European Research Project for the Dynamic Measurement of Mechanical Quantities

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Abstract

This first article of this issue of PTB-Mitteilungen presents an overview of the research project IND09 *Traceable Dynamic Measurement of Mechanical Quantities*, in which a total of nine national metrology institutes participated to provide traceability to the dynamic measurement of the three mechanical quantities, force, pressure and torque. The work was focused on developing traceable dynamic calibration methods, mathematical modelling, and evaluation of measurement uncertainty, considering both mechanical sensors as well as the complementary electrical amplifiers. This project began in September 2011 and lasted three years, and was supported by the European Metrology Research Programme of the European Union.

1 Introduction

In many industries such as automotive, aerospace, wind power plants, manufacturing, medicine, industrial automation and control, dynamic measurements of mechanical quantities are tasks consistently applied today. Moreover, together with an increased number of dynamic measurement applications, the quality of the measurements is a very important aspect.

Although many measurements of the three magnitudes force, pressure and torque are performed under dynamic conditions, current transducers and amplifiers are calibrated statically. There are still no specific standards or guidelines for the dynamic calibration of these quantities.

It is well known that various mechanical transducers have a specific dynamic behaviour where the sensitivity under dynamic input load deviates from the static value. Also, the various electrical components of the measuring chain may have an additional frequency response that has to be taken into account for accurate and reliable measurements.

To advance the dynamic metrology, nine European national metrology institutes participated in a research project dedicated to traceable dynamic measurement. This project IND09 was entitled *Traceable Dynamic Measurement of Mechanical Quantities* and was funded by the European Metrology Research Programme (EMRP) in the European Union with 46 % of a total volume of nearly 3.6 million euros. The project started in September 2011 and lasted three years.

The project aimed to develop and provide the future basis of traceability for dynamic measurements. To achieve this goal, it was necessary to develop and investigate various dynamic calibration facilities, their mechanical and electrical components, to develop the corresponding mathematical model and to estimate the associated measurement uncertainty.

The investigations were focused on the traceability of the dynamic responses of different transducers, as well as the corresponding electrical instrumentation for conditioning, amplification and data acquisition. With respect to the dynamic calibration, excitations with sinusoidal signals and shocks have been investigated to study wide ranges of amplitude and frequency.

2 Work Packages

The project was structured into seven work packages (WPs), of which four were technical, one was interdisciplinary and two were administrative in nature:

- WP 1: Dynamic force
- WP 2: Dynamic pressure
- WP 3: Dynamic torque
- WP 4: Amplifiers
- WP 5: Mathematics and statistics
- WP 6: Impact
- WP 7: Coordination

The coordination and interaction among the various work packages are illustrated in figure 1.

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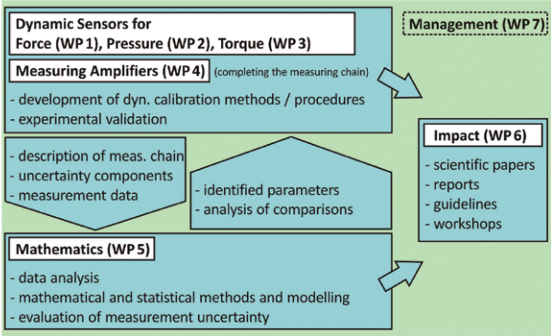

Figure 1:
Interaction between work packages [1].

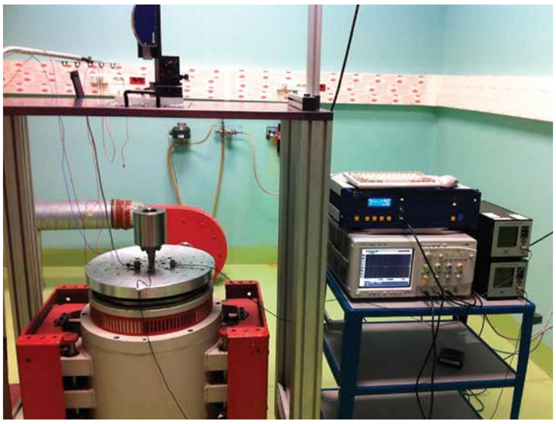

Figure 2:
Calibration device for sinusoidal forces at CEM.

