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SET-UP FOR THE DYNAMIC CALIBRATION OF BRIDGE AMPLIFIERS FROM DC UP TO 10 kHz

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ABSTRACT
Measurements of mechanical quantities are often carried out with transducers having a bridge output. These output signals are conditioned using bridge amplifiers. If dynamically changing quantities are going to be measured traceably, the bridge amplifier has to be calibrated dynamically.
This paper describes a dynamic bridge amplifier calibration set-up based on the new PTB dynamic bridge standard. The calibration is carried out by synchronous sampling of the bridge amplifier output voltage and a reference signal provided by the calibrated dynamic bridge standard. The dynamic bridge standard enables calibrations in a frequency range from DC (static calibration) up to 10 kHz. An overview of the different measurement uncertainty contributions is given and the first measurement results show a good agreement with a previously established measurement set-up..

Section: RESEARCH PAPER

Keywords: Dynamic bridge amplifier calibration, traceability, dynamic measurement, dynamic bridge standard

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1. INTRODUCTION

Mechanical quantities such as acceleration, force, torque or pressure are often measured with transducers based on strain measurement by means of strain gauges or sensor elements based on the piezoresistive effect. These sensing elements change their resistance proportionally to the strain (strain gauge) or the compression/tension (piezoresistive element). However, both transducer principles require signal conditioning by bridge amplifiers.

In many applications these mechanical quantities change rapidly over time, thus requiring a dynamic calibration in order to be traceable. Up to now, bridge amplifiers – as well as the corresponding transducers – have almost exclusively been calibrated statically.

To overcome this problem, a joint European project [1, 2] carried out research on procedures, measuring devices, and the mathematical tools to establish dynamic calibrations. For signal conditioning electronics – which includes all kind of measuring amplifiers – it is known that deviations between static and dynamic behaviour exist [3]. These deviations may influence dynamic measurements significantly. Therefore, one outcome of this project was a newly developed dynamic bridge standard [4] which enables bridge amplifier calibrations from a static regime (DC) up to frequencies of 10 kHz, which was incorporated in the calibration set-up described here.

This paper is a revised and extended version of a contribution at the IMEKO 23rd TC3, 13th TC5 and 4th TC22 International Conference in Helsinki, Finland, 2017 [5].

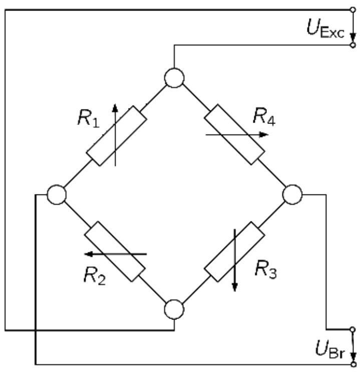

Figure 1: Wheatstone bridge circuit with four resistive sensing elements $R_1 \dots R_4$, excitation voltage U_{Exc} and bridge output voltage U_{Br}.

2. DYNAMIC BRIDGE STANDARD

Bridge amplifiers are always connected to some kind of Wheatstone bridge circuit, as depicted in Fig. 1. The resistive sensing elements (e.g. strain gauges or piezoresistive sensor elements) are connected as a quarter bridge (one sensing element of variable resistance), half bridge (two sensing elements) or full bridge (four sensing elements) in order to maximise the output signal of the bridge. What all configurations of a Wheatstone bridge have in common is that the output voltage level U_{Br} depends on the bridge excitation voltage U_{Exc} (in this case a DC voltage) featuring a ratiometric output, which is typically given in $\mathrm{mV/V}$. The excitation voltage is supplied by the bridge amplifier. The output of the bridge amplifier is therefore proportional to the ratio of bridge output voltage and the excitation voltage.

As a result of this, the bridge output voltage U_{Br} has no connection to ground. In the bridge amplifier calibration, this bridge voltage U_{Br} must be ratiometrically provided by the dynamic bridge standard based on the excitation voltage, which is done in the form of a calibrated voltage ratio and phase.

