

TRACEABLE DYNAMIC MEASUREMENT OF MECHANICAL QUANTITIES: OBJECTIVES AND FIRST RESULTS OF THIS EUROPEAN PROJECT

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Abstract: Nine European National Metrology Institutes (NMIs) are collaborating in a new project funded by the European Metrology Research Programme (EMRP) to establish traceable dynamic measurement of the mechanical quantities force, pressure, and torque.

The aim of this joint research project (JRP) is to develop appropriate calibration methods, mathematical models, and uncertainty evaluation. The duration of the project is 3 years for a global amount of €3.6 million. It began in September 2011.

Keywords: dynamic force, dynamic torque, dynamic pressure, traceability, measurement uncertainty

INTRODUCTION

In aerospace, medicine, production, transport and process control, dynamic measurements are generally performed under dynamic conditions, whereas sensors and measuring amplifiers are typically calibrated under static conditions. High-speed data acquisition and modelling are necessary to develop advanced dynamic measurement methods. With important applications in the automotive industry, engineering, petrochemical and pharmaceutical industries, but also for the study of properties of materials, the development of new technologies and standards is required.

The project directly addresses the current lack of traceability for the measurement of dynamic mechanical quantities, including traceability of the response of transducers and of signal acquisition and conditioning instrumentation to dynamic stimuli. Achieving traceability also requires new developments in modelling and uncertainty analysis and propagation. The next generation of metrology systems will rely on further advances in mathematics and information technology, and on the development of reliable mathematical models, enhanced capabilities for data analysis, and trustworthy software [1].

The project is split into five technical work packages that address the following topics:

- Dynamic Force (WP 1)

- Dynamic Pressure (WP 2)
- Dynamic Torque (WP 3)
- Characterisation of Measuring Amplifiers (WP 4)
- Mathematical and Statistical Methods and Models (WP 5)

The coordination and the interaction between the different work packages is described in Figure 1.

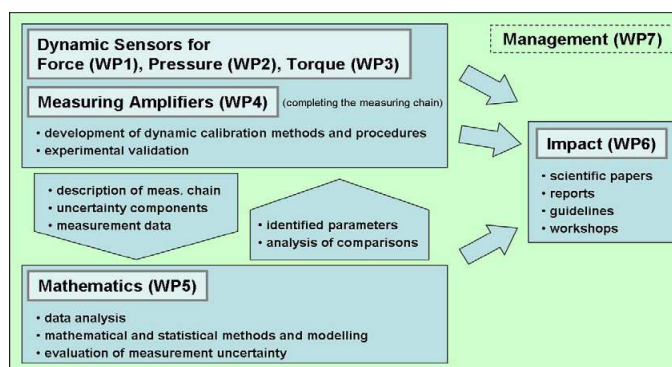


Figure 1. Coordination and interaction between work packages

The subsequent sections of this paper describe the aims and recent achievements of each technical work package.

WP 1 : DYNAMIC FORCE

This work package aims to provide methods and standards for the measurement of sinusoidal and shock forces. Primary sine force facilities will cover the frequency domain from DC to 2 kHz with amplitudes up to 10 kN. For shock domain calibration, amplitudes up to 250 kN will be possible.

Sinusoidal force calibration facilities

Participants are CEM (Spain), LNE (France) and PTB, who is the pilot.

A set of force transducers to be used in the scope of this project was defined and is presented in Table 1.

	Transducer-1	Transducer-2	Transducer-3
Type	Kistler 9175B	HBM U9B	Interface 1610
Range	8 kN/±4 kN	±1kN/±1 kN	±2 kN/±2 kN
Frequency	10 Hz-1.5 kHz	10 Hz-1.5 kHz	10 Hz-1.5 kHz
Amplifier	Charge Amplifier	Bridge Amplifier	Bridge Amplifier

Table 1. List of chosen force transducers

Principle of measurement

The three participants have developed their own facilities, which all work according to the principle described below.

Each shaker system consists of an electrodynamic exciter and an appropriate power amplifier. A function generator supplies the desired excitation signal. This signal directly modulates the current that drives the coil of the shaker armature. The acceleration of the top mass connected to the force transducer under test defines the traceability of the acting dynamic force. This acceleration is measured by means of a Polytec laser vibrometer or by a reference accelerometer. The principal measurement set-up for sinusoidal force excitation is shown in Figure 2. Detailed information about the measuring principle and the evaluation methods for sinusoidal force calibration is found in [2, 3].