The following sections provide a brief summary of the issues and activities in the work packages, with special emphasis on the dynamic force as an example.

2.1 Dynamic force (WP 1)

This work package focused on measuring the dynamic force using two types of excitation, sinusoidal excitation tests in the institutes PTB (Germany), LNE (France) and CEM (Spain), and with shocks (PTB). WP 1 was coordinated by PTB.

Several transducers of different designs and physical principles were selected for the tests: resistive sensors (based on strain gauges) and piezoelectric sensors, measuring ranges from 1 kN to 30 kN, suitable for tensile and compressive forces.

For the calibration with sinusoidal forces [2, 3], each of the participants used their own device employing an electrodynamic shaker and a load mass mounted on top of the transducer under calibration. As an example, the corresponding device of the Spanish metrology institute CEM is presented in figure 2.

When this mechanical system vibrates, the mass loading generates a dynamic force according to Newton's second law: force is the product of mass and acceleration. The measurement of this inertial force acting on the top of the transducer provides the reference for the dynamic calibration. This measurement is based on the determination of the mass and the acceleration measurement using laser vibrometers or accelerometers. Thus traceability is achieved by a primary method [4].

The result of the sinusoidal calibration is the frequency response of the complex sensitivity (magnitude and phase) defined as the ratio between the output signals of the transducer under calibration and the reference force (proportional to the acceleration).

This mechanical system, into which the sinusoidal excitation is introduced at the base of the force transducer, has a characteristic resonance because of the elastically coupled load mass. The elasticity may be considered as an inherent property of the force transducer, assuming that the two couplings on each side of the transducer, that is, to the loading mass and the vibrating platform, are rigid. This is reasonable as the components are firmly screwed.

As an example, figure 3 shows the measurement of the resonance of the force transducer HBM U9B / 1 kN which is coupled to a load mass of 1 kg. It is noted that the ratio of accelerations of the load mass and the vibrating platform can exceed the value of 400, which means that the damping of this system is considerably small.

This dynamic behaviour can be described by a mass-spring-damper system of one degree of freedom (linear displacement x). Figure 4 illustrates the basic model of a force transducer with a rigidly mounted load mass m. The transducer consists of two point masses (m_H and m_B) connected by an elastic spring (stiffness k) and a viscous damper (constant d). The masses designate the top and bottom part of the force transducer, i.e. the head and base. The transducer output signal is considered to be proportional to the elongation of the measuring spring. The base of the transducer is fixed to the top of the shaker's vibrating armature.

Calibration with shock excitation has been another objective of the theoretical and experimental investigations [5–8]. This method offers the advantage of the easy generation of larger forces and spectral contents at higher frequencies. Of course, the peak force should never exceed the specified working range of the transducer under

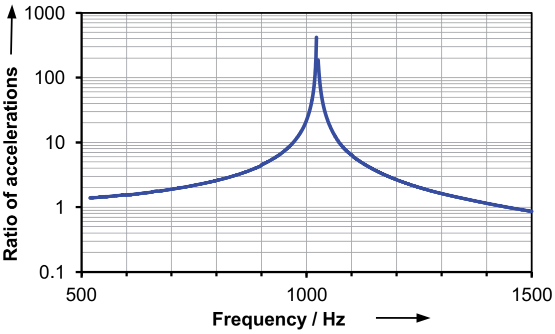

Figure 3:
Mechanical resonance of the transducer HBM U9B / 1 kN loaded with 1 kg.

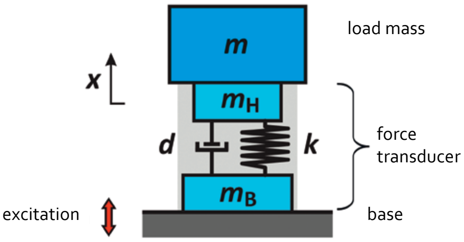

Figure 4:
Model of a force transducer applied in the sinusoidal calibration device.

calibration. Calibration devices for shock forces only exist at PTB, so far. A shock calibration device using two cubic mass bodies of 10 kg is depicted in figure 5. Its working principle is illustrated in figure 6.