The dynamic bridge standard working principle is based on two multiplying digital-to-analogue converters (MDACs) which generate output voltages proportional to their reference voltage without dependency to ground. This reference voltage is chosen to be the bridge excitation voltage $\pm U_{\mathrm{Exc}}$. A schematic diagram of the dynamic bridge standard components can be seen in Fig. 2. Subsequent to the MDACs outputs, a resistive $1/400$ voltage divider supplies the small output voltages as required for the bridge amplifier calibration. The load of a strain gauge transducer is simulated by a load resistance of 350 Ω. The output voltage of the two MDACs is used as reference for the phase calibration. For this purpose, it is conditioned by buffer amplifiers to avoid any influence on the MDAC output and is fed to connectors placed on the front panel.

The waveforms to be generated by the MDACs, which can be either static or time-dependent (arbitrary or sinusoidal), are programmed by using an optical computer link.

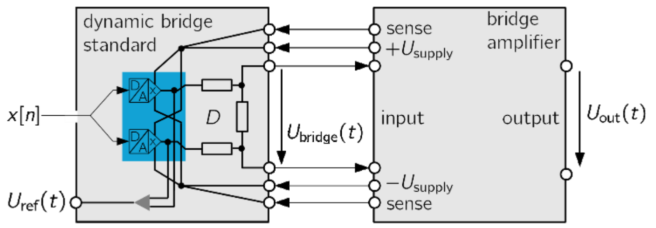

Figure 2: Schematic overview of the dynamic bridge standard.

3. IMPLEMENTATION OF A CALIBRATION SET-UP

For the calibration of a bridge amplifier, not only a bridge standard is required, but also additional data acquisition hardware, a proper data analysis, and a measurement uncertainty evaluation are necessary, too.

The calibration set-up incorporates the dynamic bridge standard described and a data acquisition system featuring two synchronised sampled data channels. The connection of the different components – including the device under test (DUT) – is depicted in Fig. 3.

The dynamic behaviour of an amplifier can be described by its frequency dependent complex transfer function $\underline{H}\,(\mathrm{i}\omega)$, with its input $\underline{X}(\mathrm{i}\omega)$ and its output $\underline{Y}(\mathrm{i}\omega)$ giving

$$\underline{H}(\mathrm{i}\omega) = \frac{\underline{Y}(\mathrm{i}\omega)}{\underline{X}(\mathrm{i}\omega)}\,. \qquad (1)$$

More commonly it is given as a magnitude response $A(\omega)$ and phase response $\varphi(\omega)$ giving

$$A(\omega) = \frac{A_Y(\omega)}{A_X(\omega)}\,, \qquad (2)$$

$$\varphi(\omega) = \varphi_Y(\omega) - \varphi_X(\omega)\,, \qquad (3)$$

with the magnitudes A_X, A_Y and phase angles φ_X, φ_Y of input and output. Based on the magnitude and phase responses, the associated complex transfer function can be derived and vice versa [3].

In the case of the calibration of a bridge amplifier, the amplifier's magnitude excitation at the input A_X is well known, because the dynamic bridge standard is calibrated. For the determination of the magnitude response, only the output of the amplifier A_Y has to be analysed. This could be done with a calibrated sampling system or even a calibrated AC voltmeter. The phase response determination requires the phase measurement between the output of the bridge amplifier $\varphi_{\mathrm{Y}}(\omega)$ and the dynamic bridge standard's reference signal, since this signal has a calibrated phase relation to the input of the bridge amplifier $\varphi_{\mathrm{X}}(\omega)$.

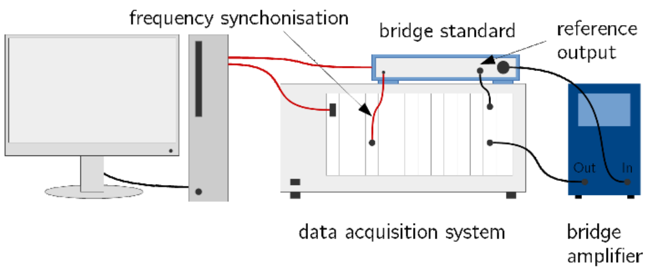

Figure 3: Components of the dynamic bridge amplifier calibration set-up.

