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DYNAMIC CALIBRATION OF FORCE, TORQUE AND PRESSURE SENSORS

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Abstract: Nine European Metrology institutes (NMIs) are collaborating together to develop appropriate methods for the dynamic calibration of force, torque and pressure sensors which are only statically calibrated at present. This work is funded by the European Metrology Research Program (EMRP) within the scope of a dedicated research project which runs over three years. This article describes the current state of progress of the different parts of the project after its second year.

Keywords: dynamic calibration, torque, force, pressure, modelling

1. INTRODUCTION

The EMRP joint research project *Traceable Dynamic Measurement of Mechanical Quantities* directly addresses the current lack of traceability for dynamic measurements of the mechanical quantities torque, force and pressure. This research includes the traceability of the dynamic response of the transducers, and in complement, of the signal acquisition and the conditioning instrumentation. To achieve this goal, new developments in modelling and uncertainty analysis and propagation are required. Future dynamic metrology systems will rely on further advances in mathematics and information technology, on the development of reliable mathematical models, of enhanced capabilities for data analysis, and of trustworthy software.

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

- Dynamic characterization of force transducers (WP 1)
- Dynamic characterization of pressure transducers (WP 2)
- Dynamic characterization of torque transducers (WP 3)
- Characterization of measuring amplifiers (WP 4)
- Mathematical and statistical methods and models (WP 5)

Figure 1 describes the coordination and the interaction between the different work packages of this joint research project (JRP).

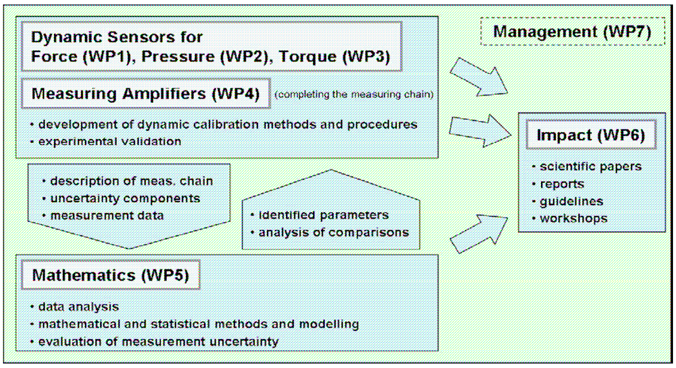

Figure 1. Coordination and interaction between work packages

2. STATE OF PROGRESS OF THE PROJECT

This paper presents the progress of the different technical work packages since the previous article [1] and especially their interaction. As other dedicated articles for each mechanical quantity will be published soon, this contribution focuses on the relationship between the mathematical and the mechanical point of view.

3. WP 1: DYNAMIC SHOCK FORCE

At PTB, a great number of shock force measurements have been performed at the modified 20 kN shock force calibration device (see Fig. 2), which now permits an on-axis interferometric measurement geometry for improved signal quality. In the figure, the laser beams of the interferometers are emphasized for more clarity.

The shock measurements covered three strain gage force transducers of differing mechanical design and different mechanical coupling. Supplementary measurement data that might be beneficial for the parameter identification process was obtained by using an additional load button. The added mass at the top of the transducer substantially reduces its fundamental resonant frequency, which is basically determined by the structural distribution of mass and elasticity.

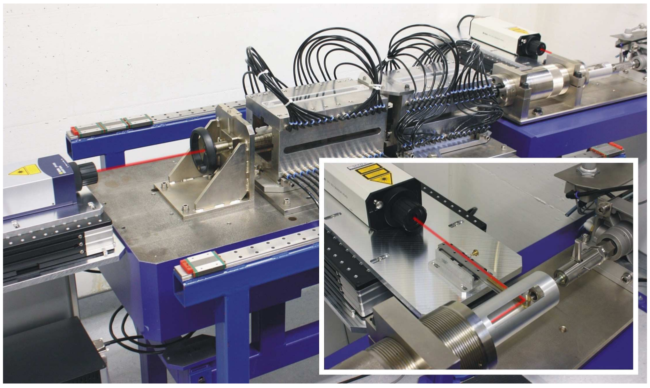

Figure 2. Modified 20 kN shock force calibration device

Figure 3 exemplarily presents shock pulses measured with two transducers of greatly differing size. The photos at left show the cube-shaped 10 kg reaction mass with the mounted force transducer before insertion into the air bearing. The big transducer was excited to strong signal ringing, whereas the small transducer does not show any ringing at all. Former investigations have shown [2, 3] that the achieved pulse shape greatly depends on the mechanical coupling and the mounting conditions of the transducer. The model-based identification of the transducer's parameters from such measurements is the focus of current activities [4].