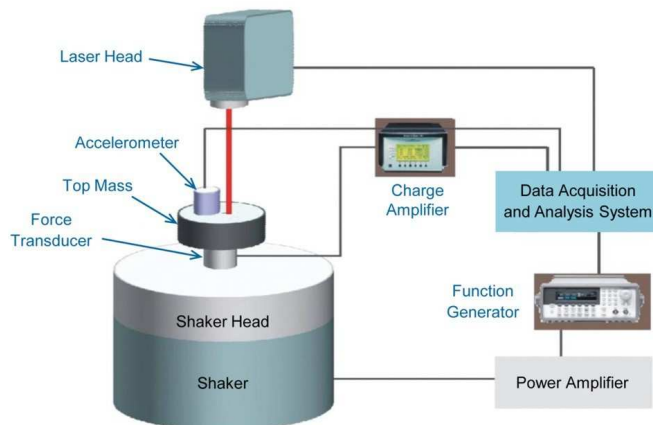


Figure 2. Schematic of the measurement set-up

CEM and LNE facilities

The CEM facilities for dynamic force measurement include the followings parts and are shown Figure 3:

- Shaker LDS 726 with amplifier PA 2000
- Laser vibrometer Polytec CLV 2534
- Oscilloscope Agilent Infinium DSO8064A
- Force transducer Kistler Type 9175 B
- Single ended accelerometer B&K 8305
- Two signal conditioners B&K 2525, to be used with force sensor and accelerometer

The LNE facilities include the followings parts:

- Shaker LDS 721 with amplifier PA 2000
- Data Physics Mobilizer acquisition and generator system
- Force transducer Kistler Type 9175 B

- Single ended accelerometer B&K 8305
- Two signal conditioners B&K 2525 and 2626, to be used with force sensor and accelerometer

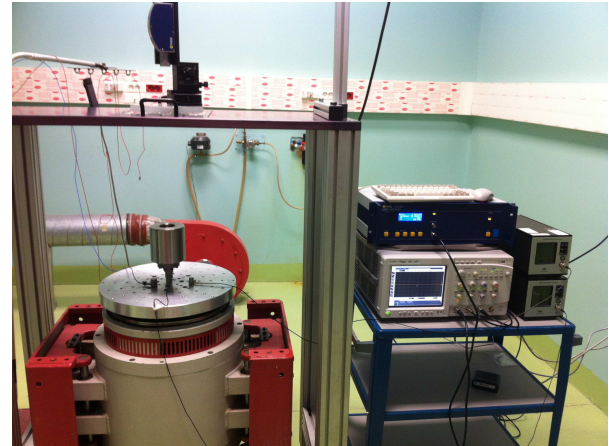


Figure 3. Photo of the CEM installation

PTB facilities

At PTB three electrodynamic shaker systems are available for the sinusoidal dynamic force calibrations to be made within this JRP. Their specifications are as follows:

- B&K-Shaker, force amplitude up to 100 N, frequency range 10 Hz to 2 kHz
- R&S-Shaker, up to 800 N, 10 Hz to 3 kHz, mounted in a rigid frame
- LDS-Shaker, up to 10 kN, 10 Hz to 2 kHz (c.f. Figure 4)

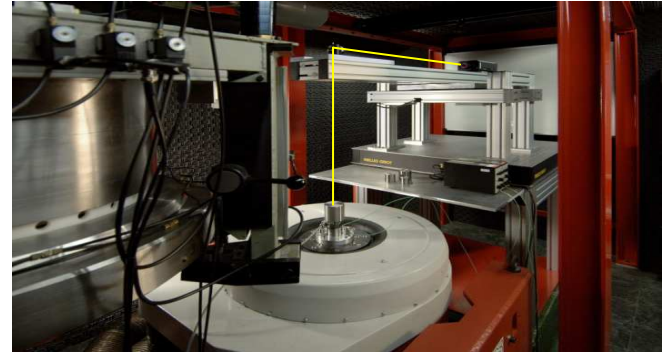


Figure 4. Photo of the PTB installation

In the first month of the project, the infrastructure has been improved and experimental investigations with single-point and scanning laser vibrometers by Polytec were carried out at PTB.

The acceleration of the top mass is measured by a laser method. Two different vibrometers are now available:

- a single-point vibrometer with a fixed measuring beam
- a scanning vibrometer that scans the target surface.

The scanning vibrometer is able to scan the acceleration distribution of the surface within an angle range of $\pm 25^\circ$ in x/y direction (z direction is defined as the vibration axis). Its laser head features an integrated digital camera system as well as a 3D unit to determine the spatial coordinates of the measuring points. The alignment of the camera system and the laser beam is realized by a special optical unit, the so-called coaxial unit.

