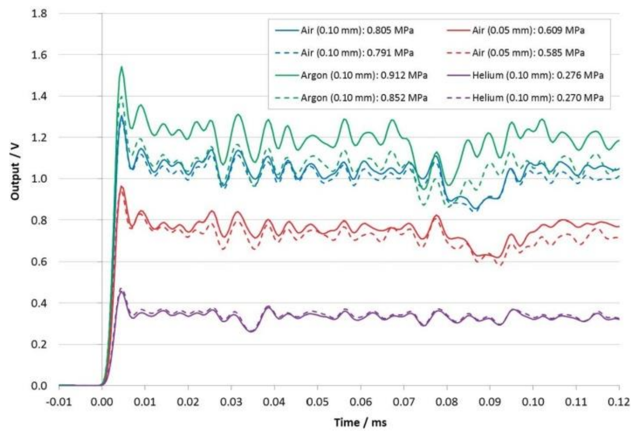
Figure 14: 1.4 MPa shock tube at NPL (left) and pressure signals measured at different positions along the driven section to estimate the shock wave velocity.



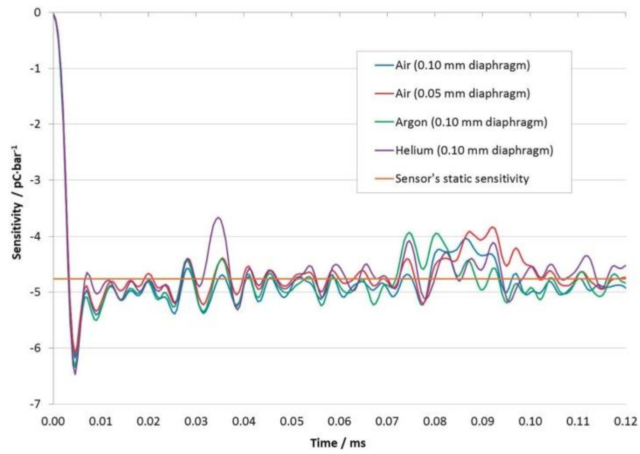
(a)



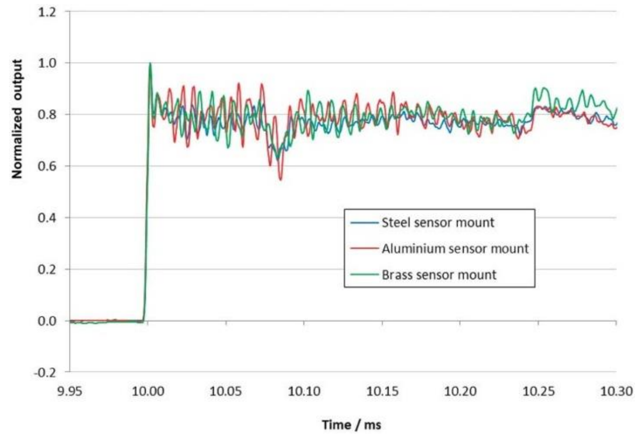
(b)



(c)



(d)



(e)

Figure 15: Experimental investigations at the shock tube at NPL: (a) comparison of different diaphragm materials used in a single diaphragm configuration, (b) effect of different driven section length, burst pressure and diaphragm configuration, (c) variation of driven gas species, (d). pressure sensor sensitivity in response to pressure step, (e) pressures steps obtained with different sensor mount material.

3.4 Primary calibration of torque transducers for traceable dynamic measurements of

periodic torque

3.4.1 Summary of the key results

A primary calibration device for torque transducers was set up and validated at PTB, the German NMI. 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.

3.4.2 Results in more detail

In the area of dynamic torque calibration, PTB was the only active participant. CMI, the Czech NMI, withdrew most of their resources short time after the start of the project, and UME, the Turkish NMI, which previously intended to participate here, focussed their activities on dynamic pressure due to lack of resources. This did not, however, inhibit the progress within this project objective by any degree.

At the very beginning of this work package, the work was focused on the structural design of torque transducers for dynamic measurements starting with a census about transducers used for dynamic applications in industry, an estimate of the required specifications, and finally an investigation of the structural designs of qualified transducers.

There are two main applications with dynamic torque excitation, namely impulse wrenches and mechanical output power measurements in test rigs. The latter example is particularly important in research and development due to increased needs to further improve the fuel efficiency of vehicles.

The measurement principle of the majority of torque transducers is based on the measurement of torsion, which is typically carried out by means of strain gauges, by far the most common sensor technology. In a strain gauge transducer, the applied torsional load deforms the mechanical structure of the torque transducer elastically. These deformations are sensed by several strain gauges bonded onto the surfaces at specific locations, in particular at spots of strong and uniform strain. The electrical resistance of a strain gauge changes proportionally with its mechanical elongation. Usually, four strain gauges are electrically connected to a Wheatstone bridge circuit (full bridge) to supply an output signal voltage that is proportional to the applied torsional load.

The prototype device at PTB was improved and extended to provide larger sinusoidal torque loads up to 20 N·m. A more powerful exciter was installed, and the air bearing was replaced by a stronger type supplied by a boosted air supply pressure. The developed dynamic torque measuring device is shown in figure 16.

