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DKD-R 3-2

Calibration of conditioning amplifiers for dynamic application

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Deutscher Kalibrierdienst (DKD) – German Calibration Service

Since its foundation in 1977, the German Calibration Service has brought together calibration laboratories of industrial enterprises, research institutes, technical authorities, inspection and testing institutes. On 3rd May 2011, the German Calibration Service was reestablished as a *technical body* of PTB and accredited laboratories.
This body is known as *Deutscher Kalibrierdienst* (DKD for short) and is under the direction of PTB. The guidelines and guides developed by DKD represent the state of the art in the respective areas of technical expertise and can be used by the *Deutsche Akkreditierungsstelle GmbH* (the German accreditation body – DAkkS) for the accreditation of calibration laboratories.
The accredited calibration laboratories are now accredited and supervised by DAkkS as legal successor to the DKD. They carry out calibrations of measuring instruments and measuring standards for the measurands and measuring ranges defined during accreditation. The calibration certificates issued by these laboratories prove the traceability to national standards as required by the family of standards DIN EN ISO 9000 and DIN EN ISO/IEC 17025.

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Foreword

DKD guidelines are application documents that meet the requirements of DIN EN ISO/IEC 17025. The guidelines contain a description of technical, process-related and organizational procedures used by accredited calibration laboratories as a model for defining internal processes and regulations. DKD guidelines may become an essential component of the quality management manuals of calibration laboratories. The implementation of the guidelines promotes equal treatment of the equipment to be calibrated in the various calibration laboratories and improves the continuity and verifiability of the work of the calibration laboratories.

The DKD guidelines should not impede the further development of calibration procedures and processes. Deviations from guidelines as well as new procedures are permitted in agreement with the accreditation body if there are technical reasons to support this action.

Calibrations by accredited laboratories provide the user with the security of reliable measuring results, increase the confidence of customers, enhance competitiveness in the national and international markets, and serve as metrological basis for the monitoring of measuring and test equipment within the framework of quality assurance measures.

This guideline has been drawn up by the Technical Committee *Force and Acceleration* and approved by the Board of the DKD.

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1 Scope of application

Sensors for kinematic or mechanical measuring variables such as acceleration, angular velocity (rotation rate), force, torque or pressure need to be complemented by a conditioning amplifier to be connected to data acquisition and/or display systems (see [9]). In combination with this amplifier, the sensor forms a measuring chain. To ensure the exchangeability of the components of this measuring chain, sensor and amplifier are to be characterised individually.

This guideline describes validated methods for the characterisation of conditioning amplifiers of different types and functions for application in dynamic measurements. The response of time varying signals is of particular interest. It is described by the complex transfer function as a function of the frequency of the input signal.

For the purpose of this guideline, the amplifier to be calibrated is assumed to be linear so that the complex transfer coefficient at a given frequency is independent of the amplitude of the input signal.

Other characteristics of conditioning amplifiers such as temperature influence, noise etc. are not covered by this guideline.

The following technical specifications help to define the scope of the guideline:

- Input measurand: Voltage, charge, resistance (voltage ratio)
- Output measurand: Voltage (for digital outputs, see 2.3)
- Typical frequency range: DC (0 Hz) to 100 kHz
- Characteristic dissemination variables: magnitude and phase of the complex transfer function

2 Calibration and evaluation concept

2.1 Generic properties of conditioning amplifiers

Strictly speaking, the conditioning amplifiers dealt with in this guideline are mostly transducers, often including adjustable transfer factors and filters for limiting the bandwidth. Figure 1 shows a summary display. The amplifiers shown in pale grey are not considered in this guideline.

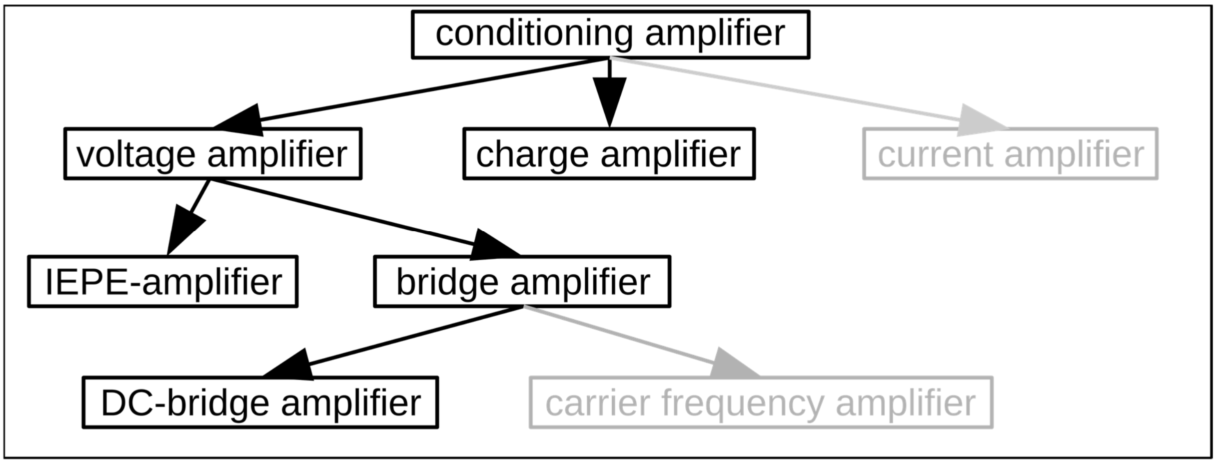

Figure 1: Types of conditioning amplifiers – summary display

A general representation of the entire measuring chain is shown in Figure 2. The sensor converts the recorded physical quantity into a transducer output quantity or into an amplifier input quantity (X_{in}), respectively. This quantity is then converted by the conditioning amplifier into a voltage (U_{out}). Usually, this voltage will then be supplied to a data acquisition device.

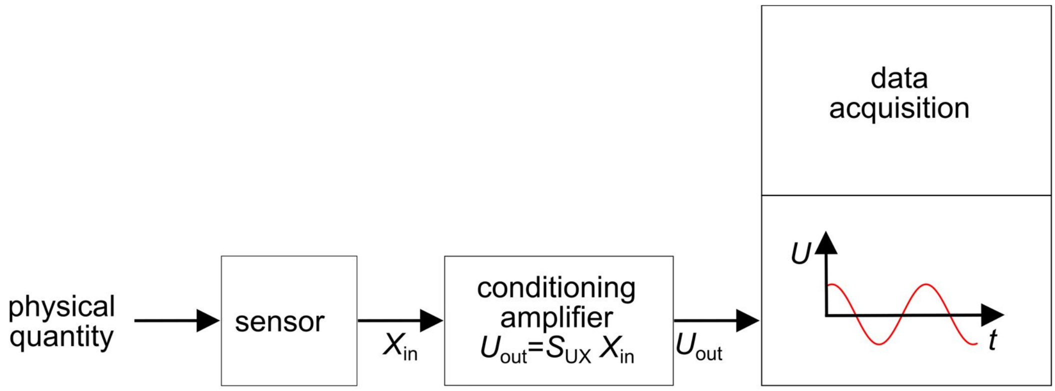

Figure 2: General representation of the measuring chain

The large number of available conditioning amplifiers with their special properties cannot be fully described here. The internal circuit concepts are as diverse as their areas of application. Figure 3 shows a generic representation of an amplifier.

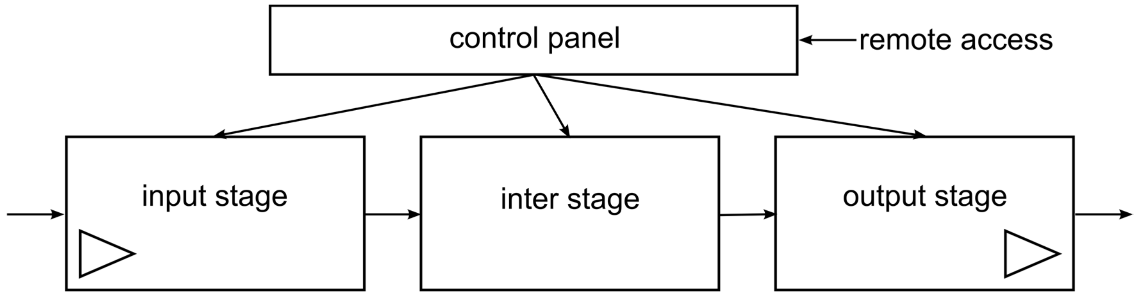

Figure 3: Generic representation of the conditioning amplifier

The sensor signal first attains the input stage; this is where the measured quantity is usually converted. Characteristic features include the input impedance and the galvanic coupling (single-ended, floating, differential), the provision of a sensor supply, bias correction, possible sensor identification (e.g.: TEDS) and error detection (sensor break, overload) or the option for feeding test signals.