The mass body on the right side of the figure is impacting onto the transducer under calibration which is mounted at the mass body on the left. A linear air bearing is used to guide the mass bodies in order to minimize friction. Again, the traceability of the dynamic force is achieved by means of laser vibrometers measuring the acceleration of the two mass bodies in the direction of the common axis of movement.

Figure 5:
Calibration device for shock forces up to 20 kN at PTB.

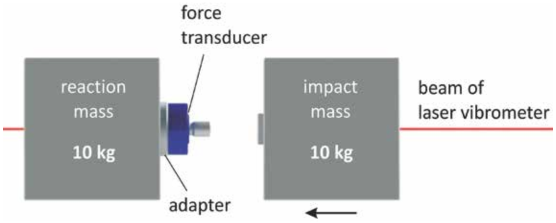

Figure 6:
Schematic drawing of the primary shock force calibration.

Typical examples of shock force signals measured with two resistive transducers of different design are shown in figure 7. The left signal was obtained with a transducer of a total mass (including the adapter) of 1.5 kg. The impact of the mass of 10 kg resulted in a pulse width of 0.7 ms followed by a strong oscillation. The main pulse shows superposed vibrations during the time of the actual contact.

The identification of the force transducer's parameters was performed using an expanded model [6], which also takes into account the potential elastic couplings. The results show that the strong vibration is caused by the inner mass m_H acting on the measuring spring of stiffness k.

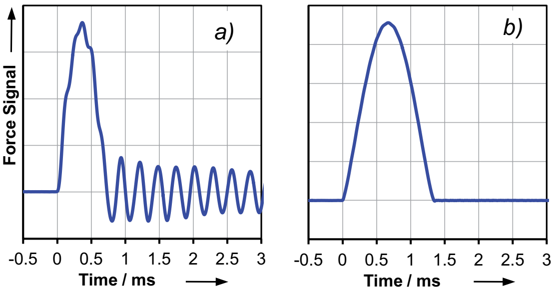

Figure 7:
Measured shock forces:
a) Interface 1610 / 2.2 kN, b) HBM U9B / 1 kN.

In contrast to this response, the second example (figure 7b) obtained with a transducer of only 0.063 kg shows a smooth pulse of 1.3 ms without noticeable superposed vibration. Obviously, the impact obtained with a mass of 10 kg is not able to excite the resonance of the transducer. Theoretical studies show that the parameter identification requires the excitation of resonances to provide the key information for the determination of the system's dynamic behaviour. A method to increase the spectral content at higher frequencies and to excite the transducer's resonance modes is the use of a smaller impact mass which generates shorter pulses. Various experimental tests have shown that a pulse of 0.1 ms is sufficiently short to excite resonances even of the small transducer [7].

To facilitate the transfer of the various dynamic calibration results, the method of the model-based calibration is proposed. The dynamic response of a transducer under calibration is described by a model, and its characteristic parameters are identified using the measured data. With respect to the model above, the transducer is characterized by the four parameters m_H, m_B, k, d. If the elasticity of the coupling to its mechanical environment cannot be neglected, the model will present additional parameters.

In general, models of more complex structures can be derived from the basic model in order to describe the various devices and mechanical couplings. For this purpose, the appropriate secondary conditions such as external excitations have to be applied, e.g. the vibration of the transducer base to generate sine forces, and other mass-spring-damper components might be added to have more degrees of freedom, if necessary.

At the end, the results obtained with different devices and different excitation methods [9] are compared. The dynamic behaviour of a transducer under calibration can be considered understood correctly if the respective models result in consistent parameters even under different measurement conditions (different load masses, accelerations and frequencies, amplitudes and pulse widths, etc.). This knowledge is required to assess the uncertainty associated with the dynamic measurement. Preliminary results show that further research is needed to understand the dynamic behaviour of the various mechanical designs of the force transducers and their coupling to the calibration devices.