The calibration of a torque transducer under test is carried out by applying sinusoidal torque excitations in a broad range of frequencies (1 Hz to 1 kHz). Based on Newton's second law; the acting torque is determined by means of a mass moment of inertia and the angular acceleration. Hence, the traceability of dynamic torque is obtained with primary methods.

To be able to characterise the dynamic behaviour of a torque transducer and the effect of the coupled components in the drive train, the approach of a model-based calibration is followed. An appropriate dynamic model was developed that can characterise the dynamic behaviour of the torque transducer as well as of the coupled mechanical environment (the calibration device). The basic model of a torque transducer consists of two mass moments of inertia elements connected by a torsional spring and a damper in parallel (see figure 17, components marked in red). As torque transducers are always coupled on both ends to their mechanical environment, which may have influence on the transducer's dynamic behaviour, the basic model was extended to include the components of the dynamic torque measuring device (marked in black).

Figure 16: Dynamic torque measuring device at PTB.

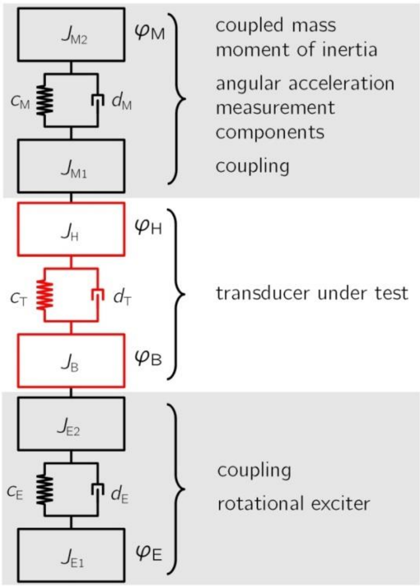


Figure 17: Model of the dynamic torque calibration device (marked in black) including the transducer under test (marked in red).

To determine the model specifications of the components of the dynamic torque calibration device, three dedicated auxiliary devices were developed at PTB. Because of the new rotor of the replaced air bearing, its moment of inertia needed to be re-determined. In addition, other measurements were performed to characterise the parameters of the couplings, their mass moment of inertia, torsional stiffness and torsional damping.

The first device for mass moment of inertia (see figure 18) is based on a compound pendulum, where the pendulum frequency depends on the applied moment of inertia. Additional mass bodies to be inserted in the pendulum lever are required to calculate the desired measurand of the device under test mounted at the rotational axis.

The second auxiliary set-up for torsional stiffness utilises PTB's static 20 N·m Torque Calibration Machine (see figure 19). Well known torque levels are applied in several load steps (procedure based on DIN 51309) and the resulting torsional angles on top and on bottom of the device under test are measured. The torque is measured by means of a reference transducer, the torsional angle by means of two autocollimators probing on mirrors clamped to the device under test. The measurements are in particular needed for the torsional couplings, which are assumed to have the lowest torsional stiffness of all elements in the drive train, and therefore have great influence on the dynamic measurement behaviour.

The third device is dedicated to torsional damping (see figure 20). For this purpose, damped free oscillations are excited by a negative torque step applied to the device under test (torsional couplings). The torque step is achieved with a brittle specimen made of technical ceramics that is supposed to break under a certain torque load. The torsional oscillations are measured by means of two rotational laser-Doppler vibrometers probing the device under test at its upper and lower part.

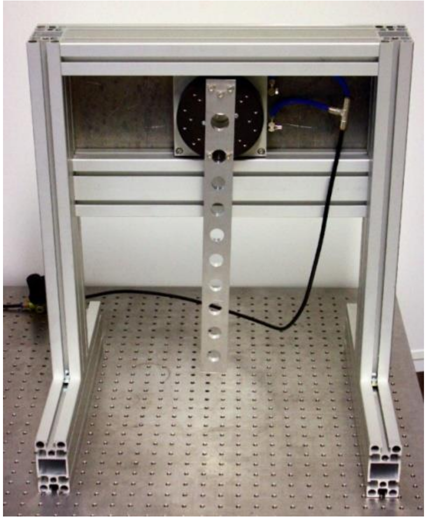


Figure 18: Measurement set-up for the determination of mass moment of inertia.

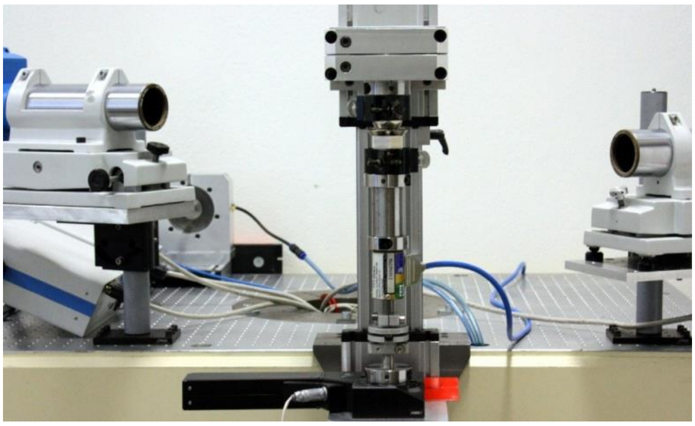


Figure 19: Measurement set-up for the determination of torsional stiffness.