The intermediate stage provides options for signal processing, such as filtering, scaling, integration, derivation or also the correction / linearization with saved transducer characteristic curves. Some of these functions are realised via digital signal processing stages.

The output signal is provided by the output stage. Characteristic features include the output impedance and the galvanic coupling (single-ended, floating, differential).

During calibration it is also recommended to pay attention to the grounding, especially to the way in which signal ground and protective earth are handled in the circuitry and whether this can be changed, if necessary

2.2 Input measuring quantity

Depending on the type of amplifier and the application, there are different input quantities (X_{in}) which shall be realised for a calibration in a traceable way. Figure 4 shows a general set-up. It is not always possible to measure the input quantity (X_{in}) directly, for instance in case of charge amplifiers. In such cases, the excitation quantity (U_{G}) is to be recorded and the input quantity (X_{in}) is to be calculated via the known and traceable transfer function (S_{XG}).

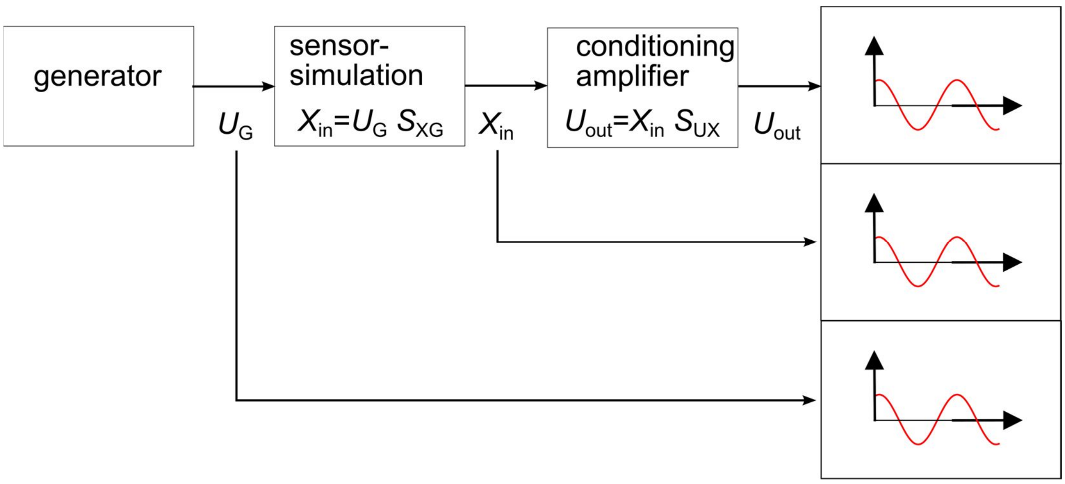

Figure 4: General representation of the calibration set-up

For the conditioning amplifiers considered in this guideline, the quantities indicated in Table 1 are realised. More details are given in the amplifier-specific Annexes.

Table 1: General description of the types of devices, measured variables and realisation principles

Type of amplifier	Input variable of the calibration	Realisation principle for the input variable
Voltage amplifier	Alternating voltage $X_{\mathrm{in}} = U_{\mathrm{in}}$	Output voltage of a function generator (sinusoidal), if applicable with output divider (attenuator)
Bridge amplifier	Voltage ratio (resistance change) $X_{\mathrm{in}} = U_{\mathrm{G}}/U_{\mathrm{S}}$	• Output voltage of a function generator and measurement of the supply voltage (U_{S}) • Modulation of the supply voltage (U_{S}) by means of a dynamic bridge standard
Charge amplifier	Alternating charge $X_{\mathrm{in}} = C_{\mathrm{n}} \cdot U_{\mathrm{G}}$	Reference capacitor fed by a function generator
IEPE amplifier	Alternating voltage with bias in case of a constant DC current supply $X_{\mathrm{in}} = U_{\mathrm{in}}$	• Suitable function generator (current sink) • IEPE simulator fed by a function generator
Inline charge-to-voltage converter	Alternating charge $X_{\mathrm{in}} = C_{\mathrm{n}} \cdot U_{\mathrm{G}}$	Reference capacitor fed by a function generator

2.3 *Output measuring quantity*

The output measuring quantity for all amplifiers covered by this guideline is a voltage which is to be recorded in relation to the input quantity. This means that a synchronous measurement in relation to the input variable is necessary to be able to represent the signal timing. This is subsequently reflected in the value of the phase.

Conditioning amplifiers with integrated AD conversion, which provide the output quantity directly as a digital signal (stream), for example data acquisition systems with integrated IEPE signal conditioning, may be calibrated according to this document provided that these data can be recorded synchronously with the input quantity.

2.4 *Transfer function*

The target quantity of the calibration is the complex transfer function ($S_{\mathrm{ux}}(\omega)$) of the conditioning amplifier from the input quantity (X_{in}) to the output voltage (U_{out}). According to the given specifications for measurement and evaluation, the input and output quantities are given in the form

$$X_{\mathrm{in}} = \hat{X}_{\mathrm{in}} \cdot \sin(\omega t + \varphi_{\mathrm{x}}) \qquad (1)$$

and $$U_{\mathrm{out}} = \hat{U}_{\mathrm{out}} \cdot \sin(\omega t + \varphi_{\mathrm{u}}) \text{ with } \omega = 2\pi \cdot f \qquad (2)$$

Hence, the following applies for the complex transfer coefficient as the ratio of the two quantities:

$$S_{\mathrm{ux}} = \frac{\hat{U}_{\mathrm{out}}}{\hat{X}_{\mathrm{in}}} \cdot \mathrm{e}^{\mathrm{j}(\varphi_{\mathrm{u}} - \varphi_{\mathrm{x}})} \qquad (3)$$

or in terms of magnitude and phase:

$$|S_{\mathrm{ux}}| = \frac{\hat{U}_{\mathrm{out}}}{\hat{X}_{\mathrm{in}}} \qquad (4)$$

$$\varphi_{\mathrm{ux}} = \varphi_{\mathrm{u}} - \varphi_{\mathrm{x}} \qquad (5)$$

According to the transfer function, the conditioning amplifiers can be divided into two groups. The first group is connected to the sensor by DC coupling; its frequency response is limited only by an upper cut-off frequency (cf. Figure 5, above). The second group is connected to the sensor by AC coupling (mostly for technical reasons); the transfer function of both high and low frequencies is limited, i.e. it shows both a high-pass and a low-pass behaviour (cf. Figure 5, below).

