Calibration of Bridge-, Charge- and Voltage Amplifiers for Dynamic Measurement Applications

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1 Introduction

For the dynamic measurement of mechanical quantities, the European research project *Traceable Dynamic Measurement of Mechanical Quantities* within the framework of the European Metrology Research Programme (EMRP) focused on the development of procedures for traceable measurements of the quantities force, pressure and torque [1–3]. This Joint Research Project (JRP) conjoined experimentalists and mathematicians from nine European National Metrology Institutes (NMIs) for research on the measurands force, pressure and torque. For dynamic measurements of any of these quantities, the respective sensor typically needs to be complemented by a conditioning amplifier. Therefore, these amplifiers were included in the research work as a major component of the traceability chain.

The majority of measurements are carried out with transducers having a bridge-, charge- or voltage output. These different types of output signals need to be conditioned in order to be digitized by an analogue-to-digital converter for further processing. For the conditioning of the signals, which may include the amplification, the decoupling and the conversion of quantities, signal conditioning amplifiers – also called measuring amplifiers – are used. Both terms will be used synonymously in the subsequent text. A typical measuring chain that consists of a transducer, an amplifier and a data acquisition system (DAQ) is depicted in figure 1.

To obtain traceable measurements, all components of the measuring chain have to be calibrated and analysed regarding their influence on the measurement result and an associated measurement uncertainty has to be assigned to each component.

While such procedures are well established for static measurements, there are no standardized procedures yet in the field of dynamic measurements. The requirements for the dynamic calibration of bridge amplifiers are already included in international standards [4], although there are no commercially available calibration devices yet. Currently, standards describing the procedures of a dynamic calibration of conditioning amplifiers are under development in national and international standardization working groups, namely the German DKD Fachausschuss "Kraft und Beschleunigung" (technical committee on "Force and Acceleration") and the Working Group 6 of ISO TC 108/SC 3 "Use and calibration of vibration and shock measuring instruments". This will remedy the current lack of validated procedures within the foreseeable future.

The subsequent section will provide an overview of the current state of knowledge and will further give an outline of what is to be expected from the future documentary standards.

2 Requirements for Conditioning Amplifiers

In theory, conditioning amplifiers should have no influence on the content of the measured signal in the frequency range of interest and should only convert the signal in the desired manner. However, in reality influences of conditioning amplifiers exist and need to be determined through proper calibration. In the field of acceleration measure-

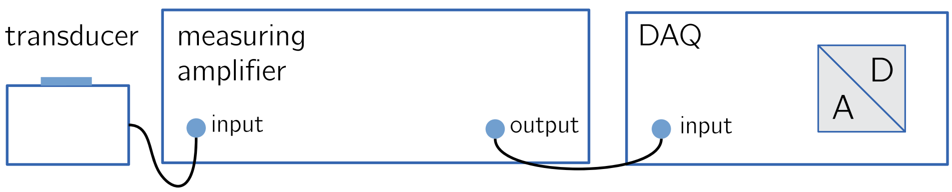

Figure 1:
Measuring chain consisting of a transducer, a measuring amplifier and a data acquisition system.

ment some experience in the dynamic calibration of charge amplifiers exists. This knowledge has now been extended to the development of calibration procedures for various types of conditioning amplifiers. Above all, the following types of amplifiers were considered in the JRP and hence, in this paper:

- Voltage amplifiers
- Charge amplifiers
- IEPE amplifiers, and
- Bridge amplifiers.

In the following paragraphs, the peculiarities of the different devices are briefly introduced.

2.1 Properties of conditioning amplifiers

Real amplifiers exhibit a frequency-dependent behaviour described by their frequency response function. This response may in turn depend to some extent on the properties of the connected source (transducer). These dependencies need to be characterized by means of calibration. To be able to calibrate a measuring amplifier, the device should be linear and time-invariant (LTI).

Linearity:
the output scaling factor should not depend on the level of the input signal of the amplifier.

Time invariance:
the frequency response function should not change over time.

The assumption of an LTI behaviour of conditioning amplifiers is a prerequisite for the applicability of the calibration procedures described in this paper.

2.2 Different types of amplifiers used for dynamic measurements

2.2.1 Voltage amplifier

Voltage amplifiers are used to condition input voltages to proportional output voltages. Two main applications exist:

- For small input voltages, voltage amplifiers are used for signal amplification.
- They are also used as unity-gain followers for a decoupling of input and output in case of load-sensitive transducer outputs or to adapt the source impedance to the connected data acquisition channel.

2.2.2 Charge amplifier

These devices are used in conjunction with piezoelectric transducers to convert the charge generated by the transducer to a proportional low impedance voltage output. The internal circuitry of the input stage of these devices typically exhibits either high-pass characteristics, or drift behaviour, if the high pass is compensated for [5].

2.2.3 IEPE amplifier

Piezoelectric transducers may be supplied with embedded integrated electronics (integrated electronic piezoelectric, IEPE), which may be named ICP®, Deltatron®, Piezotron®, or similar, depending on the manufacturer. The specifications of IEPE transducers and their power supply are not defined in a standard specification and may differ in detail from manufacturer to manufacturer. However, the known types follow a common principle. The power supply of such a transducer is realized using a two-wire connection with a constant current feed. The voltage between the rails used for the power supply changes, depending on the measured quantity. It has a bias voltage level of typically 8 V to 12 V, which corresponds to the zero point of the measured quantity. The voltage will change proportionally to the measured quantity in a range of typically 0.5 V (minimum voltage, minimum value of the measurand) to 24 V (supply voltage, maximum value of the measurand). Besides the current supply and the bias voltage level, the working principle of an IEPE conditioning amplifier is related to that of a voltage amplifier used for decoupling of input and output.