The modular vibrometer controller is equipped with different digital processing units, two velocity decoders, a displacement decoder and a digital quadrature decoder. The controller provides a frequency range from 0 Hz to 2.5 MHz with a maximum velocity of 10 m/s.

The digital quadrature encoder is used with the software VibSoft from Polytec that calculates the displacements according to the arc tangent procedure. The analogue I/Q output signals, the transducer output signal and the acceleration signal from the shaker armature measured by another accelerometer fixed on the shaker table are bundled in a junction box feeding a PC with 5 MHz sampling card from National Instruments.

Resonance of a piezoelectric force transducer

The resonance behaviour of a piezoelectric force transducer 9175B from Kistler with connected top mass was investigated on the LDS shaker system applying the above-described laser vibrometers.

Three measurement signals were acquired: the acceleration of the top mass, the force signal, and the acceleration of the shaker table. The shaker was excited with a periodic-chirp signal. The FFT analysis of the time data yields the frequency response of the acceleration ratio between top mass and shaker table. The two plots shown in Figure 5 present the amplitude and phase response of the acceleration ratio of top mass and shaker table as a function of the excitation frequency.

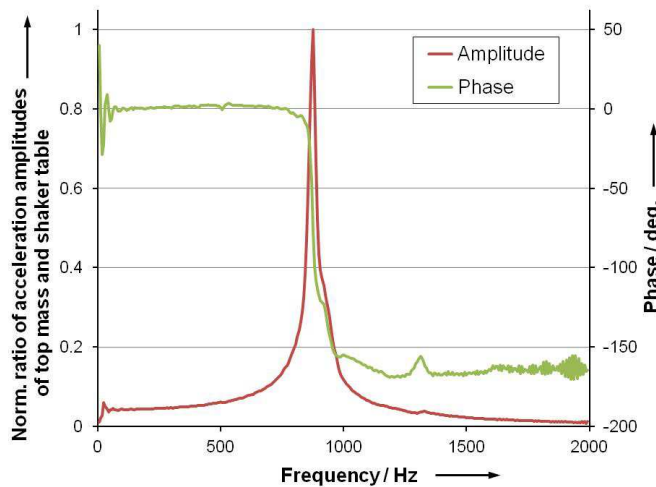


Figure 5. Measured resonance behaviour of a piezoelectric force transducer with a top mass of 6 kg

By model-based fitting of the measured frequency response it is possible to identify the dynamic parameters (i.e., stiffness, damping) of the force transducer.

Shock force calibration facilities

Force calibrations with pulse-shaped forces will be performed on two devices specified for 20 kN and 250 kN shock force amplitude at PTB [4, 5, 6]. Both devices use two colliding impact mass bodies guided by air bearings. Measurements of the inertial forces during the moment of

impact by laser vibrometers provide traceability of the dynamic force.

Within the scope of this EMRP project, the 20 kN shock force calibration device was modified to improve the signal quality of the vibrometer measurement by applying an on-axis measurement geometry, a geometry which was already used for the larger 250 kN device. For this purpose, some mechanical modifications of the acceleration mechanism and the shock damper were made to match with a new mounting arrangement of the vibrometers mounted on active vibration isolation tables.

For the development of methods for validated primary shock force calibration, a model-based analysis of the dynamic behaviour of the 250 kN shock force calibration device was carried out to understand the modal oscillations that could be observed for heavy force transducers under test [7]. Figure 6 sketches the analysed geometrical impact configuration consisting of the two cylindrical impact mass bodies (about 100 kg each) and the adapted force transducer under test (about 25 kg).

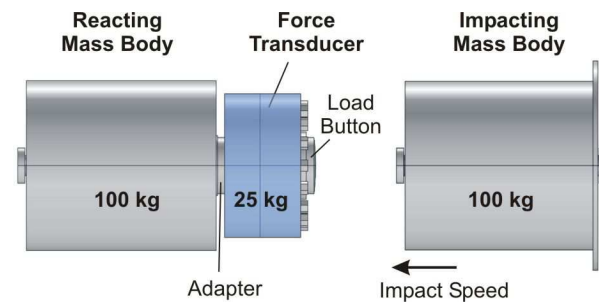


Figure 6. Drawing of the impact configuration of the 250 kN shock force calibration device with a heavy force transducer

A typical measurement result of a hard metallic impact shock is shown in Figure 7. The diagram displays the signals of the force transducer (black line) and the two inertial forces (red lines) calculated from the accelerations measured by the vibrometers at both opposing on-axis positions. With a pulse width of about 1.1 ms, the shock excited several modal oscillations which were identified by the application of auxiliary acceleration sensors and by means of a finite element analysis of the mechanical impact configuration.