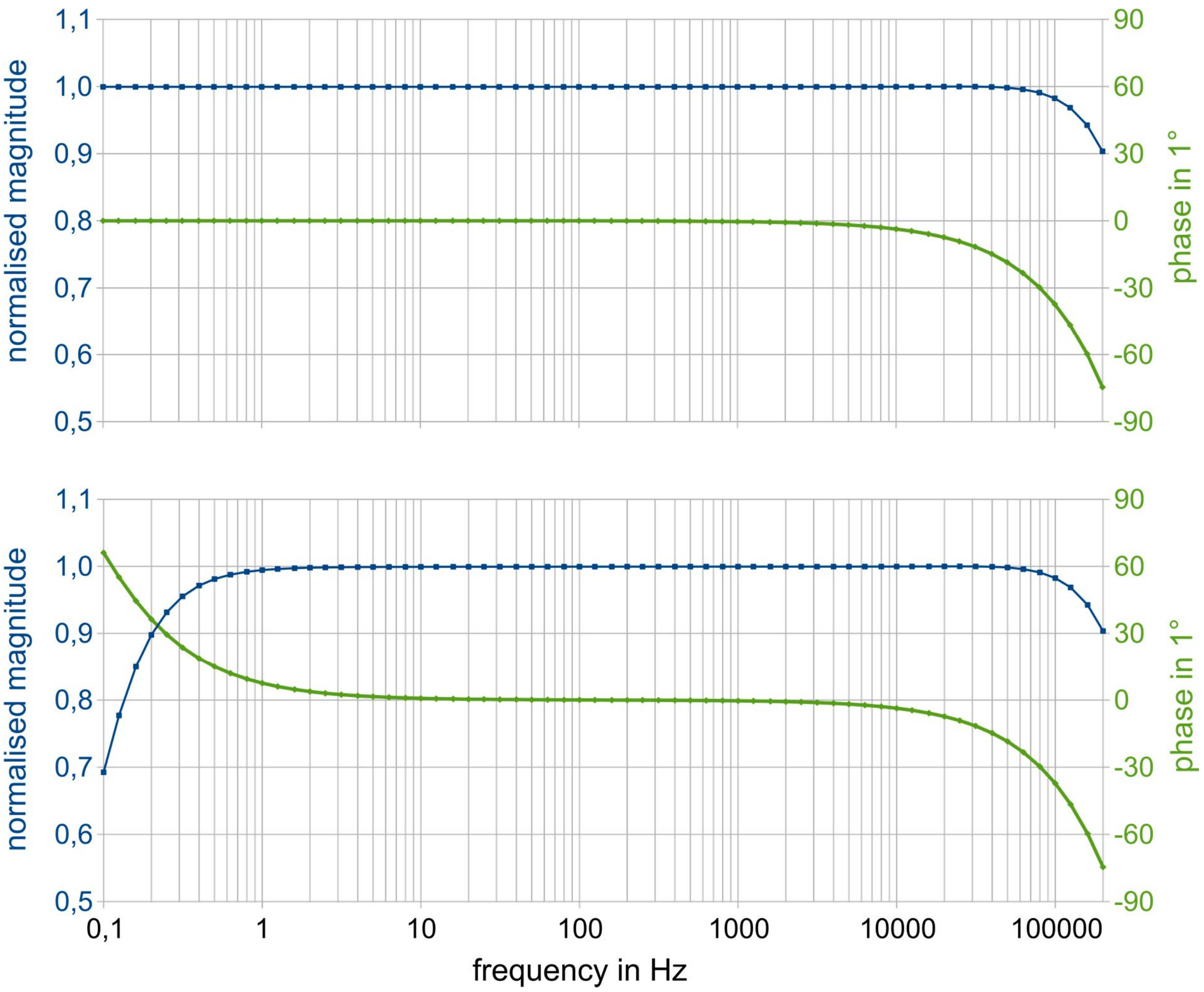

Figure 5: Graphical representation of the typical transfer functions of DC-coupled (top) and AC-coupled (bottom) conditioning amplifiers. The curves show the normalized magnitude (blue) and phase (green) of the complex transfer function.

3 Basic calibration procedure

3.1 Acquisition of measurement data

In all cases described here, the calibration is based on a synchronous sampling (where appropriate by means of a multiplexer) of the generator voltage (U_{G}) for realising the input quantity (X_{in}) and the output voltage of the amplifier (U_{out}.).

The parameter setting of the ADC used for sampling should be such that the signal is sampled by at least 2.56 points per period (sampling frequency $f_s \geq 2{,}56\,f$). When using the sine-approximation method for the evaluation of only a few signal periods, an oversampling with 50 to 100 points per period should be aspired.

The measuring range of the ADC should be selected such that the ADC is sufficiently modulated by the amplitude of its respective input voltages. The effective vertical resolution of the sampling resulting from the selected modulation and the resolution of the ADC has to meet the requirements of the desired measurement uncertainty.

The time bases (clock generators) of the ADCs used for sampling shall run synchronously. The sampling rate (f_{s}) should be the same for both ADCs in order to provide synchronous sampling. A fixed time reference between input voltage time series and output voltage time series is crucial.

Even if the input quantity is realised via a traceable signal source (calibrator), the precise and known timing relation between input and output signal is to be ensured. Here, the traceable value set on the calibrator can be used as amplitude of the input quantity.

As to the measurements, it has to be ensured that all components of the measurement set-up are in thermal equilibrium and that stable ambient conditions prevail.

3.2 General evaluation in case of sinusoidal excitation

The following section describes the analysis according to the sine-approximation method. Beyond that other frequency selective procedures based on correlation analysis or Fourier transform may alternatively be applied. However, those will not be discussed here in detail.

U_{G} is supposed to have a mono-frequent sinusoidal curve for each individual measurement and can therefore be described with $\omega = 2\pi \cdot f$ in the form

$$U_{\mathrm{G}}(t) = \widehat{U}_{\mathrm{G}} \cdot \sin(\omega t + \varphi_{\mathrm{G}}) \tag{6}$$

The curve of the output voltage of the conditioning amplifier can be described as follows:

$$U_{\mathrm{out}}(t) = \widehat{U}_{\mathrm{out}} \cdot \sin(\omega t + \varphi_{\mathrm{out}}) \tag{7}$$

After sampling, there are two time-discrete measurement series (u_i) for the originally continuous voltage curves ($U(t)$):

- $\boldsymbol{u}_{\mathrm{G},\boldsymbol{i}} = \boldsymbol{U}_{\mathrm{G}}(\boldsymbol{t_i})$ for the voltage of the generator
- $\boldsymbol{u}_{\mathrm{out},\boldsymbol{i}} = \boldsymbol{U}_{\mathrm{out}}(\boldsymbol{t_i})$ for the output voltage of the amplifier

To determine the amplitude ($\widehat{U}_y$) and phase ($\hat{\varphi}_y$) of the measured signal sequences, a function having the following form

$$u_{\mathrm{y},i}(\omega) = A_{\mathrm{y}}(\omega) \cdot \sin(\omega t_i) + B_{\mathrm{y}}(\omega) \cdot \cos(\omega t_i) + C_x(\omega) \tag{8}$$

is fitted to each of the measurement series. The best estimates are then yielded by

$$\hat{U}_y(\omega) = \sqrt{A_y^2 + B_y^2} \tag{9}$$

$$\varphi_y(\omega) = \arctan\left(\frac{B_y}{A_y}\right) \tag{10}$$

The complex frequency-dependent transfer coefficient between the output of the generator and output of the conditioning amplifier is then given by:

$$|S_{\mathrm{UG}}(\omega)| = \frac{\hat{U}_{\mathrm{out}}(\omega)}{\hat{U}_{\mathrm{G}}(\omega)} \quad \text{(magnitude)} \tag{11}$$

$$\varphi_{\mathrm{UG}}(\omega) = \varphi_{\mathrm{out}}(\omega) - \varphi_{\mathrm{G}}(\omega) \quad \text{(phase).} \tag{12}$$

If a conversion element is used for the transducer simulation with the complex frequency-dependent transfer function

$$S_{\mathrm{XG}}(\omega) = |S_{\mathrm{XG}}(\omega)|\, \mathrm{e}^{\mathrm{j}(\varphi_{\mathrm{XG}}(\omega))} \tag{13}$$

the transfer coefficient of the conditioning amplifier results for:

$$|S_{\mathrm{UX}}(\omega)| = \frac{\hat{U}_{\mathrm{out}}(\omega)}{\hat{U}_{\mathrm{G}}(\omega)} \cdot \frac{1}{|S_{\mathrm{XG}}(\omega)|} \quad \text{(magnitude)} \tag{14}$$

$$\varphi_{\mathrm{UG}}(\omega) = \varphi_{\mathrm{out}}(\omega) - \varphi_{\mathrm{G}}(\omega) - \varphi_{\mathrm{XG}}(\omega) \quad \text{(phase).} \tag{15}$$

The set-up described here can be realised by individual components discretely in the form of a generator, ADC and PC. However, it is also possible to use a spectrum or frequency response analyser which implicitly contains these devices.

3.3 Considerations on input and output impedance

Every signal input, signal output and connecting cable has an 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. The typically used coaxial cables can be modelled by a parallel capacitance, provided they are significantly shorter than the considered wavelength of the signal in the cable. Usually, this is the case for standard laboratory applications up to frequencies of 1 MHz.

For voltage measurements, the output voltage (U_{out}) of the conditioning amplifier is a function of the input voltage

$$U_{\mathrm{out}} = H \cdot U_{\mathrm{in}} \tag{16}$$

or, in the case of charge measurements, a function of the input charge

$$U_{\mathrm{out}} = H \cdot Q_{\mathrm{in}} \tag{17}$$

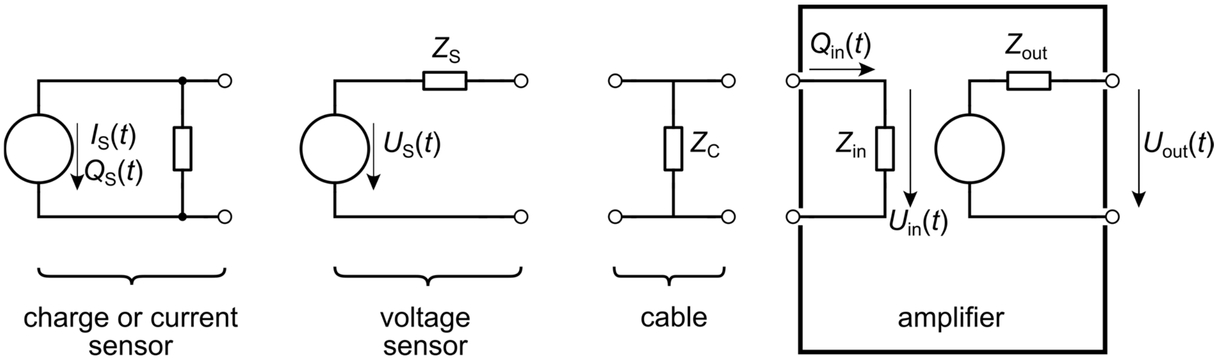

Figure 6: Equivalent circuits including impedances for current or charge measurement (left) and voltage measurement

Due to the impedances, the input voltage of the voltage amplifier is:

$$U_{\mathrm{in}} = U_{\mathrm{S}} \cdot \left(1 + Z_{\mathrm{s}}\left(\frac{1}{Z_{\mathrm{in}}} + \frac{1}{Z_{\mathrm{C}}}\right)\right)^{-1} \quad (18)$$

This also applies to the input charge (Q_{in}) at the charge amplifier and the output charge (Q_{S}) of the source.