2.2.4 Bridge amplifier

Bridge amplifiers are used for the signal conditioning of the Wheatstone bridge outputs of strain gauge or of piezoresistive transducers. The amplifier feeds the transducer's bridge circuit with a supply voltage. The voltage output of the bridge is dependent on the detuning of the bridge's resistors and additionally proportional to the supply voltage. Therefore, the output of a transducer is a ratiometric quantity and is usually given as the ratio of the bridge output voltage and supply voltage in mV/V. For correct signal conditioning, bridge amplifiers should implement this ratiometric principle by not only taking the output signal of the transducer into account, but by including the supply voltage level as well. It should be noted that for the scope of the work described here, only amplifiers providing a DC supply voltage are considered. So-called carrier frequency bridge amplifiers are typically dedicated to static measurement exercises and therefore are not discussed here.

Carrier frequency bridge amplifiers can be used in a frequency range of only about 20 % of the carrier frequency, which is usually below 5 kHz. Even then, deviations of more than 10 % in the magnitude response have to be taken into account [6]. Furthermore, it should be noted that according to the common units of the input in mV/V and the output in V, the unit of the frequency response function of these devices is, in fact,

$$\frac{\mathrm{V}}{(\mathrm{mV/V})} .$$

3 Procedures for Dynamic Calibration

The goal of a calibration is the determination of the properties of interest of the device under test (DUT) with a known measurement uncertainty. For the conditioning amplifier, which can presumably be described as an LTI system, the property of interest is the frequency response function.

3.1 Frequency response function

The complex-valued frequency response function $\underline{H}(\mathrm{i}\omega)$ describes the time-dependent input–output behaviour of an LTI system in the frequency domain for an angular frequency $\omega = 2\pi f$, where f is the frequency in Hz. For continuous systems, the frequency response function is defined as the ratio of the output $\underline{Y}(\mathrm{i}\omega)$ over the input $\underline{X}(\mathrm{i}\omega)$ as

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

Its magnitude $A(\omega)$ is given by

$$A(\omega) = |\underline{H}(\mathrm{i}\omega)| = \sqrt{\mathrm{Re}^2\left(\underline{H}(\mathrm{i}\omega)\right) + \mathrm{Im}^2\left(\underline{H}(\mathrm{i}\omega)\right)} \qquad (2)$$

and describes the conversion and scale- or gain factor of the device. The phase response function $\varphi(\omega)$ is given by

$$\varphi(\omega) = \tan^{-1}\left(\frac{\mathrm{Im}(\underline{H}(\mathrm{i}\omega))}{\mathrm{Re}(\underline{H}(\mathrm{i}\omega))}\right) \qquad (3)$$

and characterizes the signal delay between input and output.

To derive the phase angle from the complex frequency response function, a four-quadrant inverse tangent calculation should be applied. If the two-quadrant inverse tangent calculation is used, a correction of φ for $\pm\,\pi$ may be necessary as this function is only defined in the range $-\pi/2 < \varphi < \pi/2$.

3.2 Excitation signal

The dynamic excitation of the measuring amplifier's input quantity used for calibration can be carried out in different ways, e.g. by transient, random noise or periodic excitation signals. The most commonly used excitation signal is the monofrequent sinusoidal excitation. Its advantages are the selectable excitation frequency, duration and magnitude, but the comparably long measurement time to obtain the complete frequency response function is disadvantageous. Since non-sinusoidal excitations can usually be related to sinusoidal excitations by Fourier methods, all subsequent considerations will be focused on the latter.

For an excitation signal $x(t)$ of a sinusoidal excitation with the magnitude A_x, the angular frequency ω and the phase φ_x is described by

$$x(t) = A_x \cdot \sin(\omega t + \varphi_x) = a_x \sin(\omega t) + b_x \cos(\omega t) , \qquad (4)$$

with $A_x = \sqrt{a_x^2 + b_x^2}$ and $\varphi_x = \tan^{-1}(a_x/b_x)$. The output signal can be described accordingly as

$$y(t) = A_y \cdot \sin(\omega t + \varphi_y) = a_y \sin(\omega t) + b_y \cos(\omega t) . \qquad (5)$$

With this definition the frequency response function can be written in the form

$$\underline{H}(\mathrm{i}\omega) = \frac{A_y(\omega)}{A_x(\omega)} \cdot \mathrm{e}^{\mathrm{i}\left(\varphi_y(\omega) - \varphi_x(\omega)\right)} . \qquad (6)$$

The excitation frequency f should be chosen appropriately for the later application. The recommended frequency values often used in acoustics and vibration calibrations are given in ISO 266 [7]. These *recommended frequencies* are equally spaced in the frequency domain on the logarithmic scale. The width between the frequency steps can be chosen based on the desired number of frequency steps for a fixed interval.

3.3 Amplifier settings

A calibration result can only be valid for one certain set of settings of the amplifier under test, which include gain, corner frequencies of high-pass and low-pass filters, transducer sensitivity and possibly other parameters. It is essential to document the settings at which the amplifier was calibrated. These settings should be chosen according to the later application.