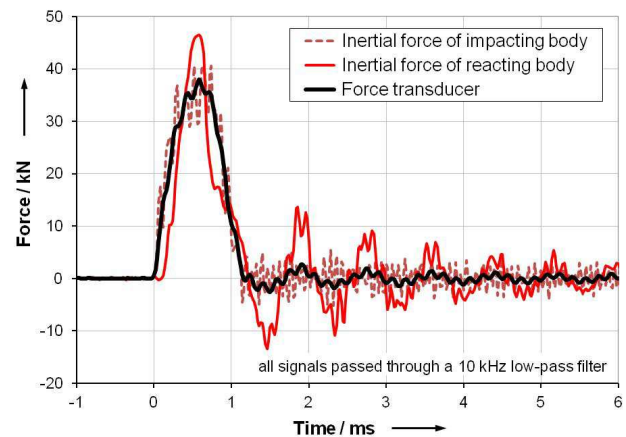


Figure 7. Shock force measurement with a heavy force transducer showing modal oscillations

WP 2 : DYNAMIC PRESSURE

This work package is concerned with development of primary dynamic pressure standards and secondary systems to calibrate industrial transducers.

The work package participants are SP (Sweden), MIKES (Finland) and PTB under the leadership of NPL.

Drop weight machines

The dynamic pressure facilities of MIKES and PTB operate according to the “drop weight” principle. At PTB, a rigid mass ball of about 3 kg is dropped on a piston of a cross sectional diameter of approximately 8 mm [8]. At MIKES, the principle is the same, but the cylindrical mass body is about 14 kg and the piston diameter is of the order of a few centimeters.

The following figures show the design of the two machines at MIKES (c.f. Fig. 8) and PTB (c.f. Fig. 9).

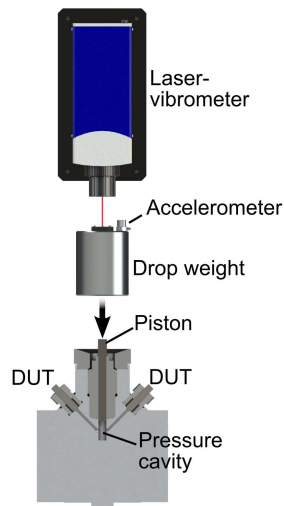


Figure 8. Design of the MIKES pressure machine

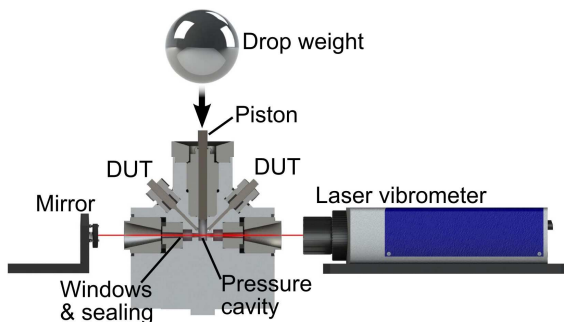


Figure 9. Design of the PTB pressure machine

The impact on the piston leads to the compression of a small volume of a hydraulic liquid within a pressure cavity that is connected to the device(s) under test (DUT), thus applying a shock pressure excitation to the DUT.

Commonly these devices are used for the comparison of DUT(s) with a reference transducer in a secondary calibration scheme. However, within the JRP, the laboratories follow two different approaches to obtain a direct pressure measurement without a reference sensor.

Figure 10 presents a dynamic pressure measurement (unfiltered data) performed at MIKES showing the deceleration of the drop weight and the corresponding pressure pulse of about 2.5 ms pulse length.