4 Measurement uncertainty

4.1 General information

The required proof of the smallest possible measurement uncertainty to be stated (best measurement capability) is given by the uncertainty budget and by way of comparison measurements using transfer standards. The transfer standards should be state-of-the art. Additional influences of the conditioning amplifier to be calibrated must also be taken into account.

The "Guide to the expression of uncertainty in measurement" (GUM) [3] is considered the relevant document when preparing the uncertainty budget.

4.2 Model equation

A model equation for calculating the quantity of the calibration result is a basic prerequisite for the evaluation of the measurement uncertainty according to GUM. The proposed model equations for magnitude and phase of the complex transfer function are derived from equations (13) and (14):

$$|S_{\mathrm{UX}}(\omega)| = \frac{\hat{U}_{\mathrm{out}}(\omega)}{\hat{U}_{\mathrm{G}}(\omega)} \cdot \frac{1}{|S_{\mathrm{XG}}(\omega)|} \cdot \prod_i (1+e_i) \tag{19}$$

$$\varphi_{\mathrm{UX}}(\omega) = \varphi_{\mathrm{out}}(\omega) - \varphi_{\mathrm{G}}(\omega) - \varphi_{\mathrm{XG}}(\omega) + \sum \Delta\varphi_i \tag{20}$$

The model equation for the magnitude is equivalent to the product equation introduced in Annex A (A 2.3) of ISO 16063-1:1999. The factors $K_i = (1+e_i)$ describe influencing quantities or corrections. The measurement uncertainty is then derived from the respective quantity (e_i) which represents the deviation from the nominal value.

The model for the phase is a sum model. The corrections or additional uncertainty components are covered by the variances of the quantities $\Delta\varphi_i$.

Accordingly, the relative standard uncertainty of the magnitude of the complex transfer function is calculated as follows:

$$\frac{u_{|S_{\mathrm{UX}}|}(\omega)}{|S_{\mathrm{UX}}(\omega)|} = \sqrt{\frac{\sigma^2_{U_{out}}}{U^2_{out}} + \frac{\sigma^2_{U_G}}{U^2_G} + \frac{\sigma^2_{S_{XG}}}{|S_{XG}|^2} + \sum \sigma^2_{e_i}} \tag{21}$$

and the (absolute) standard uncertainty of the phase as:

$$u_{\varphi_{\mathrm{UG}}}(\omega) = \sqrt{\sigma^2_{\varphi_{out}} + \sigma^2_{\varphi_G} + \sigma^2_{\varphi_{XG}} + \sum \sigma^2_{\Delta\varphi_i}} \tag{22}$$

The contributions that are to be considered as $\sigma^2_{e_i}$ and $\sigma^2_{\Delta\varphi_i}$ for a measurement uncertainty calculation strongly depend on the details of the calibration set-up and the type of conditioning amplifier. The quantities σ_i^2 describe variances according to GUM. Additional information is provided in Annex A of this guideline. However, the information provided is not intended to be exhaustive.

In regard to their measurement uncertainty, the following quantities are to be considered for all calibration set-ups mentioned in the Annex:

U_{out}	measured output voltage of the calibration item
U_{G}	measured generator output voltage for excitation

$\lvert S_{XG} \rvert$	magnitude of the complex transfer factor between generator voltage (U_G) and input quantity (X_{in}) of the calibration item (frequency-dependent). For example, capacity of the reference capacitor during the calibration of the charge amplifier
φ_U	measured phase position at the output of the calibration item
φ_G	measured phase position of the generator output voltage
$\Delta\varphi_{XG}$	phase shift of the complex transfer factor between generator voltage U_G and input quantity X_{in} of the calibration item (frequency-dependent)
φ_H	phase shift due to noise and hum
φ_{res}	phase shift due to residual influences such as operating times, time dependent instabilities (jitter, filter, long-term drift of the calibration values), ambient influences (temperature, ...), etc.

The correction factors (K_i) for the different input quantities (X_i) are:

$K_{Z,in} = 1 - e^*_{Z,in}$	impedance match at the input of the calibration item,
$K_{Z,out} = 1 + e^*_{Z,out}$	impedance match at the output of the calibration item,
$K_{R,temp} = 1 + e^*_{R,temp}$	influence of the ambient temperature on the voltage ratio,
$K_{C,temp} = 1 - e^*_{C,temp}$	influence of the ambient temperature on the sensor simulation
$K_{X,temp} = 1 + e^*_{X,temp}$	influence of the ambient temperature on the calibration item,
$K_{D,C} = 1 - e^*_{D,Ca}$	influence of the drift of the sensor simulation within the calibration interval
$K_{D,AQ} = 1 + e^*_{D,AQ}$	influence due to drift of the data acquisition (DAQ) within the calibration interval,
$K_H = 1 + e^*_H$	influence of hum and noise,
$K_{res} = 1 - e^*_{res}$	influence of residual effects such as non-linearity of the voltage measurement, distortion and harmonics, etc.

5 Information to be stated in the calibration certificate

Generally, the requirements of DIN EN ISO/IEC 17025 apply when issuing the calibration certificate. In addition, the following information is to be included in the calibration certificate:

- applied method
- measurement standards used
- settings of the amplifier (sensitivity, filter, …)
- excitation amplitude used (per frequency, if necessary)
- measurement results presented in form of a table, including the following information:
    - frequency
    - input amplitude at the conditioning amplifier
    - output amplitude at the conditioning amplifier
    - magnitude of the transfer coefficient including measurement uncertainty
    - phase of the transfer coefficient including measurement uncertainty
- where appropriate, further information necessary for the correct interpretation of the measurement results

A comprehensive statement regarding the measurement uncertainty for all results may also be given elsewhere in the calibration certificate.

Note: Conditioning amplifiers with an internal, digital processing unit usually generate a significant constant time delay between input and output signal which can be observed as a linear component in the phase of the transfer coefficient. For this type of instruments and after a corresponding evaluation, this delay may also be stated as a result in the calibration certificate.

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Annex A: Amplifier-specific procedures

A 1. Voltage amplifier

Voltage amplifiers condition an input signal supplied in the form of a voltage into an output voltage. As described in Figure 4, the set-up for calibration does not include any sensor simulation.

In simplified terms, the input quantity is

$$X_{\text{in}} = U_{\text{in}} = U_{\text{G}} \tag{23}$$

and when considering the impedance conditions at the input

$$X_{\text{in}} = U_{\text{in}} = U_{\text{G}}\left(1 + Z_{\text{s}}\left(\frac{1}{Z_{\text{in}}} + \frac{1}{Z_{\text{C}}}\right)\right)^{-1} \tag{24}$$

A 2. Bridge amplifier

A 2.1 Properties of bridge amplifiers

Bridge amplifiers are used to measure (piezo-) resistive sensors in a Wheatstone bridge circuit. They represent an application-specific design of the voltage amplifiers, equipped with some additional functions (see [10]).

A bridge amplifier supplies the connected Wheatstone measuring bridge, which is formed from the four bridge resistances, with the bridge supply voltage U_{S}. The mechanical measuring quantity in the application causes a change in at least one of the bridge resistances. As a result, the symmetry of the bridge circuit is disturbed, leading to a measurement signal (U_{m}) usually lying in the millivolt range. This voltage signal acts proportionally to the change in the bridge resistances and is supplied to a symmetrical (differential) input (see [10]).