3.4 Linearity

For the above-mentioned frequency response function used to describe the dynamic behaviour, the

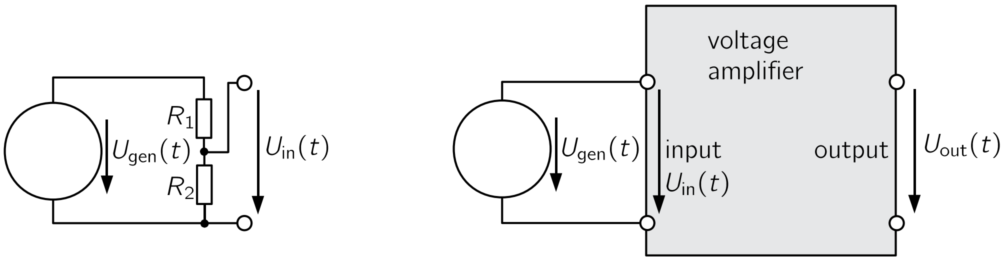

Figure 2: Schematic representation of a calibration set-up for voltage amplifiers using a signal generator and a voltage divider (left), or a signal generator only (right).

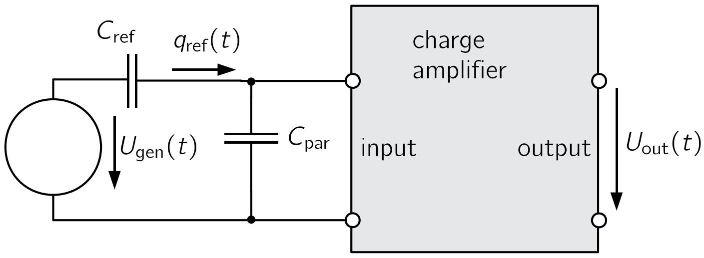

Figure 3: Schematic diagram of a calibration set-up for charge amplifiers.

linearity of the DUT is mandatory and should be ensured during calibration. Nonlinearities cause distortions of the sinusoidal shape of the output signal and can be estimated by analysing the harmonic signal components.

3.5 Stability

The requirement of the time-invariant behaviour can be proved by repeated calibrations over a prolonged period of time.

4 Calibration Set-Ups

4.1 Voltage amplifier calibration set-up

For the calibration of voltage amplifiers, a calibration set-up as depicted in figure 2 can be used. The time-dependent voltage output U_{gen} of the signal generator is coupled directly to the input of the voltage amplifier under test (in the case of small gain factors) or can be down-converted by means of a calibrated voltage divider (in the case of large gain factors).

The measurands of this set-up are the input voltage of the amplifier $U_{in}(t)$, which may be calculated from a calibrated generator voltage and the output voltage $U_{out}(t)$ of the amplifier. In terms of equations (4) and (5), this means

$$x(t)=U_{in} \cdot \sin(\omega t+\varphi_{in}) \text{ and} \quad (7)$$

$$y(t)=U_{out} \cdot \sin(\omega t+\varphi_{out}) \,. \quad (8)$$

4.2 Charge amplifier calibration set-up

In order to calibrate a charge amplifier it is necessary to convert the generator voltage from the previously described set-up to an input charge q_{ref} [8]. For this purpose, a high precision capacitance C_{ref} is employed as shown in figure 3.

Assuming that the input impedance of the charge amplifier is negligible, the reference charge q_{ref} for the charge amplifier under test can be derived as

$$q_{ref}(t) = U_{gen}(t) \cdot C_{ref} \,. \quad (9)$$

In terms of equation (4) the input measurand is given as

$$x(t) = U_{gen} \cdot C_{ref} \cdot \sin(\omega t + \varphi_{in}) \,. \quad (10)$$

Under this assumption, parallel capacities C_{par} (e.g. from the transducer cable) will not influence the amount of charge at the amplifier input. However, it was found that the total capacitance at the input ($C_{ref} + C_{par}$) may influence the charge amplifier's frequency response function [9]. This effect is typically small, but may not be negligible in applications with a demand for low measurement uncertainties.

4.3 IEPE amplifier calibration set-up

IEPE conditioning amplifiers can be calibrated using a measuring set-up similar to a set-up for low gain voltage amplifiers. Instead of a direct connection of the signal generator and the amplifier under test, an IEPE simulator is connected between the signal generator and the IEPE conditioner [10], converting the generated voltage into an IEPE transducer-like output signal. This set-up is depicted in figure 4.

For the determination of the frequency response function of an IEPE signal conditioner, two connection schemes are possible with such a set-up:

- Calibration with a calibrated IEPE simulator. If the IEPE simulator's frequency response

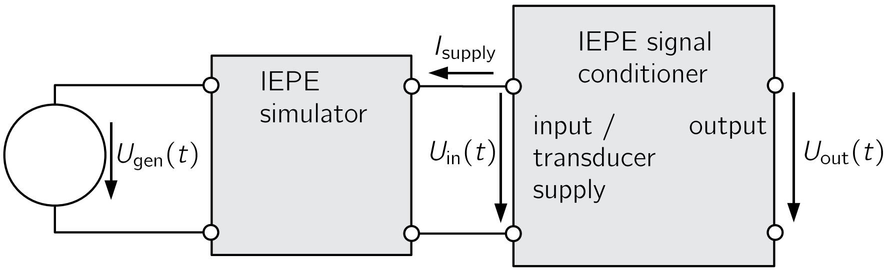

Figure 4: Calibration set-up for IEPE conditioning amplifiers including an IEPE simulator.