2.2 Dynamic pressure (WP 2)

This work package, which was led by NPL, was dedicated to the measurement of dynamic pressure investigating the following two methods:

A. Shock tube:
NPL (UK), SP (Sweden)

B. Drop weight:
PTB, MIKES (Finland), UME (Turkey)

The first method uses a shock tube to generate pressure steps in a tube filled with gas at low pressure. The device consists of a closed system of two tubes which are connected by a thin membrane (figure 8). To generate a step with a short rise time, the pressure is built up in the first section until the membrane breaks, causing a compression wave front which propagates along the second section with hypersonic speeds. The high speed results in a rapid increase in pressure in less than a microsecond. This resulting step is the input signal to the device under calibration which is located at the far end of the low pressure section.

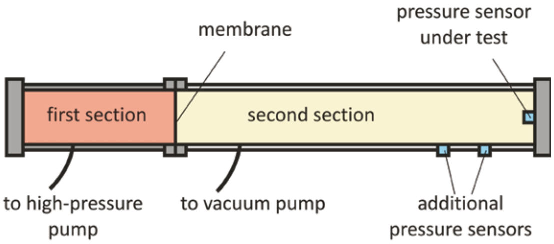

Figure 8:
Schematic drawing of a shock tube.

Figure 9 shows a shock tube made of plastic tubes used for the tests at NPL. The first section (high pressure) measures 0.7 m in length and the second (low pressure) 2 m.

The shock tubes within the project have been investigated in various aspects [10, 11], among them the characterization of the devices, the influence of the material onto which the sensor under calibration 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 second method for the dynamic calibration of pressure transducers uses a drop weight system to generate pressure pulses in the range of a few hundred megapascals and a few milliseconds duration. For this purpose, a mass body is dropped from a given height to impact onto the piston of a high-pressure chamber. The impact force drives the piston into to a small internal cavity filled with a hydraulic fluid and thus generates a pressure pulse. The sensors under calibration are connected to this cavity through thin holes.

Figure 9:
Shock tube at NPL.

The collaborating NMIs pursue different procedures for measurement traceability. While UME uses its device only for secondary calibrations, PTB and MIKES made some progress in establishing traceability with primary methods.

The metrologists at MIKES have investigated the device illustrated in figure 10, where traceability is obtained by measuring the dynamic motion of the piston using an accelerometer or a laser vibrometer.

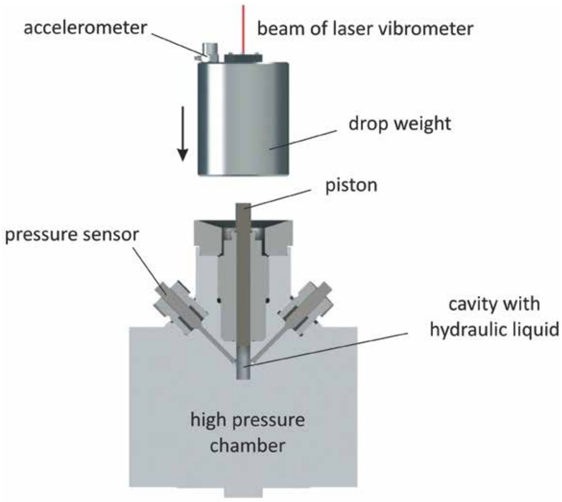

Figure 10:
Schematic drawing of the dynamic pressure calibration device at MIKES.

Figure 11 shows the device that has been developed at PTB [12]. The beam of a laser vibrometer passes through the cavity with the hydraulic fluid and is retro-reflected. The dynamic pressure instantaneously affects the density of the liquid resulting in a change of its refractive index, which means that the laser vibrometer detects a variation of displacement. By means of a static calibration to determine the relationship between pressure and refractive index, this optical method may provide traceability to dynamic pressure using primary methods.