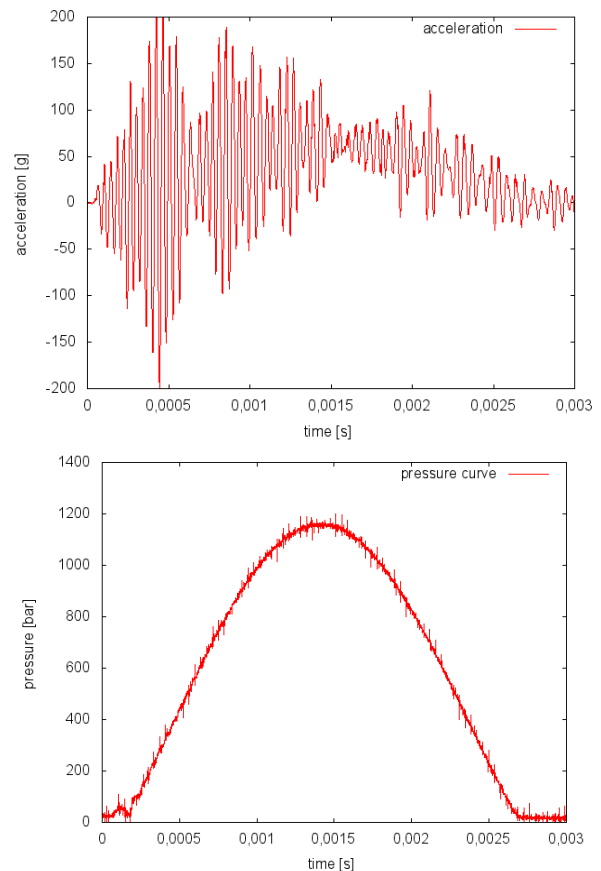


Figure10. Acceleration and pressure curves

The MIKES device is modified to measure the motion of the piston or the deceleration of the drop-weight during impact to deduce the force transmitted by the piston's cross-section into the hydraulic fluid. Thus via force and cross-section or via displacement and compressibility the actual pressure in the cavity can be determined. The first method gives rough estimations of pressure values, while the latter takes into account cavity and fluid effects, thus providing more information, improved traceability, and smaller uncertainties. The exact determination of the cavity volume, and changes in it due to piston movement, is the key requirement.

The PTB device is under modification to allow for an interferometric measurement of the optical path length through the pressure cavity, i.e., the hydraulic medium. This path length changes as the refractive index of the transmission medium varies as the fluid is compressed. In this approach the actual dynamic pressure can be linked to a static calibration of the optical measurement. The goal is to avoid any effects of inertia in the traceability chain between static and dynamic pressure. Preliminary tests of the measurement scheme are currently being performed in parallel to the modification of the drop weight device.

Shock tube

The dynamic pressure facilities of NPL operate according to another principle: the shock tube. They have developed a 1.4 MPa plastic shock tube with interchangeable driven sections of 2 m, 4 m, and 6 m lengths. It includes a pressure transducer located in the centre of the end-wall. It works by means of a pressurization system based on bottled nitrogen, using either single or double diaphragms. Future work will include shock wave velocity measurement (via side-wall mounted sensors) and end-wall acceleration measurement. The photographs in Figures 11 and 12 illustrate the shock tube and a diaphragm after the test.

NPL have begun the design of a 7 MPa steel shock tube and plan to develop a second steel shock tube with a maximum pressure of 20 MPa.

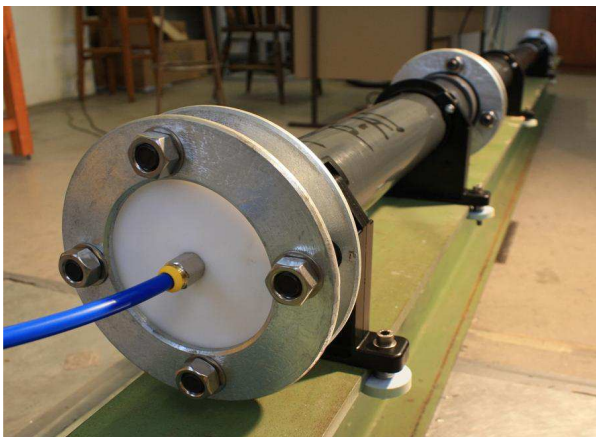


Figure 11: Plastic shock tube of 0.7 m driver section and 2 m driven section.



Figure 12. Burst aluminum diaphragm

A comparison of the different driven sections of the plastic tube, with different burst pressures and diaphragm arrangements, has been carried out. Results indicate that varying the burst pressure has the greatest influence on the characteristics of the end-wall pressure trace.

WP 3 : DYNAMIC TORQUE

This work package is concerned with the development of methods and devices for dynamic torque measurements to provide a validated primary torque calibration for sinusoidal torque.

Three national metrology laboratories are involved in this work package: PTB, who is the work package leader, CMI (Czech Republic) and UME (Turkey). In addition, HBM (www.hbm.com), a leading German manufacturer of force and torque sensors, is taking part in the work as a collaboration partner.

PTB is currently the only participating NMI with research activities in this field of dynamic measurement. At PTB, an existing measurement set-up has been modified and improved to be able to provide dynamic torque calibrations of up to 20 N·m torque amplitude and up to 1 kHz excitation frequency [9, 10, 11].

In the first months of this JRP, a new rotational exciter by Acutronic, Switzerland, was installed and commissioned (see Fig. 13). This exciter is able to achieve the required specifications and is equipped with an integrated rotational acceleration sensor. The rotational exciter is controlled by a state-of-the-art control system for sinusoidal excitation made by DataPhysics, USA.