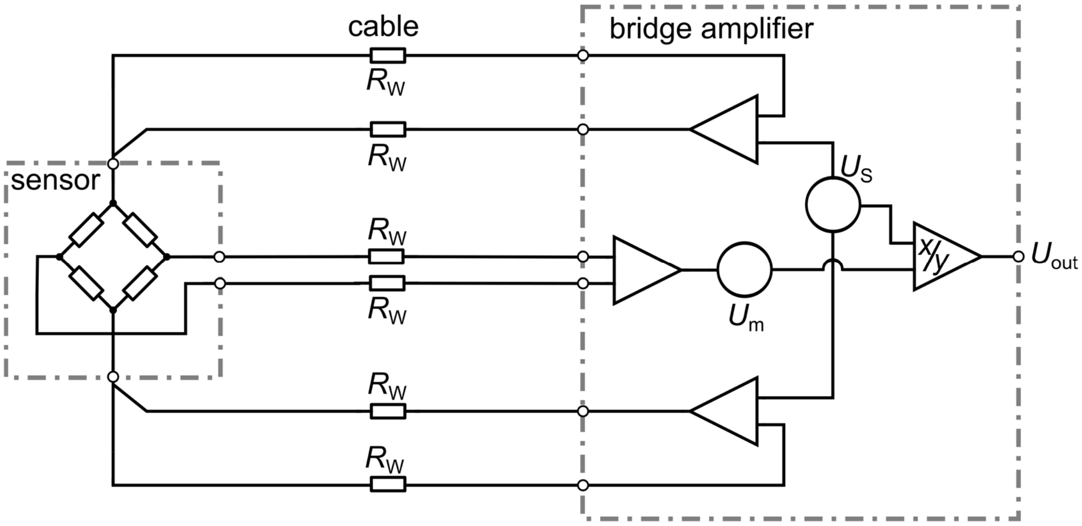

Figure 7: Principle diagram of a bridge amplifier with a sensor connected with six-conductor feedback

Basically, the input quantity of the bridge amplifier is the ratio of bridge output voltage (U_{m}) and bridge supply voltage (U_{S}), measured in mV/V. Accordingly the value of the transfer function is given in the unit mV/V. There is, however, the possibility to consider a dedicated bridge supply voltage separately. In this case the transfer function is handled in analogy to a voltage amplifier.

The bridge can be supplied both by a direct voltage and by an alternating voltage (with a carrier frequency conditioning amplifier = CF conditioning amplifier). Owing to their restricted application options for dynamic measurements, carrier frequency conditioning amplifiers are not considered here. (For more information see [11]).

An additional option to avoid deviations is the six-conductor feedback (four lines for realisation of the supply voltage and two lines for logging the measuring signal), cf. Figure 7. The supply current (I_s), which is powered by the supply voltage (U_S), causes voltage drops in the line resistors of the measuring cable (R_w); this means that the full supply voltage is no longer present at the actual bridge. This influence can be avoided by using a six-conductor feedback. For this, a further transducer line pair is also required at the two supply lines and the two measuring lines. A special control circuit in the amplifier now compensates all voltage drops in the current carrying lines. This method renders the measuring result mostly independent of the supply line resistances (e.g. caused by changed cable lengths and cross-sections).

Moreover, bridge amplifiers basically offer the possibility of a zero-signal adjustment, i.e. a corresponding parallel shift of the amplifier's characteristic curve, thus simplifying the application of this type of amplifier.

A 2.2 Calibration of bridge amplifiers

A purely static calibration of bridge amplifiers is carried out by means of voltage ratio calibrators or bridge standards that simulate the Full Wheatstone Bridge [8]. However, it is not possible to determine the frequency-dependent transfer function by means of this method.

To determine the transfer function in relation to the frequency, a sinusoidal signal generator simulates the measuring voltage (U_m). This is done by connecting the generator to the measuring input of the amplifier. The supply voltage of the conditioning amplifier should be loaded within the specifications in a sensor-like manner (cf. R_L in Figure 8). The value (quantity) of the load resistance used is to be indicated in the calibration certificate.

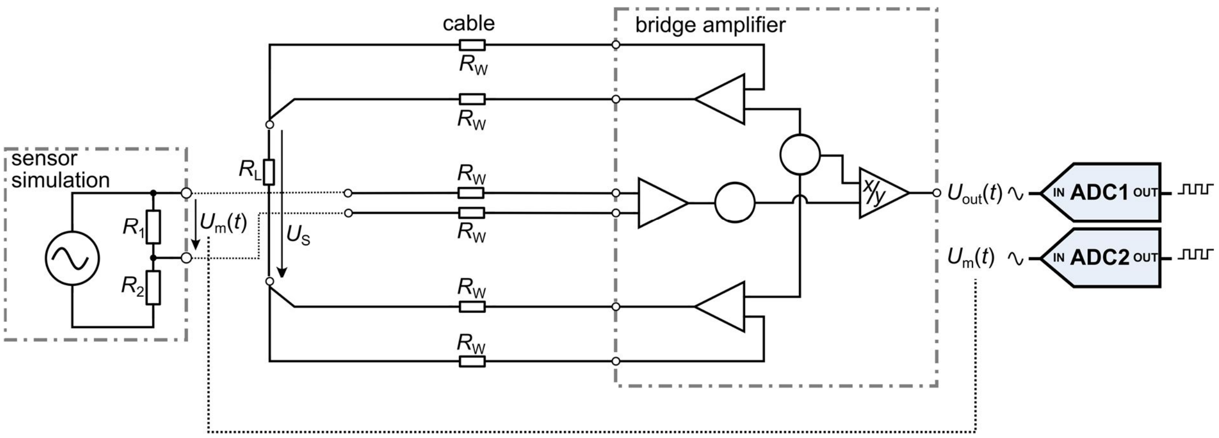

Figure 8: Set-up for the calibration of bridge amplifiers

If present, feedback lines are to be connected to the supply lines. A voltmeter measures the bridge supply voltage (U_s) at the load resistor (R_L). The applied feeding voltage is to be documented in the calibration certificate, including the nominal and the measured value.

In the simplified case, the input quantity (X_{in}) of the calibration is calculated from the ratio of generator voltage and supply voltage

$$X_{\mathrm{in}} = \frac{U_{\mathrm{m}}}{U_{\mathrm{S}}} \tag{25}$$

Considering the input impedances conditions of the bridge amplifier, the input quantity is calculated as follows

$$X_{\mathrm{in}} = \frac{U_{\mathrm{m}}}{U_{\mathrm{S}}} \cdot \left(1 + Z_{\mathrm{s}}\left(\frac{1}{Z_{\mathrm{in}}} + \frac{1}{Z_{\mathrm{C}}}\right)\right)^{-1} \quad \text{(cf. Figure 6)} \tag{26}$$

The generator signal (U_{G}) and the output voltage of the conditioning amplifier (U_{out}) are samples simultaneously. Meanwhile the constancy and stability of the supply voltage has to be ensured – irrespective of the input signal.

As an alternative to the described set-up, a so-called “dynamic bridge standard” can also be used as sensor simulation [15]. Such devices generate a dynamic measurement signal derived from the bridge supply voltage of the DUT and adjusted by a given transfer coefficient. Hence, with the use of a traceably calibrated dynamic bridge standard the acquisition of U_{m} (or $\frac{U_{\mathrm{m}}}{U_{\mathrm{S}}}$) becomes obsolete. An impedance correction might still be necessary, though.

A 3. Charge amplifiers

A 3.1 Properties of charge amplifiers

A charge amplifier is a charge-to-voltage converter, which mostly converts small charge inputs into a proportional voltage output. Due to the different input (charge) and output (voltage) quantities, this does not represent an amplifier in the strict sense of the word.

Figure 9 shows the most important components of a charge amplifier. It is equipped with an amplifier circuit whose output signal is fed back capacitively to the negative input via a highly insulating capacitor (C_{fb}). The actual realisation of the feedback circuit either results in a high-pass behaviour or a drift of the output signal. On the one hand, the drift causes a shift of the zero point during measurement. On the other hand, the drift limits the maximum measurement time as it eventually causes the amplifier to overload. An internal feedback resistor is used to counteract both effects which, in turn, results in a high-pass behaviour of the transfer function.

