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A NEW CALIBRATION 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.

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

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.

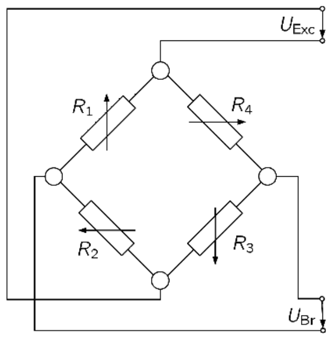

Figure 1: Wheatstone bridge circuit with four resistive sensing elements $R_1 \dots R_4$, excitation voltage U_{Exc} and bridge output voltage U_{Br}.

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} has to 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

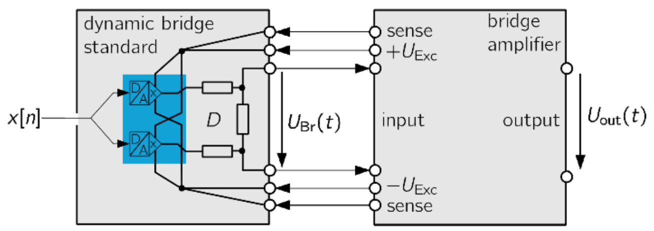

Figure 2: Schematic overview of the dynamic bridge standard.

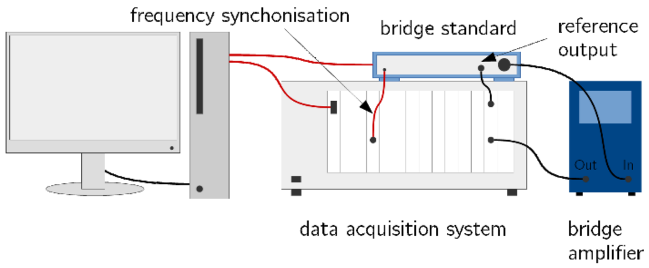

Figure 3: Components of the dynamic bridge amplifier calibration set-up.

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.

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

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

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

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

$$\varphi(\omega) = \varphi_Y(\omega) - \varphi_X(\omega)\,, \tag{3}$$

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 $\varphi_{\mathrm{X}}(\omega)$.

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 ($f_{\mathrm{s}} \ll 500$ kHz), the resolution is 24 bits. The PXI-5922 digitiser card was thoroughly analysed in terms of its dynamic properties, precision, and metrological suitability [5, 6]. Additionally, automated calibration procedures exist for this acquisition card at PTB, 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), which can be calibrated traceably to PTB's frequency standards by means of a distributed frequency signal. Its one-year-stability is in a range of a few 10^{6} [7]. 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] 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.

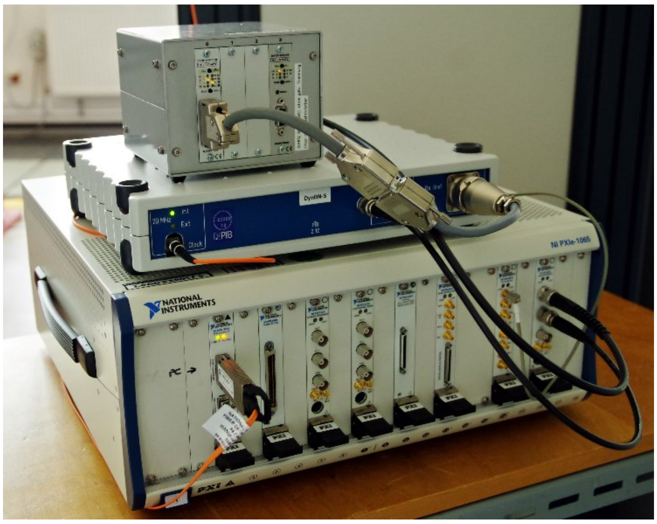

Figure 4: Dynamic bridge amplifier calibration set-up consisting of a bridge amplifier under test (top), the dynamic bridge standard (middle), and the data acquisition system (bottom).

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 has to be in a range of 50 kS/s and 15 MS/s.