In addition, the air bearing of the dynamic torque measuring device was replaced by a new air bearing of improved carrying capacity for parasitic radial loads and bending moments, as the performance of the old bearing suffered from wear possibly caused by parasitic loads.



Figure. 13. Dynamic torque measuring device at PTB with the new rotational exciter

The model description of the torque measuring device with the torque transducer under test requires the parameter values of the coupled mechanical environment. To derive these parameters by experiment, two auxiliary measurement set-ups for the determination of torsional stiffness and moment of inertia have been designed and manufactured [11].

For the measurement of the torsional stiffness, in particular of the two couplings, PTB's static 20 N·m torque calibration machine was utilized to provide a defined torsional load. The resulting torsion angles are measured by means of two autocollimators directed at small mirrors attached to the tested structure.

The mass moment of inertia has to be determined for the couplings, the torque transducer under test, and the mechanical components coupled at the top of the dynamic torque measuring device (rotor of the air bearing, radial grating, coupling). For this purpose, a compound pendulum with airborne rotor that carries the device under test was designed and manufactured at PTB. The mechanical swing of the pendulum is measured by means of an optical angle measurement system. The oscillation frequency of the pendulum depends on the acting mass moment of inertia. By adding different auxiliary bodies of known mass moment of inertia, the wanted mass moment of inertia of the device under test can be calculated by extrapolation.

The next activities in WP 3 include the commissioning of the measuring devices for the determination of mass moment of inertia and torsional stiffness as well as the evaluation of the associated measurement uncertainties. Afterwards, the properties of the components of the dynamic torque calibration device will be determined, and the device will be assembled.

WP 4 : MEASURING AMPLIFIERS

The aim of this work package is to establish a traceable dynamic calibration procedure for measuring amplifiers, as part of the electric measurement chain for dynamic measurements of mechanical quantities in the frequency range from DC to 10 kHz.

In dynamic measurements two types of measuring amplifiers are commonly used, which are charge amplifiers for piezoelectric transducers and bridge amplifiers for strain gauge or piezoresistive transducers in Wheatstone bridge configuration.

In the case of charge amplifiers the calibration is less challenging, since the standard charge signal for calibration can be realized with help of a calibrated AC voltage source and a standard capacitor.

For bridge amplifiers the measurement task is more complex, since the measured transducer bridge output voltage U_o is a ratiometric measurand in mV/V and depends on the DC bridge supply voltage U_i , which is provided by the bridge amplifier.

Consequently, the dynamic bridge standards need to work in the same ratiometric operation principle to simulate the strain gauge or piezoresistive transducers. Figure 14 shows the operation approaches of the NPL dynamic bridge standard (Fig. 14(a)) as described in [12] and the PTB dynamic bridge standard (Fig. 14(b)) [13]. Both dynamic bridge standards (DBS) generate the dynamic bridge output voltage with the help of digital-to-analogue converters (DAC). In case of the NPL DBS in Fig. 14(a) the AC and DC components of the bridge output voltage are each generated by a separate DAC (V_1 and V_2) that uses the

bridge supply voltage V_i as DAC reference voltage and adds up the signals with help of the attenuator resistors (R_5 to R_8).

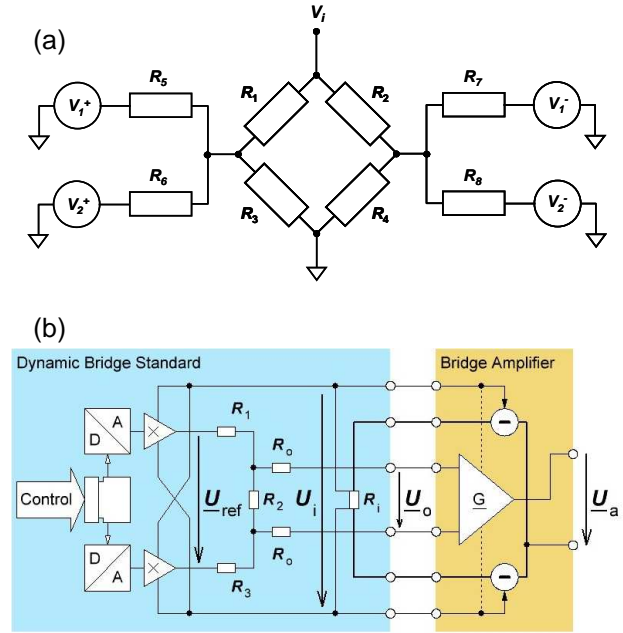


Figure 14. Schematic of the strain gauge simulation in the NPL dynamic bridge standard (a) and operation principle of the PTB dynamic bridge standard (b)

The PTB DBS in Fig. 14(b) uses multiplying DACs (MDACs) to generate a static or dynamic signal (U_{ref}), which is supplied to a resistive 1/200 voltage divider (resistors R_1 to R_3) with known amplitude and phase behaviour to generate the bridge standard output signal U_o .