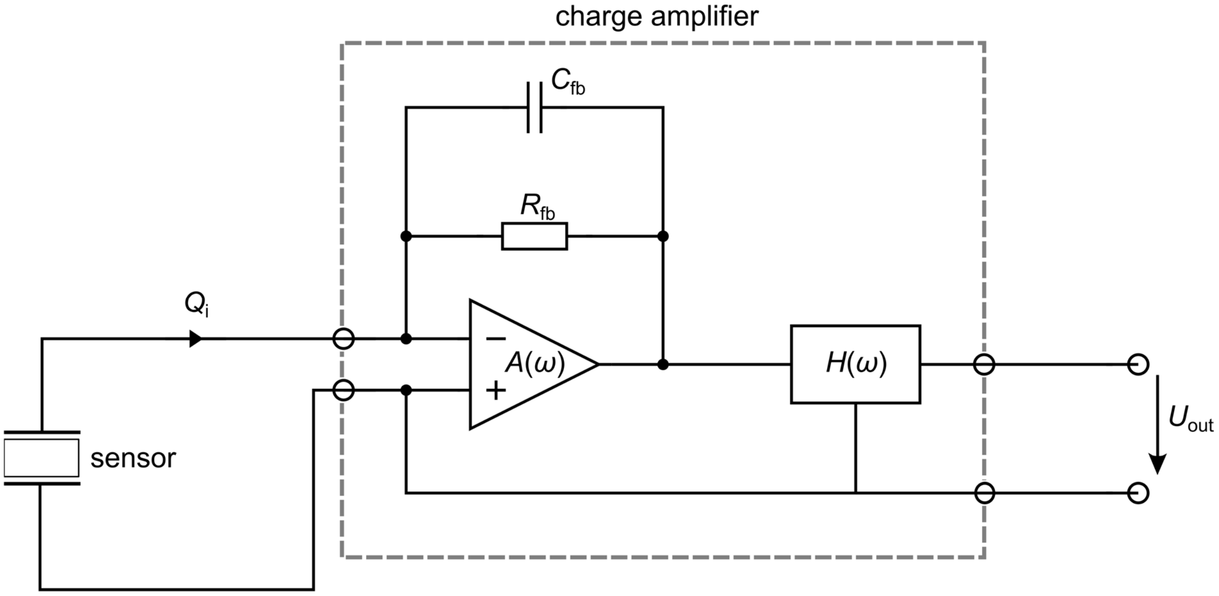

Figure 9: Schematic circuit diagram of a charge amplifier including the essential components

At high frequencies, the transfer function is usually limited by an internal downstream voltage amplifier having a frequency-dependent amplification factor $(H(\omega))$, generating a low-pass behaviour. The total response of this amplifier depends on the details of implementation and, therefore, cannot be represented in general terms.

A 3.2 Calibration of charge amplifiers

For calibration, the sensor is replaced by a traceable charge source consisting of a voltage generator ($U_{\mathrm{G}}(\omega)$) and a reference capacitor (C_{n}). The set-up can be realized in different levels of complexity depending on the measurement uncertainty requirements of the application and whether the dependence on the source impedance needs to be covered. The considered impedances are mainly of capacitive kind. The following applies:

$$Q_{\mathrm{c}}(\omega) = C_{\mathrm{n}} \cdot U_{\mathrm{G}}(\omega) \tag{27}$$

In a first order approximation, the transfer function of charge amplifiers is independent of the source impedance of the connected sensor. However, this only applies within certain limits, which in turn depend on the type of instrument and, ultimately, on the (complex) input impedance of the charge amplifier (for further details see Section A.3.2.3 and [12]). The influence of the impedance ratios at the input of the amplifier is accounted for in varying degrees in the procedures described below.

The calibration certificate must state the value of the reference capacitor used, the charge amplitude and, if applicable, the applied overall capacitance (source impedance).

A 3.2.1. Simplified method without possibility of adapting the source impedance

The reference capacitance (C_n) is to be selected in such a way that – with respect to the sensor capacitance that will later be used in connection with the charge amplifier – its influence on the calibration result can be neglected. (This is either the case when adapting the reference capacitance to the sensor capacitance or with a sufficiently low input impedance $|Z_\mathrm{i}(\omega)|$ of the charge amplifier.)

The set-up for this procedure is shown in Figure 10. A voltage generator is connected via its output (U_G) to a reference capacitor (C_n). The voltages U_G and U_out are connected to the high-impedance inputs of the measurement data acquisition system.

The input quantity for this set-up is

$$X_\mathrm{in} = C_\mathrm{n} \cdot U_\mathrm{G} \tag{28}$$

The output resistance of the voltage generator, along with the reference capacitor and the connecting cables, represents the source impedance in this set-up. To keep the influence of this impedance for subsequent sensor measurements as low as possible, the output resistance of the generator should be as low as possible (usually 50 Ω), and the reference capacitor along with the connecting cables should have a capacity comparable to that of the sensor being used later on with the charge amplifier including connecting cable (see[12]).

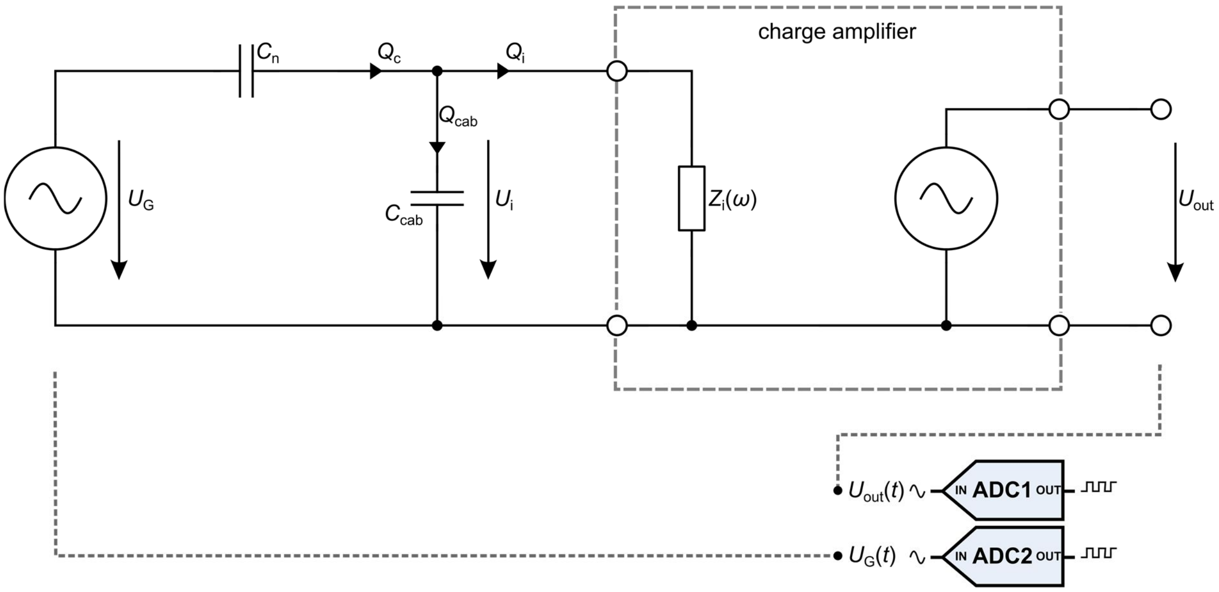

Figure 10: Set-up of the simplified procedure for the calibration of charge amplifiers

A 3.2.2. Extended method with source impedance matching

To take account of the influence of the sensor impedance on the transfer behaviour of the charge amplifier, it is possible to add an adjustable capacitance (C_{var}) – as shown in Figure 11 – to the set-up described above. The adjustable capacitance (C_{var}) is connected in parallel to the sensor simulation consisting of U_{G} and C_{n}; it adds up to the total source impedance of the set-up. However, owing to the parallel connection, it has no influence on the charge quantity generated by U_{G} and C_{n}. For the input quantity of this set-up, the following still applies:

$$X_{\mathrm{in}} = C_{\mathrm{n}} \cdot U_{\mathrm{G}} \tag{29}$$

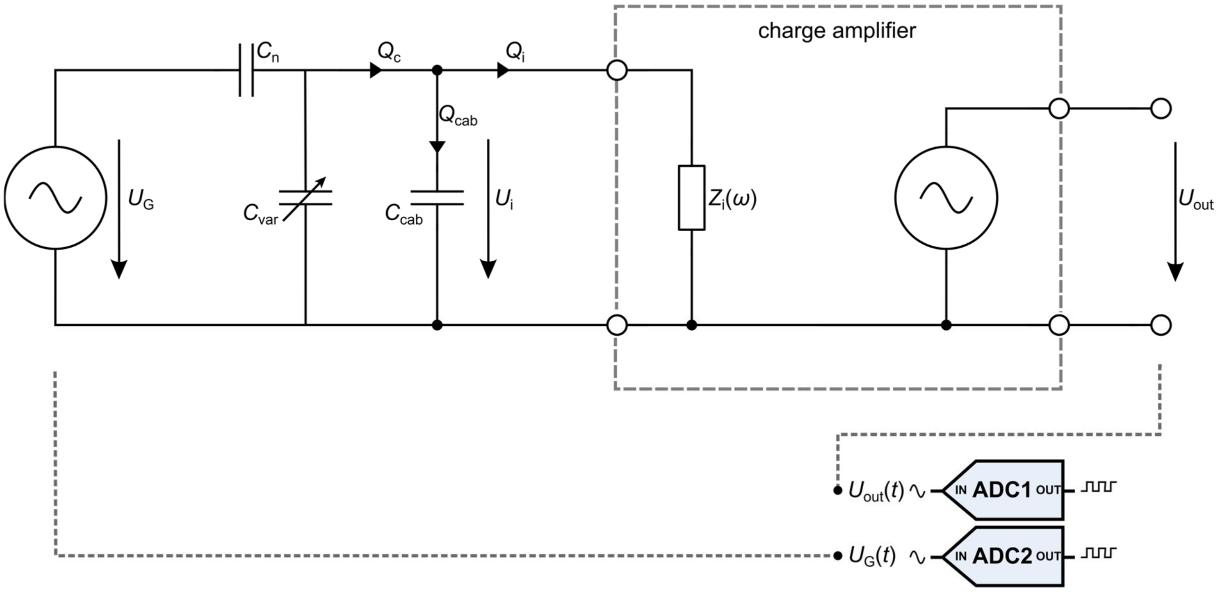

Figure 11: Variant 2 of the set-up for the calibration of charge amplifiers with fixed reference capacitance C_{n} and adjustment of the source impedance via C_{var}.

Here, the effective source impedance to be adapted to the sensor is:

$$C_{\mathrm{ges}} = C_{\mathrm{n}} + C_{\mathrm{var}} + C_{\mathrm{cab}} \tag{30}$$

The source impedances of the sensor (including its connecting cable) and of the calibration set-up can be measured by means of a suitable LCR meter (instead of the charge amplifier) and can be adapted via C_{var}. For this measurement, the generator should be substituted with a terminal resistance matching its internal output impedance.

A 3.2.3. Extended calibration with determination of the input impedance

With several measurement series according to A.3.2.2 for varying source impedances, it is possible to determine the complex input impedance (Z_{I}) of the charge amplifier and the basic transmission behaviour (S_0) as additional quantities over the measured frequency range. Thus, corrections of different source impedances or the estimation of the resulting systematic measurement error during measurement are possible.

For the input voltage of the charge amplifier U_{I}, the following applies with input charge Q_{I} and input impedance $Z_{\mathrm{i}}(\omega)$:

$$U_{\mathrm{i}}(\omega) = \mathrm{j}\omega \cdot Z_{\mathrm{i}}(\omega) \cdot Q_{\mathrm{i}}(\omega) \tag{31}$$

The following still applies for the input charge (Q_{i}):

$$Q_{\mathrm{i}}(\omega) = U_{\mathrm{G}} \cdot C_{\mathrm{n}} - U_{\mathrm{i}}(C_{\mathrm{n}} + C_{\mathrm{var}} + C_{\mathrm{cab}}) \tag{32}$$

Assuming the output voltage to be proportional to the input charge (Q_{i}), the base transfer coefficient (S_0) would be defined as:

$$S_0(\omega) = \frac{U_{\mathrm{out}}(\omega)}{Q_{\mathrm{i}}(\omega)} \tag{33}$$

With these relations and the adjustments to the impedance correction from Section 4 – and after some reformulations for the source impedance-dependent charge transfer coefficient – the following applies

$$S_{\mathrm{uq}}(\omega) = \frac{S_0(\omega)}{1 + \mathrm{j}\omega Z_{\mathrm{i}}(\omega)(C_{\mathrm{n}} + C_{\mathrm{var}} + C_{\mathrm{cab}})} \tag{34}$$

The quantities of interest for the calibration are now $S_0(\omega)$ and $Z_{\mathrm{i}}(\omega)$, which describe the amplifier as a whole.

Considering the reciprocal value of equation (34), a linear regression can be performed by means of several independent measurements of $S_{\mathrm{uq}}(\omega)$ for different values of the variable capacity C_{var}. The regression line (for a frequency ω) is given as

$$\frac{1}{S_{\mathrm{uq}}(\omega)} = \frac{1}{S_0(\omega)} + \frac{Z_{\mathrm{i}}(\omega)}{S_0(\omega)} \mathrm{j}\omega(C_{\mathrm{n}} + C_{\mathrm{var}} + C_{\mathrm{cab}})\ , \tag{35}$$

which means it has the axis intercept $\frac{1}{S_0(\omega)}$ and the slope $\frac{Z_{\mathrm{i}}(\omega)}{S_0(\omega)}$. Since these are complex quantities, real and imaginary part must be fitted separately. This results in the two equations:

$$\mathrm{Re}\left(\frac{1}{S_{\mathrm{uq}}(\omega)}\right) = \mathrm{Re}\left(\frac{1}{S_0(\omega)}\right) - \mathrm{Im}\left(\frac{Z_{\mathrm{i}}(\omega)}{S_0(\omega)}\right) \omega(C_{\mathrm{n}} + C_{\mathrm{var}} + C_{\mathrm{cab}})\ , \tag{36}$$

$$\mathrm{Im}\left(\frac{1}{S_{\mathrm{uq}}(\omega)}\right) = \mathrm{Im}\left(\frac{1}{S_0(\omega)}\right) + \mathrm{Re}\left(\frac{Z_{\mathrm{i}}(\omega)}{S_0(\omega)}\right) \omega(C_{\mathrm{n}} + C_{\mathrm{var}} + C_{\mathrm{cab}}), \tag{37}$$

$S_{\mathrm{uq}}(\omega)$ is to be calculated according to equations (11), (12) and (13) as a complex quantity of the form

$$S_{\mathrm{uq}}(\omega) = \left|S_{\mathrm{uq}}(\omega)\right| \cdot \mathrm{e}^{\mathrm{j}\varphi_{\mathrm{uq}}} \tag{38}$$

By means of the substitutions $r = \mathrm{Re}\left(\frac{1}{S_0(\omega)}\right)$ and $l = \mathrm{Im}\left(\frac{1}{S_0(\omega)}\right)$ for the axis intercepts and a somewhat complex arithmetic, it follows that:

$$S_0(\omega) = \frac{r}{(r^2 - l^2)} - \mathrm{j}\frac{l}{(r^2 - l^2)} \tag{39}$$

or as magnitude and phase:

$$|S_0(\omega)| = \sqrt{\frac{r^2 + l^2}{(r^2 - l^2)^2}} \qquad \text{(magnitude)} \tag{40}$$

$$\varphi_0(\omega) = \arctan\left(-\frac{r}{l}\right) \qquad \text{(phase)} \tag{41}$$

By means of the substitutions $s = \mathrm{Re}\left(\frac{Z_\mathrm{i}(\omega)}{S_0(\omega)}\right)$ and $t = \mathrm{Im}\left(\frac{Z_\mathrm{i}(\omega)}{S_0(\omega)}\right)$ for the slope of the regression it then follows:

$$\mathrm{Re}\big(Z_\mathrm{i}(\omega)\big) = s \cdot \frac{r}{(r^2 - l^2)} + t \cdot \frac{l}{(r^2 - l^2)} \tag{42}$$

$$\mathrm{Im}\big(Z_\mathrm{i}(\omega)\big) = t \cdot \frac{r}{(r^2 - l^2)} - s \cdot \frac{l}{(r^2 - l^2)} \tag{43}$$

A 4. IEPE Amplifiers

A 4.1 Properties of IEPE Amplifiers

IEPE amplifiers are used for conditioning piezoelectric sensors with integrated charge converter which require a constant supply current of 2 mA to 20 mA to supply the charge converter in the sensor. This is a widely accepted industrial standard, especially for force, acceleration, pressure and strain sensors. Irrespective of the manufacturer, these IEPE sensors (Integrated Electronics Piezo-Electric) are also referred to as CCLD sensors (Constant Current Line Drive). Alternatively – and depending on the manufacturer – they are referred to by protected trade names such as Deltatron, Piezotron, Isotron, ICP or others. Though exhibiting minor differences, they all adhere to the same principle. So far, there is no common industry standard describing this analogue interface.