4. 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

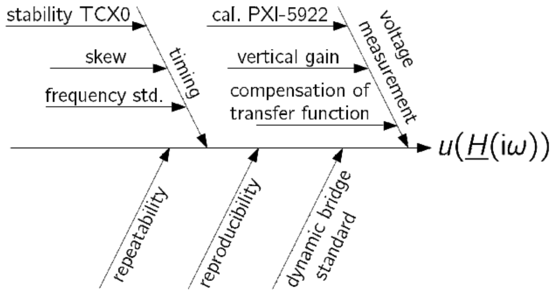

Figure 5: Ishikawa diagram of the measurement uncertainty contributions for a dynamic bridge amplifier calibration.

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.

5. MEASUREMENT UNCERTAINTY CONTRIBUTIONS

The measurement uncertainty will be evaluated according to the *Guide to the Expression of Uncertainty in Measurement* (GUM) [8] and its *Supplement 1* (GUM S1) [9] by means of Monte Carlo simulations.

For the evaluation of the uncertainties, the measurement set-up will be modelled and repeated simulation measurements will be carried out. The resulting distribution of the magnitude and phase responses of the device under test will then be estimated. The dynamic bridge standard will not be part of the uncertainty estimation; it will be included as one sub-model with known uncertainty contributions from its calibration.

The different measurement uncertainty contributions are depicted in Fig. 5. Additionally to the aforementioned contributions of the dynamic bridge standard, two large sources of uncertainty remain:

1) Data acquisition: Numerous contributions arise from the uncertainties of the voltage measurement, i.e. the calibration of the digitiser card and from the timing properties of the data acquisition system.
2) 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. 5) 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 measurement uncertainty evaluation requires extensive measurements with different devices under test and numerous repetitions, which have not yet been carried out. Therefore, only this overview of the identified uncertainty contributions can be given, and the measurement uncertainty evaluation will be part of a subsequent publication.

6. 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 [10]. The results of the magnitude and phase responses are given in Fig. 6 and Fig. 7, 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.

7. 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 [11], 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.

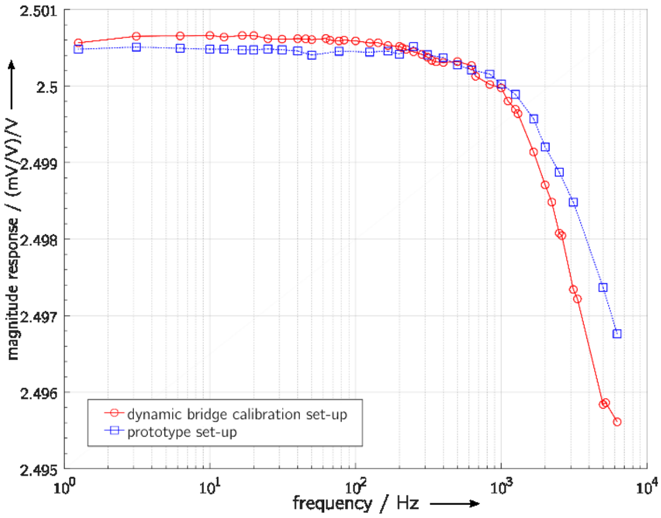

Figure 6: Magnitude response calibration results of a bridge amplifier using a prototype of the dynamic bridge standard (blue) and of the actual set-up (red).

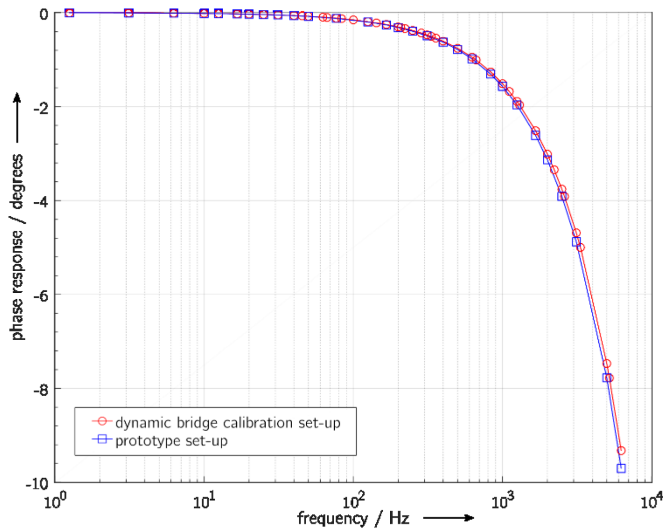

Figure 7: Phase response calibration results of a bridge amplifier using a prototype of the dynamic bridge standard (blue) and of the actual set-up (red).

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