4. DATA ACQUISITION

In our set-up – depicted in Fig. 4 – we simultaneously sample the bridge amplifier output and the dynamic bridge standard reference signal by means of two synchronous sampling data acquisition channels. The hardware used for the data acquisition is a PXIe system with a high-resolution digitiser card from National Instruments (PXI-5922[1]) which has a flexible resolution of 18 bits to 24 bits. With sampling rates applicable for the calibration of bridge amplifiers ($f_s \ll$500 kHz), the resolution is 24 bits. The PXI-5922 digitiser card was thoroughly analysed in terms of its dynamic properties, precision, and metrological suitability [6, 7]. Additionally, automated calibration procedures exist for this acquisition card at PTB (cf. section 6), as it is widely used in the *Realization of Acceleration* working group.

The oscillators of the different systems, namely the oscillator of the dynamic bridge standard and of the data acquisition system, are synchronised to avoid spectral leakage. The dynamic bridge standard is equipped with an optical clock input. The PXIe system is equipped with a timing and synchronisation card (PXIe-6672), which features a stable oscillator (TCX0). Its one-

[1] Commercial instruments are identified in this paper only to adequately specify the experimental set-up. Such identification does not imply recommendation by PTB, nor does it imply that the equipment identified is necessarily the best available for the purpose.

year-stability is in a range of a few 10^{6} [8]. The 20 MHz reference frequency for the dynamic bridge standard is then generated by direct digital synthesis (DDS) based on the 10 MHz TCX0 oscillator. The electrical frequency output provided by the PXIe card is converted to an optical link as required by the bridge standard.

Dynamic bridge excitation signals are generated by two MDACs with a sampling frequency which is a fraction of the reference frequency. Based on this sampling frequency, the sinusoidal waveforms can be generated based on a finite number of data points per oscillation period, which, are then repeatedly output. The sampling frequencies and the acquisition time of the data acquisition were chosen based on two criteria:

1) The sampling rate should be multiples or integer fractions of the bridge standard's sampling rate. Generally, it would not be favourable to sample with a higher sampling rate than the signal generation rate. However, the chosen digitiser card has a minimum sampling rate of 50 kS/s, requiring a down-sampling of the data after acquisition. This decimation process is carried out by calculating an averaged decimated waveform from the original data.
2) The sampling rate was chosen to achieve a finite number of samples for the selected number of oscillations to be acquired. The corresponding acquisition time should include an integer number of periods of the excitation frequency.

The sampling frequency of the chosen digitiser cannot be chosen arbitrarily. It is to be chosen to be an even integer divider of the sampling frequency of 120 MS/s for the bitstream input of the incorporated delta-sigma analogue-to-digital converters (ADCs) and must be in a range of 50 kS/s and 15 MS/s.

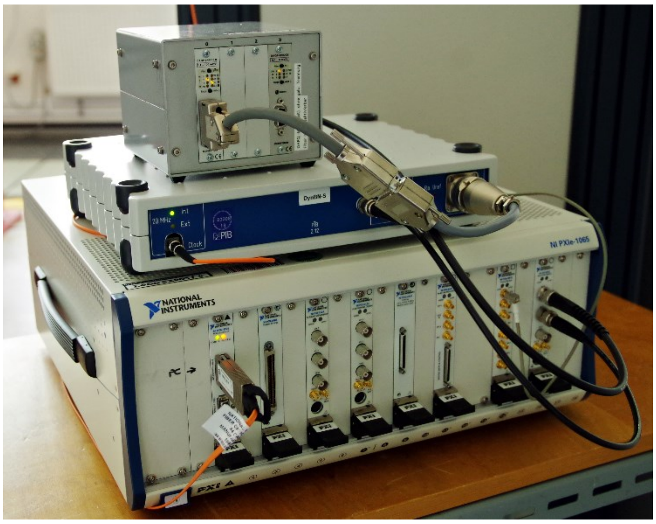

Figure 4: Dynamic bridge amplifier calibration set-up consisting of a bridge amplifier under test (top), the dynamic bridge standard (middle), and the data acquisition system (bottom).

5. DATA ANALYSIS

The acquired and synchronously sampled waveforms of the two input channels make up the input for the data analysis. One data channel is the reference output of the dynamic bridge standard, and therefore contains a signal with a known relation to the input of the transducer, while the second data channel contains the voltage output of the device under test.

The transformation of the time series data into the frequency domain is carried out by digital Fourier transform (DFT). Because of the synchronised generation and acquisition frequencies, spectral leakage can be avoided. The sampling of full periods of the sinusoidal waveform allows us to go without any windowing prior to the DFT.