To match DBS impedances to the typical impedances of strain gauge transducers, the NPL DBS uses the bridge resistors (R_1 to R_4) themselves and the PTB DBS uses the input resistor (R_i) and the two output resistors (R_o).

In the past month the NPL DBS prototype and PTB DBS prototype were modified and therefore extended in order to provide a sinusoidal reference signal, which is in-phase with the signal that simulates the strain gauge bridge voltage.

A preliminary frequency-dependent amplitude and phase characterization of a commercial bridge amplifier was carried out with help of the PTB DBS and is shown in Fig. 15. The phase information was determined with the help of the MDAC signals, which are used as reference voltage U_{ref} , and the bridge amplifier output voltage amplitude U_a . The measurements were carried out with a single synchronized sampling voltmeter, which is alternately sampling U_{ref} and U_a with the help of a low resistive signal switch [14]. The results for amplitude and phase show characteristics similar to a low-pass filter with decreasing values beyond measurement frequencies of 1 kHz.

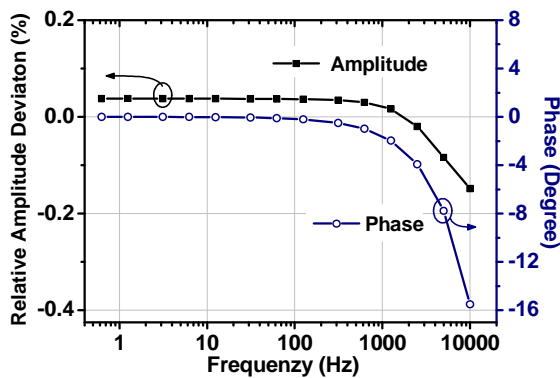


Figure 15. Example measurement with the PTB dynamic bridge standard of the frequency dependent relative amplitude deviation and the phase of a typical strain gauge bridge amplifier in the 2 mV/V measurement range

The next step in the project will be the traceable calibration of the DBS developed at NPL and PTB with respect to amplitude and phase.

WP5: MATHEMATICAL AND STATISTICAL METHODS AND MODELLING

The approach to modelling the new primary standard methodologies that are being developed during the course of the JRP is summarised below.

Approach and underlying assumptions

Our fundamental assumption is that all measurement systems that will be considered during the course of this JRP can be regarded as linear and time-invariant. This allows us 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.

Thus we expect that the measuring systems under consideration will be modelled by sets of linear ordinary differential equations, or by equivalent rational functions in the Laplace domain. We also expect that analysis will be performed mainly in the frequency domain.

To allow meaningful interpretation of calibration results, we intend as far as possible to develop parametric “white box” system models that take into account the known physical and engineering characteristics of the measuring system being developed during the course of the JRP, and to ensure traceability the methods set out in the *Guide to the expression of uncertainty measurement* [15] and its supplements will be applied. Any new methods that we develop will be in accordance with the underlying philosophy of the GUM and we intend that they can be viewed as implementing and extending the GUM methodology. Bayesian methods will be employed so as to allow prior knowledge obtained either from experiments or from experts to be incorporated into the uncertainty evaluation process.

Relevant prior work by the WP 5 team

The methods being developed rely on important prior work by members of the WP5 team, specifically:

- prior work on analysis of dynamic measurements by PTB [16, 17, 18, 19] and in particular their work on the implementation of uncertainty evaluation methods based on the *Guide to the expression of uncertainty in measurement*;
- prior work on dynamic calibration of accelerometers and force transducers by PTB, including analysis of sinusoidal and shock excitation measurements and analysis of comparison measurements between different laboratories [20, 21, 22, 23, 24, 25];
- joint work by mathematicians at PTB and NPL to study dynamic pressure measurements carried out by NPL experimentalists using a shock tube that is located at the UK's Cranfield University [26];
- joint work by PTB, NPL and the SP Technical Research Institute of Sweden on deconvolution methods for the analysis of dynamic measurements [27];
- joint work by PTB and NPL on the implementation of a GUM Monte Carlo method for dynamic measurements [28].

Example modelling for the measurand dynamic torque

In this section, the general approach of a model-based analysis is exemplarily presented for the measurement of dynamic torque. The model will describe the dynamic behaviour of the dynamic measuring device at PTB, which was introduced in the previous section of WP 3.