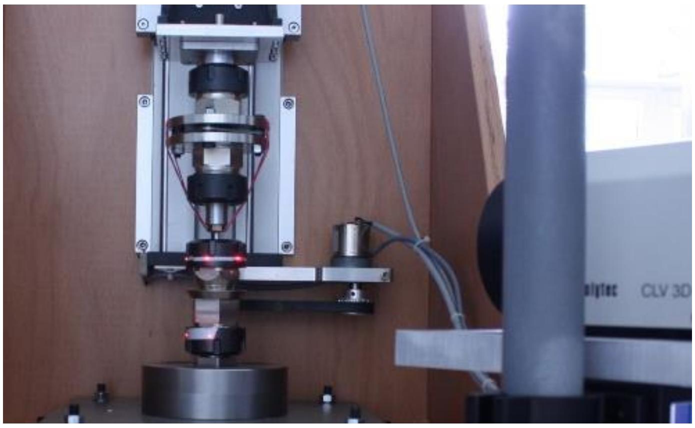


Figure 20: Measurement set-up for the determination of torsional damping.

To characterise the dynamic behaviour of the electrical measurement components and to correct their influences accordingly, the frequency response of the applied measuring amplifiers were determined in cooperation with the project members working in the calibration of measuring amplifiers.

At the end, the model parameters of a torque transducer under test had to be identified from measurement data. For this purpose, the model parameters of the calibration device itself were determined first using the dedicated three auxiliary devices. Chosen as an example, the parameter identification of a shaft-type torque transducer gave satisfying results. The parameter identification was elaborated in cooperation with the project members working in mathematical and statistical modelling.

3.5 Traceable dynamic calibration of amplifiers

3.5.1 Summary of the key results

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.

3.5.2 Results in more detail

Traceable dynamic measurements of mechanical quantities require traceable dynamic calibration procedures for measuring amplifiers (sometimes called conditioning amplifiers), since the amplifiers are a complementary part of the electric measurement chain of each sensor.

The project covered the investigation and calibration of two types of measuring amplifiers which are commonly used in dynamic measurements. These two types are bridge amplifiers for strain gauge or piezoresistive transducers in Wheatstone bridge configuration and charge amplifiers for piezoelectric transducers.

For the calibration of bridge amplifiers, dynamic bridge standards were developed at NPL and PTB which enable frequency-dependent amplitude and phase measurements. For the phase calibration, the dynamic bridge standard system needs to provide a reference signal. In the project it was decided and agreed between PTB and NPL to modify the bridge standard systems in order to provide a sinusoidal reference signal. After modification and validation of the dynamic bridge standards at NPL and PTB, it was possible to investigate bridge amplifiers at both sites in a dynamic way up to 10 kHz. The calibration of the dynamic bridge standards provided, for the first time, the ability to perform a traceable dynamic calibration of bridge amplifiers. Previously, bridge amplifiers could only be calibrated statically.

The calibration result of PTB's dynamic bridge standard is shown in figure 21. The technology of PTB's dynamic bridge standard was offered to industry as a licence product. To validate and compare the dynamic bridge standards of PTB and NPL, a comparison of the different bridge standard systems was carried out. In addition to the newly developed DAC-based dynamic bridge standards in NPL and in PTB, a formerly developed inductive dynamic bridge standard (of PTB) was included in the comparison. The comparison measurements revealed certain discrepancies for the amplitude and phase calibrations of the bridge amplifier which was used as a travelling standard (see figure 22). However, extending e.g. the amplitude uncertainties of all measurements in the shown calibration measurements to 0.1% (which was the target in the project) would give consistent results.

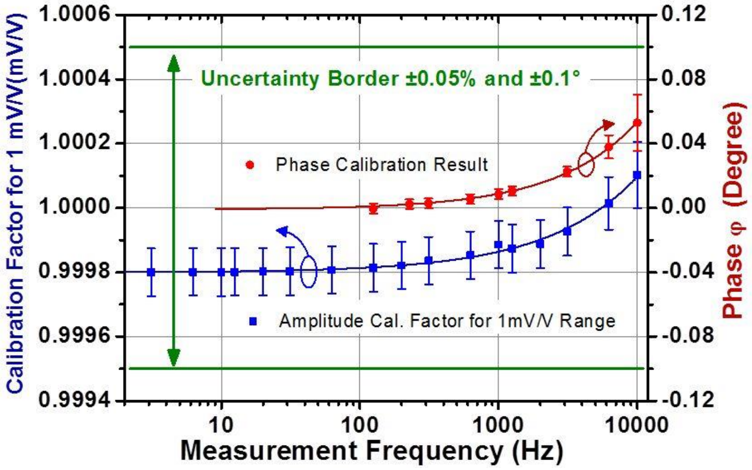


Figure 21: Calibration result (magnitude and phase) of PTB's dynamic bridge standard at 1 mV/V amplitude range. All measured corrections and their uncertainties lie within uncertainty borders of 0.05% for amplitude and 0.1° for phase.

Calibrations of different types of bridge amplifiers were performed using PTB`s dynamic bridge standard (see figure 23). It was found that the amplifiers show deviations in magnitude and phase response from their nominal values depending on the measurement frequency and parameters like the chosen filter setting.