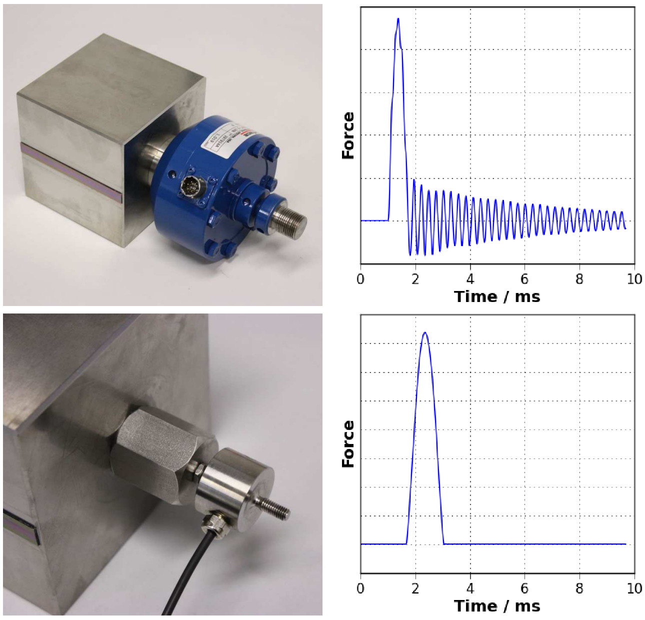

Figure 3. Examples of shock force measurements: mounted force transducers (left), typical shock pulses (right)

4. WP 3: DYNAMIC TORQUE

The primary dynamic torque calibration device at PTB (see Fig. 4) was equipped with a more powerful rotational exciter and a reinforced air bearing [1]. At reassembly, all components were aligned, adjusted and the device was tested. An improved air supply now enables an adjustable air pressure ranging from 0.65 MPa to 1.5 MPa, instead of a fixed level of 0.65 MPa before.

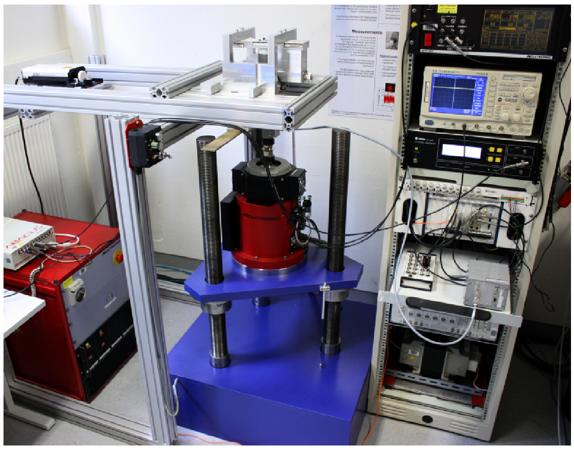

Figure 4. Dynamic torque calibration device equipped with a new exciter and a new air bearing

Three dedicated auxiliary measuring set-ups have been designed to determine the mass moment of inertia, torsional stiffness [5] and rotational damping [6] of the various mechanical components. These set-ups have been commissioned and tested. The mass moment of inertia and the torsional stiffness properties have been measured.

The measuring set-up for the rotational damping generates torsional oscillations by means of a negative step excitation. The free decay of these oscillations is analysed for the determination of the damping. The negative torque step is generated by a specimen which is to break at a certain torque load by brittle failure. The oscillations are measured by means of two rotational vibrometers on top and on bottom of the device under test. First measurements showed promising results (see Fig. 5). Brittle specimens of different materials and dimensions were used. However, the variation and repeatability of the measurement results and the data processing should be improved, if possible.

The measurement uncertainties of all measurands need to be evaluated and will be presented in future.