Based on the outcomes of the two DFTs and the calibration results of the dynamic bridge standard, magnitude and phase responses of the device under test at each excitation frequency can be calculated as described in Section 3. The magnitude response is derived only based on the output of the device under test, as the input magnitude is known from the bridge standard's calibration data. The phase response (i.e. the frequency-dependent phase delay) requires input from both measurement channels, as the absolute phase position cannot be derived from calibration data.

For each frequency point, repeated measurements are carried out (the number of repetitions can be set) and the mean and the standard deviation are calculated giving information about the stability of the input-output relation of the device under test for each calibration frequency.

6. MEASUREMENT UNCERTAINTY EVALUATION

The measurement uncertainty will be evaluated according to the *Guide to the Expression of Uncertainty in Measurement* (GUM) [9] and its *Supplement 1* (GUM S1) [10] by means of Monte Carlo simulations.

The GUM distinguishes between two types of measurement uncertainty contributions, which both will be considered for the measurement uncertainty estimation:

1) Type A uncertainty contributions: These can be determined by statistical analysis of measurements.
2) Type B uncertainty contributions: These include all contributions, which cannot be estimated by statistical analysis. They can include data sheet content, results from calibrations (of e.g. components of the set-up), operator know-how, record from previous measurements, or other prior knowledge.

The measurement is modelled by a mathematical model function f propagating all the input quantities $X_1 \dots X_n$ to the measurement result Y giving

$$Y = f(X_1, X_2, \dots, X_n) \ . \qquad (4)$$

Each input quantity can be described mathematically by its distribution, which leads to estimations for the value of the input quantity, as well as its uncertainty. Depending from the sources of information about the input quantity and its properties the according distributions (Gaussian distributed, rectangularly distributed, …) were assigned.

Independent calibrations of components of the calibration set-ups are incorporated in the uncertainty estimation as sub-models, i.e. the distributions of the calibration result will be assigned to the according input quantity X. This is the case for two components:

6.1. Calibration of the dynamic bridge standard

The bridge standard was calibrated the frequency domain in advance by calibrating the resistive voltage divider, the MDACs and the signal conditioners of the outputs. The expanded measurement uncertainties ($U(k=2)$) of this calibration are 0.03 % (magnitude) and 0.05° (phase angle) for frequencies up to 1 kHz and 0.05 % (magnitude) and 0.1° (phase angle) for frequencies above 1 kHz up to 10 kHz.

Table 1. Type B measurement uncertainty contributions of the calibration set-up.

input quantity	uncertainty contribution	distribution
dynamic bridge standard (magnitude)	$u_{rel} \leq 2.5 \times 10^{-4}$	Gaussian
dynamic bridge standard (phase)	$u \leq 0.05°$	Gaussian
dynamic bridge standard systematic (mag.)	$u_{rel} \leq 5 \times 10^{-4}$	Gaussian
frequency standard	$u_{rel} = 1 \times 10^{-10}$	Gaussian
stability TCX0 (1 year)	$u_{rel} = 1 \times 10^{-6}$	rectangular
temperature stab. TCX0 (0 °C – 55 °C)	$u_{rel} = 2 \times 10^{-6}$	rectangular
skew	$u = 5 \times 10^{-10}$ s	rectangular
cal. PXI-5922 (magnitude)	$u_{rel} \leq 2.5 \times 10^{-6}$	Gaussian
PXI-5922 systematic deviations (magnitude)	$u_{rel} = 6 \times 10^{-4}$	Gaussian
PXI-5922 DC accuracy (magnitude)	$u_{rel} = 5 \times 10^{-4} +$ $u = 1 \times 10^{-5}$ V	rectangular rectangular

There exist systematic effects, which are in the same order as the expanded measurement uncertainty for the magnitude transfer function and less than 0.2° for the phase angle at 10 kHz.

6.2. Calibration of the digitiser channels

The two digitiser input channels were calibrated dynamically using a voltage calibrator. In typical conditioning amplifier calibration set-ups, it is not necessary to calibrate the data acquisition hardware so thoroughly, if input and output are acquired simultaneously and a second measurement with swapped input channels is carried out. In this case, possible influences due to the different input channel characteristics can be corrected. However, in case of the dynamic bridge standard, this procedure is not applicable: As the magnitude response is only derived from the bridge standards output (cf. section 3), all influences due to the digitalisation need to be determined.