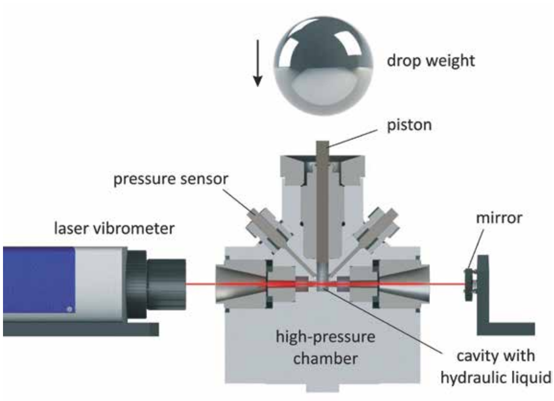

Figure 11:
Schematic drawing of the dynamic pressure calibration device at PTB.

2.3 Dynamic torque (WP 3)

The third work package involved only CMI (Czech Republic) and PTB. The German institute coordinated and performed the majority of the activities.

The work focused on the investigation of methods and procedures for the calibration of torque transducers with sinusoidal torque. The metrologists at PTB developed a device with a rotary vibration exciter to excite torsional oscillations up to 500 Hz and a maximum range of 20 N·m (figure 12).

Figure 12:
Device for dynamic torque calibration at PTB.

Dynamic traceability is achieved with a primary method in the same way as explained above for sinusoidal force applying Newton's second law for rotation, wherein the torque is defined as the product of moment of inertia and angular acceleration.

The torque transducer under calibration is coupled to the rotational exciter (below) and the moment of inertia (above) by means of clamping sleeves. The angular accelerations at both sides were measured by means of a rotational vibrometer and the built-in angular acceleration sensor of the exciter.

Similar to the procedures in dynamic force, the modelling of the rotational device and the torque transducer is performed with a corresponding rotational mass-spring-damper system [13]. To determine the parameters of the various mechanical components which are included in this model, three dedicated devices were developed to measure the moment of inertia, rotational stiffness and damping [14, 15].

2.4 Amplifiers (WP 4)

The institutes PTB (coordination) and NPL were involved in this work package.

In general, it is required to know the dynamic behaviour of the various electrical components of the measuring chain in addition to those of the sole transducer. Assuming a minimum range of 10 kHz which is desired for the dynamic measurement of the considered mechanical magnitudes, the typical instrumentation may have a frequency response that should not be neglected. The activities in this WP have focused on the dynamic characterization of the following components.

A. Bridge amplifiers for resistive sensors like strain gauges.

B. Charge amplifiers for piezoelectric sensors.

For the dynamic calibration of bridge amplifiers, both institutes developed their own dynamic calibration standard that is able to provide an adequate reference input signal.

The operation principle of PTB's dynamic bridge calibration standard is illustrated in the simplified scheme of figure 13. Like a strain gauge transducer, the instrument provides a ratiometric output signal U_0 with respect to the supply voltage U_i of the bridge amplifier. It is capable of generating arbitrary dynamic signals from zero to more than 10 kHz using two MDACs (multiplying digital-to-analogue converter). More detailed information about this device is found in [16, 17].

Figure 14 shows the result of a dynamic calibration of a bridge amplifier showing the frequency response in magnitude and phase.

Further research within the project on the calibration of charge amplifiers has shown that

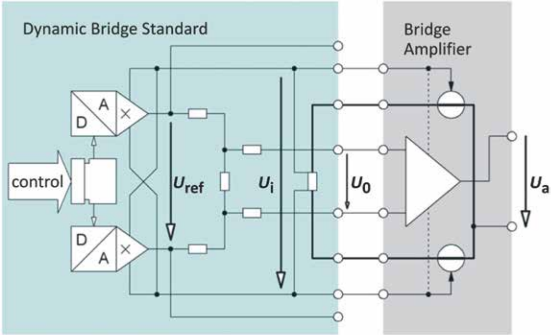

Figure 13:
Schematic diagram of PTB's dynamic bridge standard.

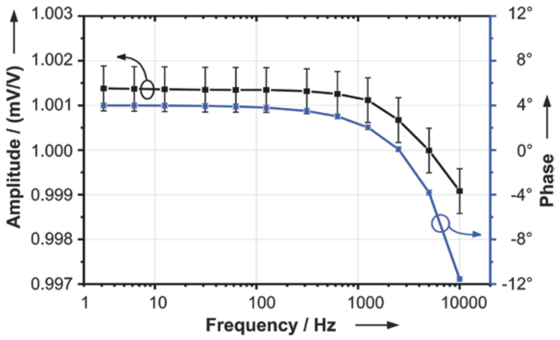

Figure 14:
Frequency response (magnitude and phase) of a bridge amplifier.

significant errors can occur at high frequencies because of the difference of the source impedances of the piezoelectric sensor under calibration and the charge standard [18].