For the dynamic calibration of charge amplifiers, the existing calibration procedures based on a calibrated AC voltage source and a standard capacitor in order to generate a standard charge signal were improved, extended in frequency range (up to 100 kHz), and applied to calibration measurements for dynamic pressure. Systematic uncertainty contributions for charge amplifiers, which were formerly unknown or ignored, were determined. A comparison of different commercially available charge amplifiers was carried out at PTB.

Comparison measurements of different voltage amplifiers and IEPE amplifiers for piezoelectric sensors with integrated electronics were also performed at PTB.

As a major result of the research on the dynamic calibration of measuring amplifiers, German DKD guideline and an international ISO draft standard on methods and procedures for the traceable dynamic calibration of measuring amplifiers were prepared.

The results gained in the objective on the dynamic calibration of measuring amplifiers were introduced into the experimental work of the previously described research fields for the dynamic calibration of force, pressure and torque transducers (objectives 1 to 4).

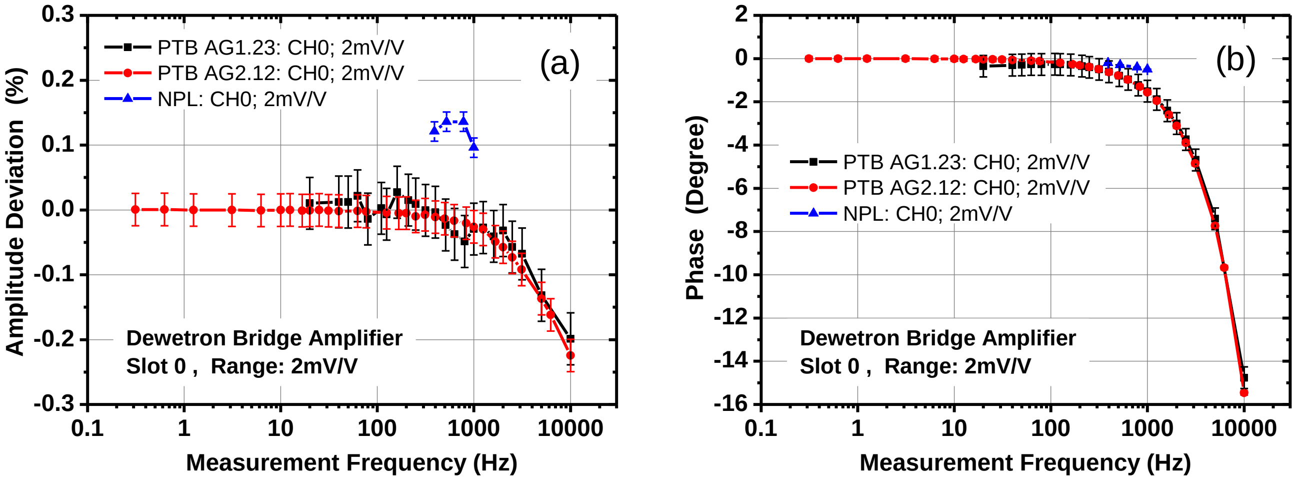


Figure 22: Comparison results of the calibration of a Dewetron Bridge-B amplifier (slot 0) with respect to amplitude (a) and phase (b) for the range of 2 mV/V.

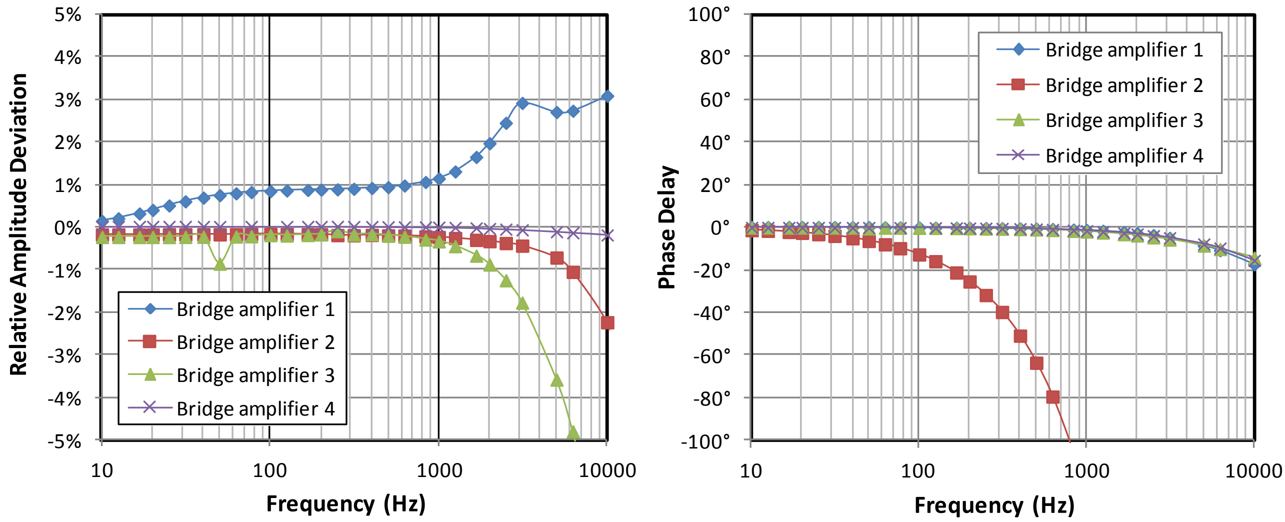


Figure 23: Measured magnitude and phase response of four commercially available bridge amplifiers

3.6 Provision of secondary calibration standards

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 (Germany) for dynamic force calibration and at NPL (UK) 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 (Finland) 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.