The calibration of the digitiser channels was carried out using a Fluke 5700A voltage calibrator (which was itself calibrated dynamically before). For the calibration, both input channels were connected to the voltage calibrator's outputs and voltages of known magnitude and frequency were generated. From the acquired signal, the root mean square (RMS) value was derived for each frequency point of the calibration. The digitiser card shows a characteristic transfer function, which could be compensated, as it is dependent on the sampling rate, only [6, 7]. Figure 5 shows a calibration results for a sampling rate of 50 kS/s (the same rate as used for the calibration measurements).

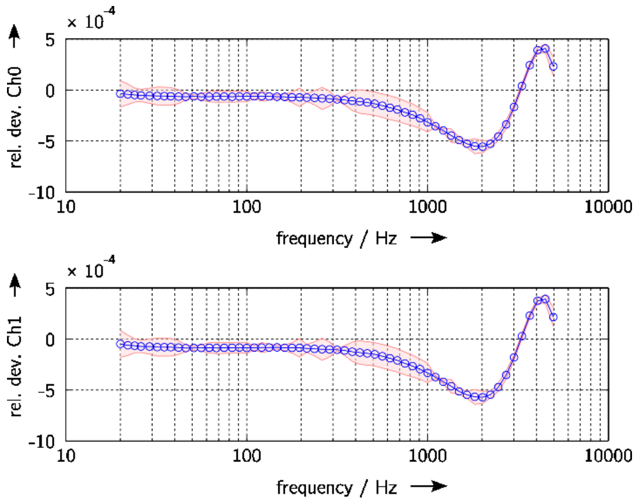

Figure 5: Calibration result of a PXI-5922 digitiser card. Given in blue are the relative deviations, given in red is the assigned measurement uncertainty $U(k=2)$. The sampling rate was 50 kS/s, the input voltage span ±5 V.

The stable local oscillator of the PXIe timing and synchronisation card was calibrated traceably to PTB's frequency standards by means of a distributed frequency signal.

The different measurement uncertainty contributions are depicted in Fig. 6, detailed information about the different type B contributions, including their distributions, are given in table 1.

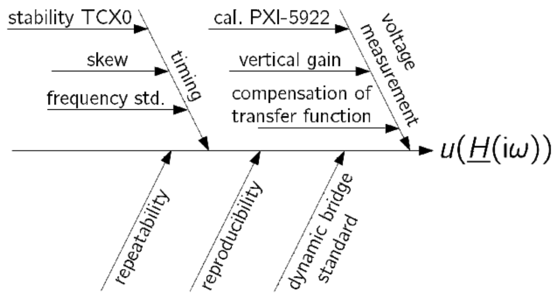

Figure 6: Ishikawa diagram of the measurement uncertainty contributions for a dynamic bridge amplifier calibration.

6.3. Statistical analysis of the measurements

The type A uncertainty contributions will be analysed as well: The stability of the measurement set-up and of different devices under test will be assessed by carrying out many repeated measurements in a short time (named 'repeatability' in Fig. 6) and by repeating the calibration at larger intervals including disconnecting all cables and turning the calibration devices and devices under test off between measurements (named 'reproducibility').

A complete evaluation of the type A uncertainty contributions requires extensive measurements with different devices under test and numerous repetitions, which have not yet been carried out.

6.4. Correction of systematic effects

Both, signal acquisition card and dynamic bridge standard show a frequency dependent change in their transfer function. The GUM recommends a correction of all systematic effects. However, if necessary, it is possible to treat those systematic effects as uncertainty contributions [11]. Both magnitude related systematic contributions are in the same range as the random measurement uncertainty component of the calibration of the dynamic bridge standard. Therefore, in a first step, these will not be corrected, but included in the measurement uncertainty estimation as input quantities. In future, these could be corrected in order to reduce the resulting measurement uncertainty for the bridge amplifier calibration.