2.5 Mathematics and statistics (WP 5)

Four national institutes participated in this interdisciplinary work package: PTB, NPL, LNE and INRIM (Italy). The work was coordinated by PTB and NPL, depending on the tasks.

Previous work [19–21] on the calibration of accelerometers already paved the way for the proposed dynamic calibration method using a model-based calibration, which is applied to the mechanical parameters of this project.

The math work package supported the four technical packages WP 1–4 in analysing the data, modelling the mechanical systems, identifying and determining the parameters of the dynamic models, and developing methods of measurement uncertainty evaluation. Several studies with emphasis on mathematics have been developed, e.g. [22–25], considering the mathematical description, identification procedures, fitting methods, statistical analysis, filtering or the deconvolution of data [26].

Figures 15 and 16 show two examples of collaboration in the field of shock force calibration. In the context of the identification of the parameters of a force transducer, the first example compares the measured force signal to the calculated responses using three models of different degrees of freedom. The second example displays a spectral analysis of shock-excited vibrations in order to elaborate suitable models.

2.6 Impact (WP 6)

The dissemination of the results produced in a JRP is an important task within the EMRP and, therefore, was dedicated to an extra work package led by LNE.

The work of this joint research project has been presented at metrology conferences, particularly those of IMEKO and the Workshop on Analysis of Dynamic Measurements, and in journals and reports. In addition, participation in committees and working groups, e.g. [27, 28], has already provided progress in developing future standards in the dynamic measurement of mechanical quantities.

The project website [29] and the web repositories of the EMRP and the conferences offer free access to most of the work.

3 Conclusions

With the support of the research programme EMRP of the European Union, the joint project made extensive progress in the field of dynamic measurement of the three quantities force, pressure and torque.

For the first time in this field of metrology, joint international research has been conducted in dynamic measurement. New devices and methods for the dynamic calibration with primary traceability methods have been developed in several national institutes, which are the key requirements for future dynamic calibrations. In addition, first comparisons have been performed in dynamic force and dynamic pressure. To understand the dynamic behaviour, the method of model-based calibration is proposed in this project.

The work has given great impetus to the European metrology community to continue the chosen way, which finally will result in specific rules and guidelines to disseminate the dynamic procedures to the industrial users.

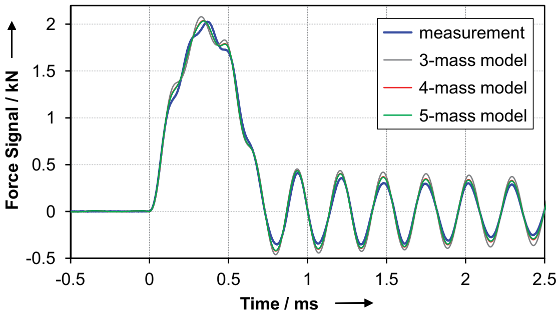

Figure 15:
Comparison of measured and modelled shock force responses.

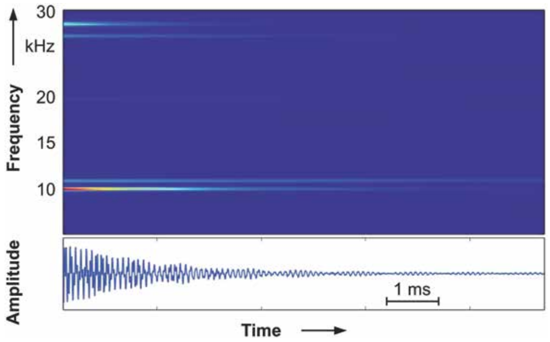

Figure 16:
Spectrogram of excited vibrations in shock force calibration.

Acknowledgements

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