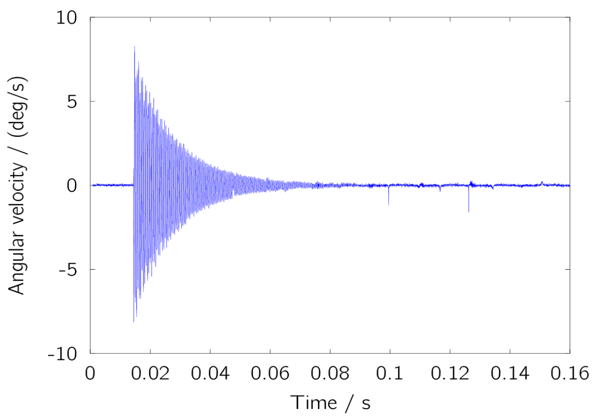

Figure 5. Decay of oscillations after a negative step excitation (raw data acquired by a rotational vibrometer at the top of the DUT)

After reassembly and testing of the improved dynamic torque calibration device, first measurements with a torque transducer under test have been carried out. Software for the data acquisition and the data processing was developed. The raw output of the rotational vibrometer is acquired and demodulated. Furthermore, the analogue output of the angular accelerometer at the bottom of the measuring device and of the device under test is acquired, too.

The measurement data provides the input for a model-based parameter identification of the transducer under test[7], which is currently under development. The derived frequency responses of the different signals will be used for the parameter identification by means of a non-linear least squares approximation. Based on the known model parameters of the measuring device and the acquired data, the unknown parameters of the transducer under test are going to be identified.

5. WP 4: DYNAMIC BRIDGE AMPLIFIER CALIBRATION

For the dynamic calibration of bridge amplifiers, a dynamic bridge standard is required as described in [1].

The operation principle and calibration of the PTB dynamic bridge standard (DynBN) is described in [8] and [9] and is schematically shown in Fig. 6. The strain gauge bridge output voltage is simulated by multiplying digital-to-analogue converters (MDACs) in series with a resistive voltage divider. This allows to generate calibration signals in the range ±2.5 mV/V in steps of 0.002 mV/V. The MDACs pick up the DC bridge supply voltage U_i from the bridge amplifier to generate output voltage (U_o) signals with 16 bit resolution. Consequently, the bridge standard works in a ratiometric operation mode as a strain gauge transducer itself.

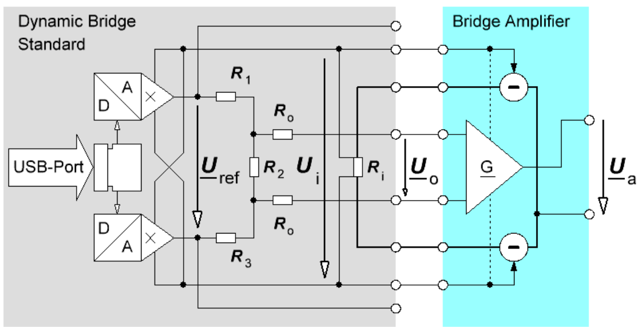

Figure 6. Function principle of the PTB dynamic bridge standard. Connected to a bridge amplifier, the DynBN simulates a dynamic strain gauge transducer output voltage.

The DynBN can either be operated in a static or a dynamic mode with arbitrary periodic signals up to a frequency of 10 kHz. The MDAC signal, which is externally provided as the reference signal U_{ref} (see Fig. 2), 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 in mV/V. The input resistor R_i and the output resistors R_o are used to match the bridge standard impedance to the typical impedances of strain gauge or piezo-resistive transducers in a Wheatstone bridge configuration. The reference voltage $\underline{U}_{ref}$ is used for phase measurements.

The calibration result of the DynBN for a 1 mV/V signal as a function of the signal frequency can be seen in Fig. 7.

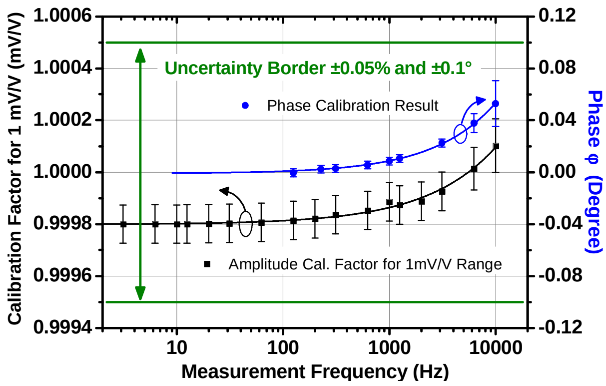

Figure 7. Calibration result of the PTB dynamic bridge standard. For a 1 mV/V bridge signal, the signal amplitude and phase was calibrated as a function of the signal frequency.