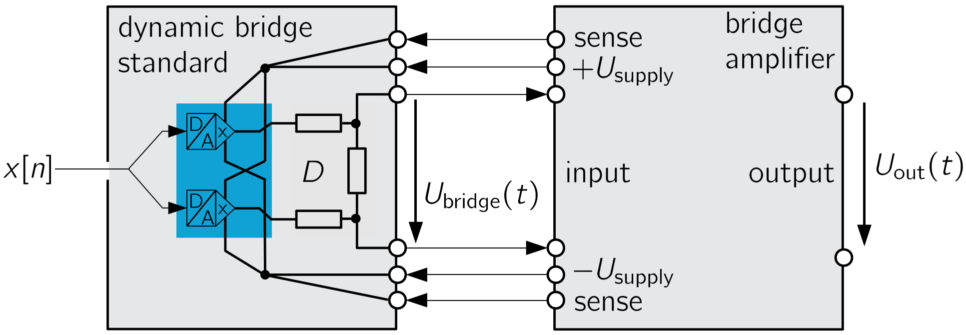

Figure 5: Schematic representation of a bridge amplifier calibration set-up with an MDAC dynamic bridge standard.

function was determined prior to the calibration of the IEPE conditioning amplifier, a known input voltage can be used for the excitation following

$$x(t)=U_{gen} \cdot \sin(\omega t+\varphi_{in}) \quad (11)$$

and applying a correction according to the procedures described in section 9.

- Calibration by measuring U_{in} instead of U_{gen}. If the output signal of the IEPE simulator is acquired instead of the input signal, the influences of the IEPE simulator are excluded from the measurement.

$$x(t)=U_{in} \cdot \sin(\omega t+\varphi_{in}) + U_{offset} \quad (12)$$

However, it has to be kept in mind that there will be a voltage offset U_{offset} due to the IEPE feeding, which can lead to reduced voltage measurement precision due to the disadvantageously large input voltage ranges of the data acquisition device. Additional influences due to the voltage measurement in the measuring chain must be analysed as well.

4.4 Dynamic bridge standard calibration set-up

For the dynamic calibration of bridge amplifiers, different calibration set-ups have been developed at the NMI level. They all feature a ratiometric measurement principle. An older approach generates the small excitation voltages by means of an inductive coupling, which is limited at low frequencies [11]. Therefore, no DC measurement (f = 0 Hz) is possible.

A new approach generates the bridge signals by using two multiplying digital-analogue converters (MDACs) and a resistive voltage divider [12–13]. The principle is depicted in figure 5. With this principle, bridge excitation frequencies down to DC are possible; in fact, arbitrary signals could be generated as well. As part of work package 4 of the aforementioned EMRP project, the dynamic bridge standards were further developed to enable phase measurements and a traceable calibration was carried out. An international bilateral comparison of the different dynamic bridge standards is currently under way to ensure comparability in the range of the estimated measurement uncertainties.

The dynamic bridge standard simulates the output signal of a strain gauge transducer. The device is connected to the bridge amplifier under test and provides a similar input resistance to a strain gauge transducer. The output voltage of the simulated bridge depends directly on the bridge supply voltage, because the supply voltage is the reference voltage for the multiplying DACs. In the case of bridge amplifiers equipped with a control of the bridge excitation voltage by means of a 6-wire connection using sense wires, these wires are connected to the MDACs in the bridge standard so as to behave similarly to a real transducer.

As the dynamic bridge standard generates the predefined traceable voltage ratio, the measurand for a magnitude calibration of a bridge amplifier is solely the output voltage of the amplifier. In order to determine the phase response, the dynamic bridge standard supplies a complementary normalized signal output, which provides a signal synchronous to the voltage ratio. With reference to this 'synchronization signal', the time delay and therefore the phase response of the amplifier can be calibrated.

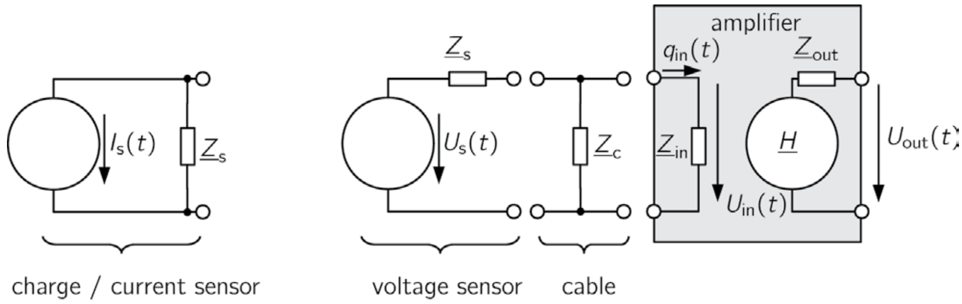

Figure 6.
Schematic diagram including impedances for current or charge measurements (left) and for voltage measurements (right).

5 Data Acquisition and Analysis

The methodology presented here is implemented in the respective laboratories of PTB and to our knowledge in many other NMI laboratories, namely in the field of vibration metrology. Nevertheless, other valid set-ups and methods are conceivable.

To calculate the frequency response function (see equation (1)), the input and output quantities have to be acquired with two measurement channels. For proper signal acquisition, several criteria should be complied with:

- Common sample clock for the two channels (or sample clocks of an integer ratio).
- Synchronous start of sampling.
- Common sampling interval (window width) of an integer multiple of the mains period.
- Sample frequency that covers the bandwidth of the nominal frequency *f* and existing harmonics (Nyquist criterion).

Considering this in all of the previously described set-ups, two sampled time series of sinusoidal voltage signals $\{x_i\}$ and $\{y_i\}$ are acquired[1], which is – irrespective of a constant factor (e.g. C_{ref}) – a discretized realization of the continuous signals $x(t)$ and $y(t)$ (see equations (4) and (5)).

Through the application of a linear least squares fit of the named equations to the sampled time series, the parameters a_x, b_x and a_y, b_y can be determined easily. With the transformations given in section 3.2, the frequency response function is thus derived according to equation (6) by subsequent measurements at all desired angular frequencies ω.