6.5. Application of the Monte Carlo simulation

The measurement uncertainty evaluation will be carried out by means of a Monte Carlo simulation according to GUM S1. For this purpose, repeated simulation of the measurement will be carried out. The different input quantities will be modelled according to their input distributions. The resulting distribution of the output describes the measurement result including its uncertainty.

7. FIRST MEASUREMENT RESULTS

To obtain a first impression of the performance of this new set-up, measurements were carried out with a bridge amplifier under test which had previously been dynamically calibrated. The previous calibration had been carried out with an earlier prototype of the dynamic bridge standard in conjunction with a sampling voltmeter [12]. The results of the magnitude and phase responses are given in Fig. 8 and Fig. 9, respectively.

The chosen bridge amplifier shows only small deviations (in a range of a few 10^{-3} for the magnitude response) from the ideal behaviour in the chosen frequency range. The measurement results agree very well both in terms of magnitude and phase, although the individual frequency responses of the corresponding bridge standards have not yet been compensated for. The differences between the results of the two measurements are even a little smaller than the largest single type B measurement uncertainty contribution.

8. SUMMARY AND OUTLOOK

This paper describes a dynamic bridge amplifier calibration set-up based on the new PTB dynamic bridge standard. The output of the bridge standard and the device under test is sampled synchronously by a high-precision digitiser. A synchronisation of the oscillators of both the data acquisition system and the bridge standard avoids spectral leakage.

The new calibration set-up enables dynamic calibrations of bridge amplifiers according to the measurement conditions required by ISO 4965-2 [13], in which a dynamic signal on a constant bias is stipulated.

The first measurement results of the new set-up agree very well with measurements previously carried you with a prototype of the dynamic bridge standard.

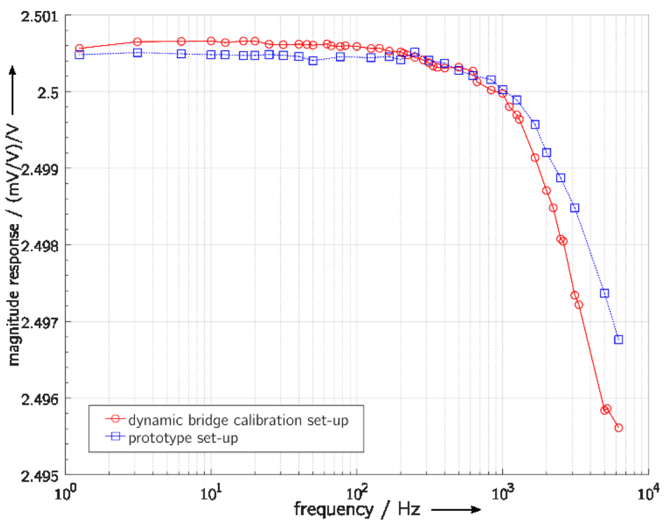

Figure 7: Magnitude response calibration results of a bridge amplifier using a prototype of the bridge standard (blue) and of the actual set-up (red).

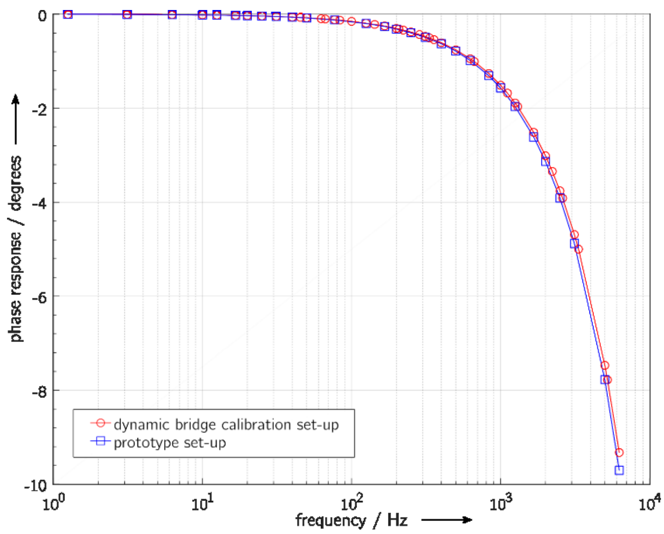

Figure 8: Phase response calibration results of a bridge amplifier using a prototype of the dynamic bridge standard (blue) and of the actual set-up (red).

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