3.7 Characterisation of the dynamic behaviour of transducers

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.

The mathematics and statistics work was shared between the four European NMIs that have the greatest experience in mathematics and statistics for metrology, typically because they have specialist groups dedicated to these topics. PTB (Germany) provided support to experimentalists working on torque and force calibrations (especially shock based calibration methods) and contributed their expertise in deconvolution and software development. LNE (France) focused on supporting metrologists concerned with sinusoidal dynamic force calibrations. INRIM (Italy) provided mathematics and statistics support to experimentalists at PTB and MIKES (Finland) who were working on the development of drop-weight methods of dynamic pressure calibration. NPL (UK) supported experimentalists at SP and NPL who were developing shock tube based methods for dynamic pressure calibration.

The results of mathematical and statistical modelling was a series of reports that set out mathematical definitions of measurands for dynamic measurements of force, torque, pressure and electrical amplifiers, a mathematical component model of measuring chain, statistical modelling of dynamic measurements and measurement uncertainty, and advice on evaluation of measurement uncertainty. A key conclusion that underpins all work was that all measuring systems should be regarded as linear and time-invariant. This allowed to apply convolution and deconvolution methods and to regard the input-output characteristics of a system to be completely described by the system's impulse response. Excitation signals employed included stepped-sine/sinusoidal, impulse/shock, and chirp excitation. The measuring systems under consideration were modelled by sets of linear ordinary differential equations, or by equivalent rational functions in the Laplace domain, and analysis was performed mainly in the frequency domain.

To support NMI-level calibration, the key outputs were documented and tested software for the three application areas, force, torque and pressure and case study reports showing the results of the software in action. The early stages of the work focused on simulations of measuring systems, the later used real measurement data as soon it was available. The software was written mainly in Matlab following modern software engineering practices and was made available to colleagues via the internal project website.

3.8 Procedures for uncertainty evaluation

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.

The methods set out in the Guide to the expression of uncertainty in measurement (GUM) and its supplements were applied to estimate the uncertainty in measurement. New methods are in accordance with the underlying philosophy of the GUM and can be viewed as implementing and extending the GUM methodology. To allow meaningful interpretation of calibration results, it was intended to develop parametric "white box" system models, as far as possible, that take into account the known physical and engineering characteristics of the measuring system being developed during the course of the research project.

A Monte Carlo method was successfully developed, in accordance with GUM Supplement 1, 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.

3.9 Enable industry-level traceable dynamic measurements by design of appropriate deconvolution filters

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.

To support application level implementation, the software tools described above were extended to implement secondary level calibrations and to perform deconvolution using calibration information. This approach was demonstrated on simulating dynamic pressure data, but by the end of the project it had not been successfully demonstrated on force and torque calibrations, although in both these latter cases parameter identification software has been made available via the project internal website together with reports that document the outcomes of this process.

3.10 Summary of key results

The key results and conclusions across all objectives are summarized as follows:

- Core achievements of the research project are the development and set-up of several dynamic calibration (and research) facilities in the participating NMIs that were not readily or not at all available without the project. Based on the availability of these new devices and several that existed prior to the start of the project, dedicated investigations and developments took place and led to new findings or the confirmation of existing presumptions in the field of metrology of dynamic measurements. These dynamic calibration devices for force, torque, and pressure use periodic and shock-like excitations; they are listed in the following.
    - Periodic force calibration devices at PTB, CEM and LNE
    - Shock force calibration devices at PTB
    - Pressure shock tubes at NPL and SP
    - Low pressure pulse device at NPL
    - High pressure primary drop weight devices at MIKES and PTB
    - Periodic torque calibration device at PTB
    - Electrical dynamic bridge standard including phase at PTB
- Development of auxiliary devices for dynamic torque to determine the parameters of the components of the calibration device
- Development and validation of dynamic bridge standards for magnitude and phase calibration of bridge amplifiers
- Validation of methods for the traceable dynamic calibration of the four most common conditioning amplifier types
- For all measurands, the dynamic response of the complementary conditioning amplifier in the measuring chain is of critical importance.
- Development of the respective measurement methods applying a model-based approach to describe the dynamic behaviour of the transducer under calibration and its environment by model parameters.

- The model-based approach to dynamic calibration is feasible and may provide the means for the dissemination of units in the future. This approach comprises time series data of dynamic processes as actual measurands and model parameters with their associated uncertainties as calibration results.
- The respective mathematical procedures and software implementations for data analysis, parameter identification und uncertainty calculation were developed. The GUM approach to measurement uncertainty can be extended to cover the field of dynamic measurement.