6 Influence of the Impedance

Every signal input, signal output and connecting cable has its inherent complex impedance which, if not taken into account, can add systematic deviations to the measurements. Figure 6 shows the two set-ups for the voltage and for the charge measurements. If the typically used coaxial cables are significantly shorter than the wavelength of the signal, they can be modelled by a parallel capacitance $\underline{Z}_c$.

The output voltage $\underline{U}_{out}$ of a measuring amplifier is dependent on the output scaling factor described by the frequency response function $\underline{H}$ as

$$\underline{U}_{out} = \underline{H} \cdot \underline{U}_{in} \quad (13)$$

for voltage amplification, and

$$\underline{U}_{out} = \underline{H} \cdot \underline{q}_{in} \quad (14)$$

for charge conditioning, respectively.

The voltage at the input of the amplifier $\underline{U}_{in}$ can deviate from the sensor output voltage $\underline{U}_s$ because of the influences of the impedances

$$\underline{U}_{in} = \underline{U}_s \cdot \left(1 + \underline{Z}_s \left(\frac{1}{\underline{Z}_{in}} + \frac{1}{\underline{Z}_c}\right)\right)^{-1}. \quad (15)$$

Accordingly, the input $\underline{q}_{in}$ of a charge measurement can deviate from the output charge $\underline{q}_s$ according to

$$\underline{\theta}_{in} = \underline{\theta}_s \cdot \left(1 + \underline{Z}_s \left(\frac{1}{\underline{Z}_{in}} + \frac{1}{\underline{Z}_c}\right)\right)^{-1}. \quad (16)$$

7 Measurement Uncertainty Contributions of Realized Calibration Facilities

The measurement uncertainties for dynamic calibrations are based on the quality of the device under test as well as on the calibration set-up. The major components for the measurement uncertainty of the set-up can be (see [8–12]):

- Non-linearities of the A/D conversion for single frequency ratio measurement.
- Calibration uncertainties of the used reference capacitance (for charge amplifier calibration).
- Calibration uncertainties of the IEPE simulator (for IEPE amplifier calibration).
- Calibration uncertainties of the dynamic bridge standard (for bridge amplifier calibration).
- Noise of the input voltage (generator) and of the output voltage (conditioning amplifier).

[1] In the case of the dynamic bridge standard, the input is not acquired but defined by the programmed signal. However, the analysis procedure is easily adaptable.

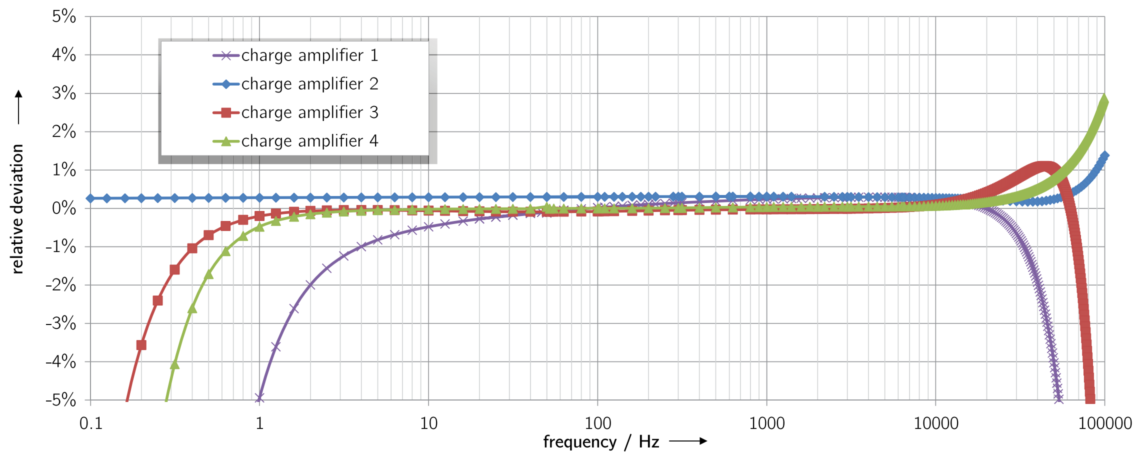

Figure 7:
Magnitude responses of four different commercially available charge amplifiers in the frequency range of 0.1 Hz to 100 kHz.

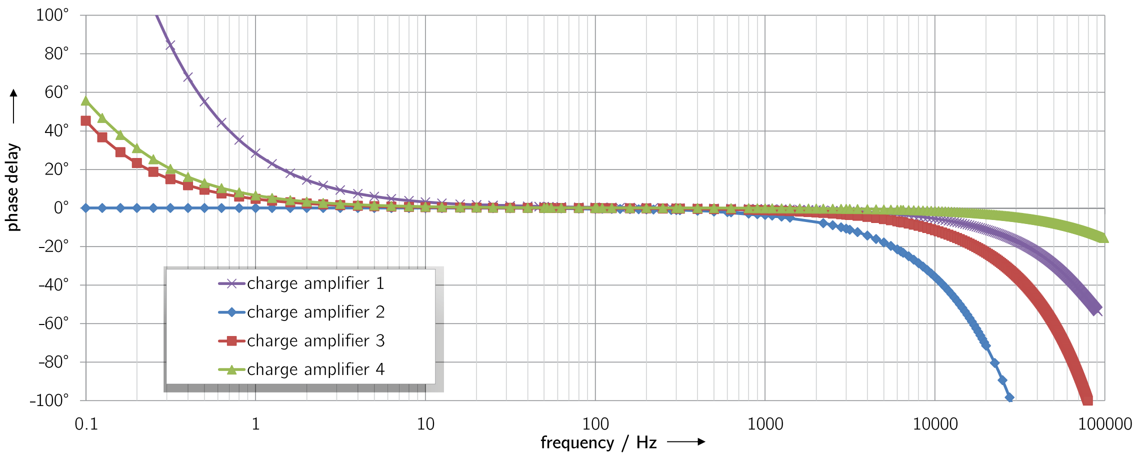

Figure 8:
Phase responses of four charge amplifiers in the frequency range of 0.1 Hz to 100 kHz.