It can be seen that the amplitude and the phase show a frequency dependence. However, in the whole frequency range up to 10 kHz all corrections including their uncertainties (k=2) stay within the uncertainty borders of ±0.05% for amplitude and ±0.1° for phase. These uncertainties are in principle sufficient for bridge amplifier calibrations. Consequently, a bridge amplifier calibration using these uncertainty borders could be done without taking into account the detailed corrections shown in Fig. 7.

The calibration of a Dewetron (Bridge B) bridge amplifier was carried out with the PTB dynamic bridge standard and is shown in Fig. 8.

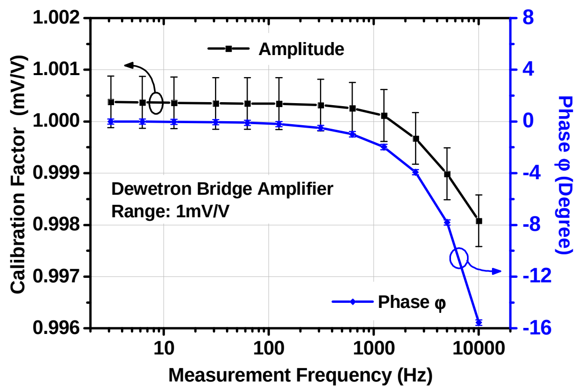

Figure 8. Calibration of a Dewetron (Bridge B) bridge amplifier in the 1 mV/V measurement range. All filters were switched off.

In comparison with the bridge standard characterisation result shown in [1], the corrections from Fig. 8 are used. However, it is sufficient to use the uncertainty borders of ±0.05% for amplitude and ±0.1° for phase in the calibrations. The bridge amplifier calibration results for amplitude and phase show a characteristic similar to a low-pass filter.

Such calibrated bridge amplifiers can now be used for the calibration of strain gauge force and torque as well as of piezo-resistive pressure sensors, since the calibration of the electrical components of the measurement chain is a prerequisite for the dynamic calibration of the transducer.

6. WP 5: MATHEMATICS AND STATISTICS WORK PACKAGE

Our current fundamental assumption is that all measuring systems that are considered during the course of this project 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.

Excitation signals employed for dynamic force calibration will include both stepped-sine/sinusoidal and impulse/shock excitation. At present, only stepped-sine/sinusoidal excitations are being considered for torque and only impulse/shock methods are being considered for dynamic pressure calibration.

The measuring systems under consideration are modelled by sets of linear ordinary differential equations, or by equivalent rational functions in the Laplace domain, and the analysis is performed mainly in the frequency domain.

To ensure traceability, the methods set out in the *Guide to the Expression of Uncertainty in Measurement* (GUM) and its supplements are 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.

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. Bayesian methods are employed so as to allow prior knowledge obtained either from experiments or from experts to be incorporated into the uncertainty evaluation process.

An example of the output produced by this work package is shown in Fig. 9, in which simulation software has been used to predict the frequency responses of a shock tube method and a drop weight method of generating a broadband dynamic pressure signal.

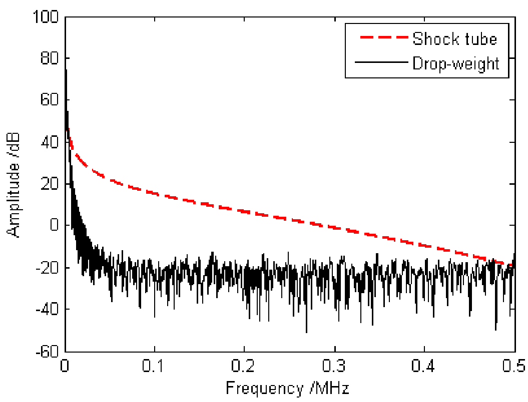

Figure 9. Comparison of simulated frequency responses for the generation of broad band dynamic pressure signals

7. CONCLUSIONS

Thanks to the funding of this European Metrology Research Programme, the European metrology community has the opportunity to extend dynamic measurements to the force, torque and pressure domains. 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 these three mechanical quantities.

Now, measurement data is available for all quantities thanks to the set-ups developed in the frame of this project or earlier and is ready to be analyzed by the statistical and mathematical methods. Modelling is now performed for all set-ups and the evaluation of the transducer's parameters including their uncertainties is under progress.

ACKNOWLEDGEMENT

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