- First international comparisons of the dynamic calibration of force transducers
- First international comparison of dynamic bridge standards used for dynamic calibrations of bridge amplifiers in magnitude and phase
- Establishment of dynamic calibration services for dynamic force and dynamic pressure, which now can be used by industry
- Preparation of new international standards and guidelines for dynamic measurement, e.g. a German DKD guideline and an international ISO draft standard on methods and procedures for the traceable dynamic calibration of measuring amplifiers, draft DKD guidelines on the dynamic force transducer calibration and dynamic calibration of materials testing machines
- Important new knowledge for the parameter identification gained:
    - The mechanical mounting conditions of the employed transducers are critical for reproducibility, comparability and measurement uncertainty. To achieve well-defined conditions, the fastening torque of screw connections should be controlled, e.g. by using torque wrenches.
    - The mechanical environment of the transducer in terms of masses, coupling stiffness but also cross contamination (e.g. environmental vibration) is crucial and has to be considered.
    - Knowledge of transducer design is often needed to choose an appropriate model.
    - For force and torque measurements, the mass loading needs to be considered in the model to understand the dynamic system response.
    - For dynamic pressure measurements, the pressure mitigating medium does not influence the sensor’s response significantly.
    - Uncertainty of model parameters can be estimated by Monte Carlo simulations.

4 Actual and potential impact

The need of the project is a consequence of the great importance of accurate dynamic measurements of the mechanical quantities force, torque, and pressure, which is required in many industrial branches of industry, and the current lack of a metrological infrastructure for dynamic mechanical quantities. As there was no joint international research effort in the field of dynamic measurements before, documentary standards or commonly accepted guidelines for dynamic calibration were lacking. This lack has been recognised for some time, and a number of organisations (both NMIs and commercial entities) have attempted to remedy this. However the solutions offered so far, including those offered as services by some NMIs, have often lacked traceability, or were application-specific, not well-grounded in physical or engineering theory, limited only to aspects of testing rather than calibration, or do not conform with metrological best practice as codified in the GUM.

To provide the metrological base for accurate dynamic measurements of force, pressure and torque, the European NMIs participating in this research project developed facilities and methods for calibrating sensors under dynamic conditions allowing dynamic measurements traceable to national measurement standards. The project set up new unique dynamic calibration facilities, developed the respective measurement methods for periodic and shock-like excitations and supplemented this experimental work with substantial mathematical modelling and data analysis including the necessary procedures for measurement uncertainty calculation.

Summary of dissemination activities

A major intention of the joint research project was to raise awareness and to distribute fundamental knowledge about the metrology of dynamic measurements. 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. The related dissemination activities worked mainly through publications. 33 papers were published in international journals and conference proceedings.

The key outputs of major scientific interest were published in high-level journals of metrological science, typically "Metrologia". Examples of these are:

- T. Bruns, E. Franke, M. Kobusch, "Linking dynamic to static pressure by laser interferometry", Metrologia, 50, 580–585, 2013.
- A. Malengo, F. Pennecchi, "A weighted total least-squares algorithm for any fitting model with correlated variables", Metrologia, 50, 654–662, 2013.
- C. Matthews et al., "Mathematical modelling to support traceable dynamic calibration of pressure sensors", Metrologia, 51, 326–338, 2014.
- L. Klaus, T. Bruns, H. Volkers, "Calibration of bridge-, charge- and voltage amplifiers for dynamic measurement applications", Metrologia, 52, 72-81, 2015.

The dissemination activities further included 53 presentations: 18 contributions to the Workshops on Analysis of Dynamic Measurements, 13 contributions to the International Measurement Confederation (IMEKO) conferences and congresses, 3 contributions to the Conference on Precision Electromagnetic Measurements (CPEM), as well as other high-level measurement conferences and events including an International Bureau of Weights and Measures (BIPM) workshop on traceable dynamic measurement.

In the case of IMEKO, the contributions are available to the public via the IMEKO proceedings on the web server (www.imeko.org). The workshop contributions are available as PDF-versions of the presented slides. In contrast to journal publications, these meetings had the advantage of a direct contact to stakeholders from industries with the option of in-depth discussion. This often was the preferred means to raise awareness.

Summarizing the results of the research project, 9 articles were published in a dedicated issue of PTB Mitteilungen.

In addition, two doctoral theses on dynamic calibrations of force and torque transducers resulted from the activities of this research project:

- N. Medina, "Calibración de sensores de fuerza bajo estímulos sinusoidales: contribuciones a su caracterización", Universidad Politécnica de Madrid, 2015.
- L. Klaus, "Entwicklung eines primären Verfahrens zur Kalibrierung von Drehmomentaufnehmern mit dynamischer Anregung", PTB, 2016.

Some invited contributions highlighted the attention the project attracted in the scientific and metrological community:

- Invitation to the Association of the German Engineers (VDI):
    - T. Esward, "Current and future challenges in modelling and simulation of measuring systems", VDI/VDE-GMA FA 1.10 "Grundlagen der Messsysteme", Frankfurt, Germany, 2012.
- Invitation of two leading project members to participate in the scientific committee of a BIPM workshop dedicated to the metrological challenges of dynamic measurements in 2012
- Contributions of project members to the aforementioned BIPM workshop:
    - S. Eichstädt, "Dynamic Uncertainty - In line with GUM? - A mathematical and statistical perspective"; BIPM Workshop on Challenges in Metrology for Dynamic Measurement, Sevres, France, 2012.
    - A. Schäfer, "Challenges in dynamic torque and force measurement with special regard to industrial demands"; BIPM Workshop on Challenges in Metrology for Dynamic Measurement, Sevres, France 2012.
- Invitation to the Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV):

- T. Bruns, “EMRP IND09 Traceable dynamic measurement of mechanical quantities”, 9th meeting of the CCAUV, BIPM, Sevres, France, 2013.