Hence, a rough estimate shows that the claims of some 10^{-3} to 10^{-4} of relative combined expanded uncertainty for magnitude are feasible for charge amplifier calibration [8–9] with the proper equipment and under good conditions, depending, of course, on the details of the implementation. The relative expanded measurement uncertainties of IEPE and the bridge amplifiers, again for magnitude calibration, will be in the ranges of tenths of per cent [10–12].

Not only do NMIs carry out traceable calibrations of charge amplifiers, but accredited laboratories also compare their calibration results in a national comparison programme [14]. The measurement uncertainties of accredited calibration laboratories for the available calibrations (charge amplifiers, voltage amplifiers, but not yet bridge amplifiers) are typically in the range of 0.3 % < $U(k = 2)$ < 1 % and typically available for magnitude calibration only.

8 Measurement Results of the Calibration of Amplifiers

To show the importance of a suitable calibration for amplifiers used for dynamic measurements, different calibration results for bridge-, charge-, voltage- and IEPE conditioning amplifiers are presented. All analysed amplifiers are commercially available. They were produced by different manufacturers.

The charge-, voltage- and IEPE conditioning amplifier calibrations were carried out in a frequency range from 0.1 Hz to 100 kHz. All high- and low-pass filters were disabled or set to their lowest (high-pass filter) or highest (low-pass filter) value, respectively. The deviations in the magnitude responses are given with respect to the nominal value, set at the amplifier.

Three of the four charge amplifiers show a typical high-pass behaviour in their amplitude response (figure 7). Charge amplifier 2 has the option to disable its high-pass filter, which resulted in a much better low-frequency behaviour but also in a drifting DC bias voltage (which does not become obvious from the frequency response data). It was found that even with high-pass filters set at the lowest value, the filter settings can still influence the measuring results in the frequency range up to 10 Hz. The low-pass filters of three amplifiers (amplifiers 2, 3, 4) show a significant overshooting behaviour, which should be considered with caution. The corresponding phase response of the same four charge amplifiers is shown in figure 8. The phase and the magnitude responses can differ substantially from amplifier to amplifier.

The calibration results for the magnitude (figure 9) and phase response (figure 10) of four different voltage amplifiers show the smallest fre-

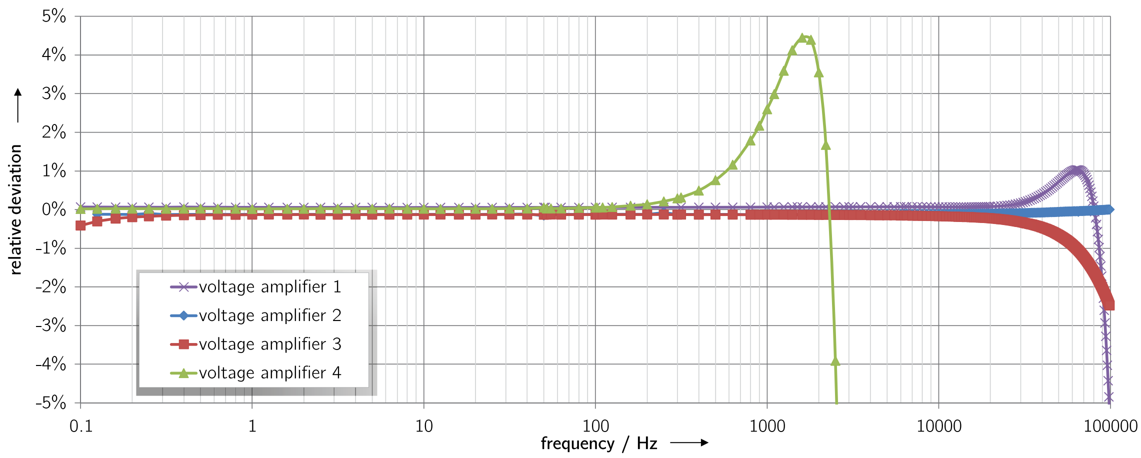

Figure 9: Magnitude responses of four different commercially available voltage amplifiers in the frequency range of 0.1 Hz to 100 kHz.