Figure 16 shows a schematic picture of this device with the main components rotational exciter, couplings, torque transducer under test, and interferometric measurement of angular acceleration.

The signal of the torque transducer will undergo conditioning before being captured by the data acquisition system. Both the signal conditioning system and the data acquisition system must be taken into account during data analysis. Information about the amplifier will take the form of calibrated frequency response values at the relevant frequencies. In addition to the torque transducer output, angular acceleration at the top of the calibration device will be measured using a traceable calibrated rotational vibrometer. After multiplication by an appropriate mass moment of inertia, this angular acceleration gives rise to a reference torque signal. Angular acceleration at the bottom of the device will be measured using a traceable calibrated sensor built in the exciter for this purpose. Data will be provided in the frequency domain, i.e., values of the frequency response functions (linking the output of the transducer with acceleration as input) will be available in a straightforward manner.

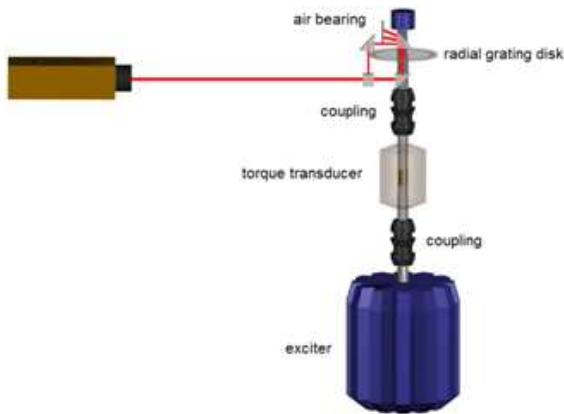


Figure 16. Schematic representation of a dynamic torque calibration device [10]

This calibration device will be modelled as a series of three torsional spring-damper systems (one for each coupling and one for the transducer), see figure 17 [11]. The aim of the measurement scheme is to identify the parameters of the model for the transducer, namely the torsional stiffness, damping, mass moments of inertia at the head and base of the transducer, and a proportionality parameter. The spring-damper system is described by an appropriate set of differential equations that can be employed in the evaluation of the model parameters of interest. The spring-damper system is then described by an appropriate set of differential equations that can be employed in the evaluation of the model parameters of interest.

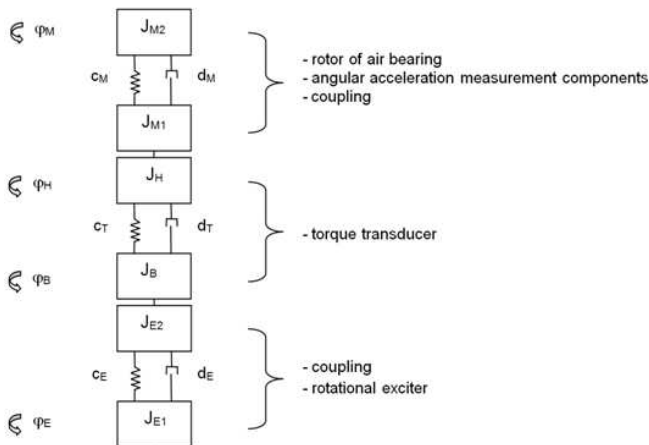


Figure 17. Model of the dynamic calibration device for torque transducers [11]

CONCLUSION

With the funding of the joint research Project IND09, the European Metrology Research Programme and the European Commission provide a unique opportunity for a group of European NMIs to develop a new field of metrology. The aim of the JRP is the development of a basic infrastructure in terms of devices and methods to provide traceability for dynamic measurements of the mechanical quantities force, torque, and pressure.

Facilities are being developed for the three mechanical quantities and for the measuring amplifiers. Data will be soon available as input to the mathematics work package.

The immediate next steps for each technical work package are:

- WP 1: to continue the characterization of the facilities for the three participating laboratories including the determination of the uncertainties components
- WP 2: to continue development of primary dynamic pressure generation systems at the four participating NMIs and then to carry out a set of comparisons between them.
- WP 3: to commission the measuring devices for the determination of the mass moment of inertia and torsional stiffness and to evaluate their uncertainties.
- WP 4: to develop a traceable calibration of the dynamic bridge standards (DBS) at both contributing NMIs (PTB and NPL) and to provide the DBS for the dynamic calibration of strain gauge bridge amplifiers
- WP 5: to begin developing modelling and uncertainty analysis software that can be used to support NMI-level primary standard calibrations for the three mechanical quantities of interest.

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