- Invitation of three project members to present the results of research to the management circle of HBM, a leading manufacturer of force and torque transducers in 2013.
- Invitation for a contribution at the “Simposio de Metrología” at CENAM, Mexico to report on the project research:
  - M. Kobusch et al., “Proyecto de investigación europeo para la medición dinámica de magnitudes mecánicas”, Memorias del Simposio de Metrología 2014, Querétaro, México, 2014.
- Invitation for a plenary lecture at the CIMMEC in Brazil to report on the project research:
  - Th. Bruns et al., “Traceable dynamic measurements of force, pressure and torque”, 3rd International Congress on Mechanical Metrology (CIMMEC), Gramado, Brazil, 2014.
- Invitation of two project members to present the project results at the DKD committee of force and acceleration in 2014.

In addition to these continuous efforts to disseminate the knowledge of the current research results, the output of the project was summarized in a web-based best practice guide that is available via the project’s website which is persistently hosted at PTB, the German NMI. The best practice guide provides practical information and advice for engineers and technicians in industry making dynamic measurements.

In conjunction with the project’s research and development, a rapid build-up of competence was generated at the collaborating institutes. Industrial stakeholders will now find a network of expertise based in any of the participating institutes.

Early impacts 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.

Spektra Schwingungstechnik GmbH, a German stakeholder of this research project was accredited as the first German calibration laboratory for dynamic force calibration of modal hammers.

Early impacts 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:

- ISO TC 108/SC 3/WG 6 "Mechanical vibration, shock and condition monitoring/…/Calibration of vibration and shock transducers", ISO 16063-43 "Methods for the calibration of vibration and shock transducers - Part 43: Calibration of accelerometers by model-based parameter identification.
- 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.
- DKD FA Kraft und Beschleunigung (committee of force and acceleration of Deutscher Kalibrierdienst, the German national calibration service): two draft guidelines have been written concerning dynamic force transducer calibration and dynamic calibration of materials testing machines.

Wider and longer-term socio-economic and policy impacts

This joint research project made extensive progress in the field of dynamic measurement of the three mechanical quantities force, pressure and torque. For the first time in this field of metrology, joint international research has been conducted in dynamic measurement. As previously described in the early impact sections, 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 an additional dynamic new branch of measurement science, the dynamic calibration, which will be followed by new international standards for dynamic measurement.

The project has given great impetus to the European metrology community to continue the chosen way. 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. We hope to continue the collaboration among the European NMIs within the planned European Centre for Mathematics and Statistics in Metrology and in future EMPIR projects. Ultimately, the development of dynamic calibration methods will potentially have great future impacts that 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.

5 Website address and contact details

The project website will be available beyond the runtime of the JRP under:

http://projects.ptb.de/emrp/ind09.html

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6 List of publications

Dynamic Force

C. Schlegel, G. Kieckenap, R. Kumme, “Dynamic calibration of bridge amplifiers used for periodical force measurement”, Proc. of Conference on Precision Electromagnetic Measurements (CPEM), 570–571, Washington, USA, 2012.

M. Kobusch, L. Klaus, T. Bruns, “Model-based analysis of the dynamic behaviour of a 250 kN shock force calibration device”, Proc. of XX IMEKO World Congress, Busan, Republic of Korea, 2012.

C. Schlegel, G. Kieckenap, R. Kumme, “Application of a scanning vibrometer for the periodic calibration of force transducers”, Proc. of XX IMEKO World Congress, Busan, Republic of Korea, 2012.

M. Kobusch, S. Eichstädt, L. Klaus, T. Bruns, “Investigations for the model-based dynamic calibration of force transducer by using shock forces”, Proc. of Joint IMEKO International TC3, TC5 and TC22 Conference, Cape Town, South Africa, 2014.

N. Medina, J. L. Robles, J. de Vicente, “Realization of sinusoidal forces at CEM”, Proc. of Joint IMEKO International TC3, TC5 and TC22 Conference, Cape Town, South Africa, 2014.

C. Schlegel, G. Kieckenap, R. Kumme, “Uncertainty contributions in sinusoidal force measurement”, Proc. of Joint IMEKO International TC3, TC5 and TC22 Conference, Cape Town, South Africa, 2014.

M. Kobusch, S. Eichstädt, L. Klaus, T. Bruns, “Investigations for the model-based dynamic calibration of force transducers by using shock excitation”, Acta IMEKO, 4 (2), 45–51, 2015.

M. Kobusch, “Characterization of force transducers for dynamic measurements”, PTB Mitteilungen, 125 (2), 43–51, 2015.

N. Medina, “Calibración de sensores de fuerza bajo estímulos sinusoidales: contribuciones a su caracterización”, Dissertation, Universidad Politécnica de Madrid, Spain, 2015, oai:oa.upm.es:38243.

Dynamic Pressure

F. Arrhén, “Step response of vacuum sensors – a preliminary study”, Proc. of XX IMEKO World Congress, Busan, Republic of Korea, 2012.

T. Bruns, E. Franke, M. Kobusch, “Linking dynamic to static pressure by laser interferometry”, Metrologia, 50, 580–585, 2013.

S. Downes, A. Knott, I. Robinson, “Determination of pressure transducer sensitivity to high frequency vibration”, Proc. of Joint IMEKO International TC3, TC5 and TC22 Conference, Cape Town, South Africa, 2014.