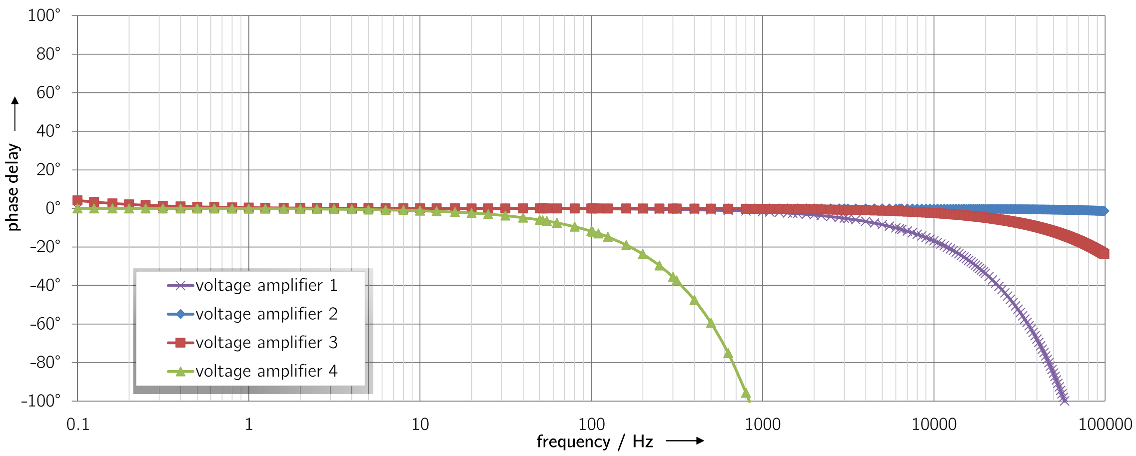

Figure 10: Phase responses of four voltage amplifiers in the frequency range of 0.1 Hz to 100 kHz.

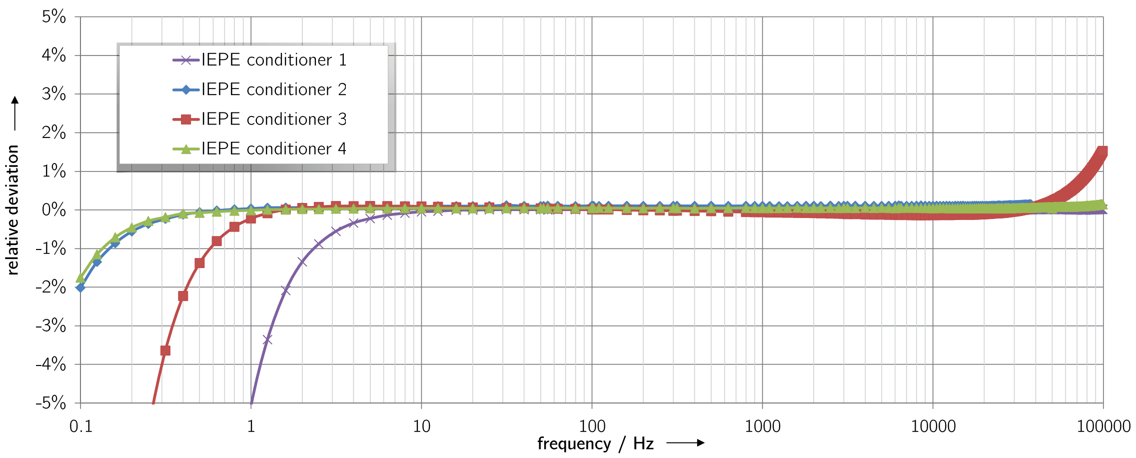

Figure 11: Magnitude responses of four different commercially available IEPE conditioning amplifiers in the frequency range of 0.1 Hz to 100 kHz.

quency-dependent deviations at low frequencies. Again, the low-pass filter can produce significant overshooting even in a frequency range of a few hundred hertz (voltage amplifier 4), which affects the phase response accordingly.

All investigated IEPE conditioning amplifiers have a significant high-pass behaviour as depicted in figures 11 and 12, which can affect low frequency measurements.

In figures 13 and 14, the magnitude and phase response of four bridge amplifiers are shown. The calibration measurements were carried out using the dynamic bridge standard of PTB in a frequency range of 10 Hz to 10 kHz. The excitation level was 2 mV/V; all filters were switched off or set to their highest value available.

It becomes obvious from the calibration results that bridge amplifiers can have a significant varying magnitude response even in low frequency regions, which shows the importance of dynamic calibrations. The phase responses of the four analysed amplifiers show significantly differing behaviour. The four bridge amplifiers under test had a phase delay of at least 15° to 20° at 10 kHz. But bridge amplifier 2 exhibited a much stronger phase delay.

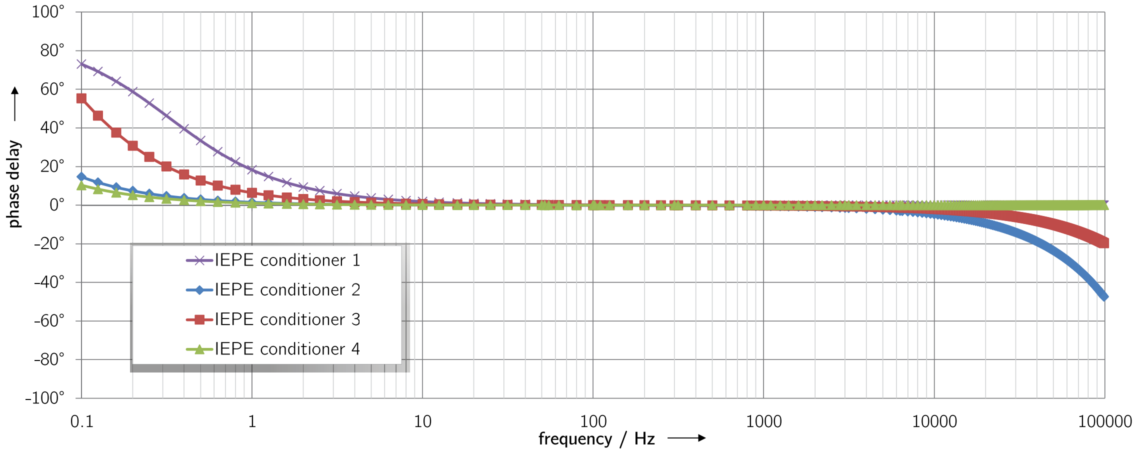

Figure 12:
Phase responses of four IEPE conditioning amplifiers in the frequency range of 0.1 Hz to 100 kHz.