S. Downes, A. Knott, I. Robinson, “Towards a shock tube method for the dynamic calibration of pressure sensors”, Proc. of Hopkinson Centenary Conference 2014, Philosophical Transactions A, Cambridge, United Kingdom, 2014.

T. Bruns, O. Slanina, “Measuring dynamic pressure by laser Doppler vibrometry”, PTB Mitteilungen, 125 (2), 38–42, 2015.

S. Downes, A. Knott, I. Robinson, “Towards a shock tube method for the dynamic calibration of pressure sensors”, PTB Mitteilungen, 125 (2), 24–37, 2015.

Dynamic Torque

L. Klaus, T. Bruns, M. Kobusch, “Determination of model parameters for a dynamic torque calibration devices”, Proc. of XX IMEKO World Congress, Busan, Republic of Korea, 2012.

L. Klaus, T. Bruns, M. Kobusch, “Dynamic torque calibration – Necessity and outline of a model-based approach”, in 5th COOMET Competition for Young Metrologists - Competition Papers, ISBN 978-3-944659-00-8, Braunschweig, Germany, 2013.

L. Klaus, B. Arendacká, M. Kobusch, T. Bruns, “Model parameter identification from measurement data for dynamic torque calibration”, Proc. of Joint IMEKO International TC3, TC5 and TC22 Conference; Cape Town, South Africa, 2014.

L. Klaus, M. Kobusch, “Experimental method for the non-contact measurement of rotational damping”, Proc. of Joint IMEKO International TC3, TC5 and TC22 Conference, Cape Town, South Africa, 2014.

L. Klaus, T. Bruns, M. Kobusch, “Modelling of a dynamic torque calibration device and determination of model parameters”, Acta IMEKO, 3 (2), 14–18, 2014.

L. Klaus, B. Arendacká, M. Kobusch, T. Bruns, “Dynamic torque calibration by means of model parameter identification”, Acta IMEKO, 4 (2), 39–44, 2015.

L. Klaus, M. Kobusch, T. Bruns, “A model-based approach for the dynamic calibration of torque transducers”, Proc. of International Modal Analysis Conference (IMAC), Orlando, USA, 2015.

L. Klaus, “Dynamic torque calibration”, PTB Mitteilungen, 125 (2), 12–17, 2015.

L. Klaus, “Entwicklung eines primären Verfahrens zur Kalibrierung von Drehmomentaufnehmern mit dynamischer Anregung”, Dissertation, PTB-MA-93, PTB, Germany, 2016.

Measuring Amplifiers

M. F. Beug, H. Moser, G. Ramm, “Dynamic bridge standard for strain gauge bridge amplifier calibration”, Proc. of Conference on Precision Electromagnetic Measurements (CPEM), 568–569, Washington, USA, 2012.

H. Volkers, T. Bruns, “The influence of source impedance on charge amplifier”, Proc. of XX IMEKO World Congress, Busan, Republic of Korea, 2012.

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J. M. Williams, AC voltage measurement at 1 kHz using a quantum waveform synthesizer and application to the measurement of dynamic quantities, Proc. of Conference on Precision Electromagnetic Measurements (CPEM), 742–743, Rio de Janeiro, Brazil, 2014.

L. Klaus, T. Bruns, H. Volkers, “Calibration of bridge-, charge- and voltage amplifiers for dynamic measurement applications”, Metrologia, 52, 72-81, 2015.

L. Klaus, T. Bruns, H. Volkers, “Calibration of bridge, charge and voltage amplifiers for dynamic measurement applications”, PTB Mitteilungen, 125 (2), 52–61, 2015.

Mathematics

A. Malengo, F. Pennecchi, “A weighted total least-squares algorithm for any fitting model with correlated variables”, Metrologia, 50, 654–662, 2013.

B. Arendacká, A. Täubner, S. Eichstädt, T. Bruns, C. Elster, “Random effects ANOVA in uncertainty evaluation”, Measurement 2013, Proc. of 9th International Conference on Measurement, Smolenice, Slovakia, 2013.

S. Eichstädt, B. Arendacká, A. Link, C. Elster, “Evaluation of measurement uncertainty for time-dependent quantities”, EPJ Web of Conferences, 77 (0003), 2014.

B. Arendacká et al., “Linear mixed models: GUM and beyond”, Measurement Science Review, 14 (2), 52–61, 2014.

C. Matthews et al., “Mathematical modelling to support traceable dynamic calibration of pressure sensors”, Metrologia, 51, 326–338, 2014.

S. Eichstädt, “Parameter identification and measurement uncertainty for dynamic measurement systems”, PTB Mitteilungen, 125 (2), 18–23, 2015.

Impact

C. Bartoli et al.: “Traceable dynamic measurement of mechanical quantities: a new European collaborative project”, Proc. of 15th International Congress of Metrology, Paris, France, 2011.

C. Bartoli et al.: “Traceable dynamic measurement of mechanical quantities: objectives and first results of this European project”, Proc. of XX IMEKO World Congress, Busan, Republic of Korea, 2012.

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M. Kobusch et al., “Proyecto de investigación europeo para la medición dinámica de magnitudes mecánicas”, Memorias del Simposio de Metrología 2014, Querétaro, México, 2014.

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