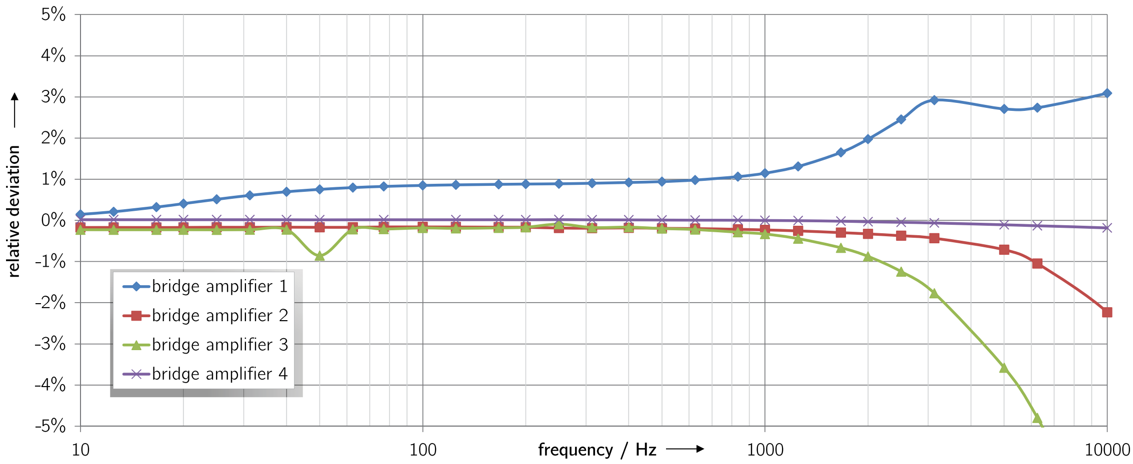

Figure 13:
Magnitude responses of four different commercially available bridge amplifiers in the frequency range of 10 Hz to 10 kHz.

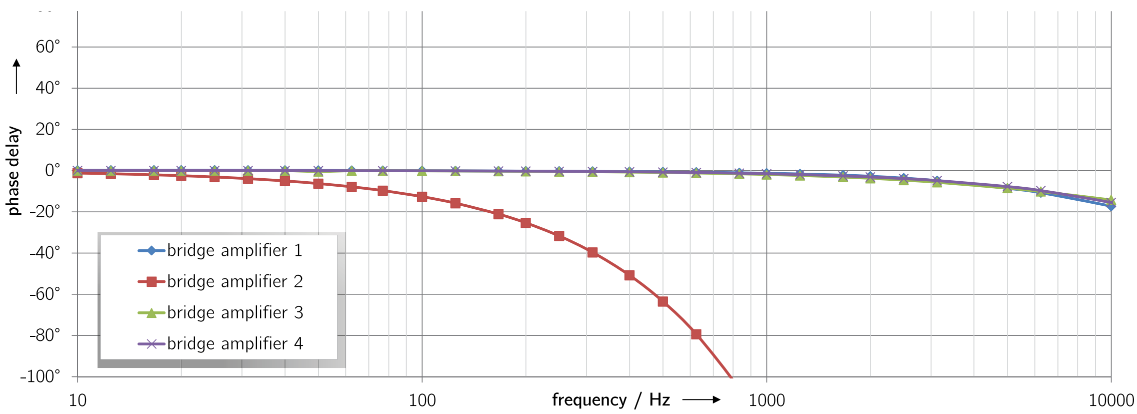

Figure 14:
Phase responses of four bridge amplifiers in the frequency range of 10 Hz to 10 kHz.

9 Correction of the Frequency-dependent Behaviour

The calibration results can be used to correct the dynamic influences of the amplifier in the measurement chain. In case the magnitude response function $A_{\mathrm{cal}}(\omega)$ and the phase response function $\varphi_{\mathrm{cal}}(\omega)$ of an amplifier are known from calibration, the magnitude $A_{\mathrm{meas}}(\omega)$ and phase $\varphi_{\mathrm{meas}}(\omega)$ of the measured data can be corrected in the frequency domain as

$$A_{\mathrm{corr}}(\omega) = A_{\mathrm{meas}}(\omega) \cdot A_{\mathrm{cal}}(\omega)^{-1} \qquad (17)$$

and

$$\varphi_{\mathrm{corr}}(\omega) = \varphi_{\mathrm{meas}}(\omega) - \varphi_{\mathrm{cal}}(\omega)\,. \qquad (18)$$

It should be kept in mind that the frequency response functions of the measuring amplifiers have to be assigned with their measurement uncertainty and will therefore influence the corrected data's uncertainty accordingly.

10 Summary

This paper shows that a dynamically calibrated measuring amplifier is a prerequisite for traceable calibration of transducers used for dynamic measurements of mechanical quantities. Guidance for the user on how different types of amplifiers could be calibrated is provided in the paper. Amplifiers of different types were exemplarily investigated. Calibration set-ups were presented for the different types of amplifiers applied with different types of sensors and the measurement uncertainties which can be realized with such set-ups were estimated. The calibration results of selected charge-, voltage- and bridge amplifiers, as well as IEPE conditioning amplifiers, have been exemplarily presented. These results demonstrate the importance of a dynamic calibration because of the deviating results obtained with different amplifiers. General assumptions regarding the suitability of a certain type of amplifier cannot be made, because all of the reviewed amplifiers showed some dependence in their frequency response function on dynamic excitation.

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