Figure 13 shows the basic operating principle of an IEPE amplifier with connected sensor. Basically, an IEPE conditioning amplifier consists of an (AC) voltage amplifier and an upstream constant current source (to supply the charge converter located in the sensor). This constant current source supplies a constant current (I_Bias) of at least 2 mA; typically, however, it is 4 mA. However, higher currents up to 20 mA may be required to operate capacitive loads (e.g. long cables). With some measuring amplifiers it is possible to adjust or even switch off the constant current. Depending on the output impedance of the connected sensor and the level of the supply current, a DC voltage is generated on the signal cable. This DC voltage is referred to as bias voltage (U_Bias). In case of an oscillation at the sensor, the AC output voltage of the sensor additively superimposes the bias voltage (U_Bias) (Figure 16). To decouple the AC voltage from the bias voltage, usually an RC high-pass filter (decoupling capacitor and load resistor) is embedded into the input stage of the conditioning amplifier. Some IEPE amplifiers offer manual or automatic DC voltage compensation of opposite polarity. The advantage consists in having a very low cut-off frequency or a transmission capability of the conditioning amplifier down to 0 Hz.

Typically, the input of these amplifiers is asymmetrical (single ended). The input measuring range covers the bias voltage plus a signal amplitude of typically 5 V. However, there are also amplifiers with symmetrical (differential) input and output stages, especially for industrial purposes or other specific requirements.

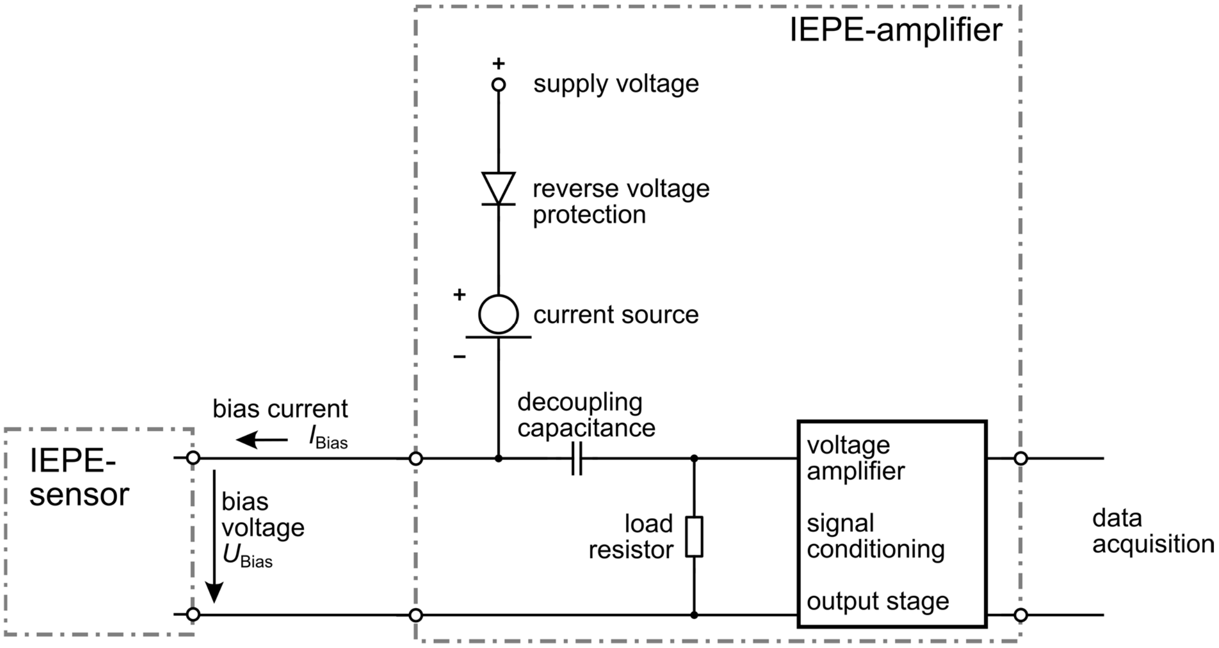

Figure 12: Principle of an IEPE amplifier with an HP filter for decoupling the open-circuit (bias) voltage

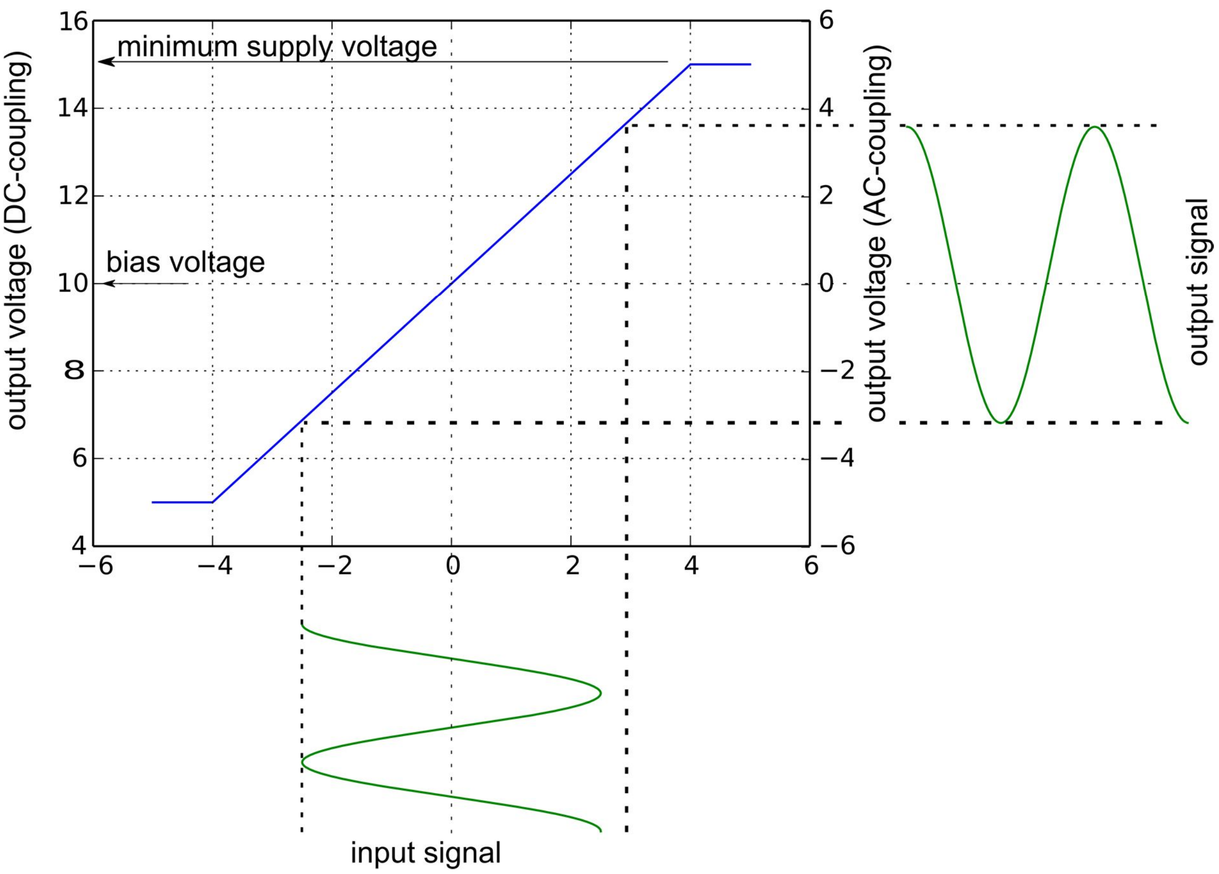

Figure 13: Illustration of the operating principle of an IEPE measuring chain

For some years now, IEPE measuring amplifiers have also been available in a mixed analogue mode (for the measuring signal) and in a digital mode (for the sensor data), following the IEEE 1451-4 standard (Transducer Electronic Datasheet, TEDS). To switch into the digital mode, the amplifier changes the polarity of the supply current. This may affect the signal quality at the time of the polarity change. Usually, the amplifier will switch to digital mode for only a short time when detecting a change of sensor.

A 4.2 Calibration of IEPE Amplifiers

When calibrating an IEPE measuring amplifier, the bias current should be switched off. Should this not be possible, the constant current supplied to the generator can be diverted by a suitable circuit to protect the generator and to avoid potential measurement errors. For that, two variants subsequently called variant A and variant B have been established. The basic set-up is shown in Figure 14.

To determine the transfer function, the voltages U_{in} and U_{out} must be measured. It should be taken into account that with active bias current, the input signal (U_{in}) contains a relatively high DC voltage (U_{Bias}). If the generator voltage (U_{G}) is used as input variable for calculating the transfer coefficient, the transfer function of the high-pass filter arrangement (variant a) and the IEPE sensor simulation (variant b) must be known. In the frequency range of the calibration, it may not significantly influence the measurement result; alternatively, the measurement result must be corrected.

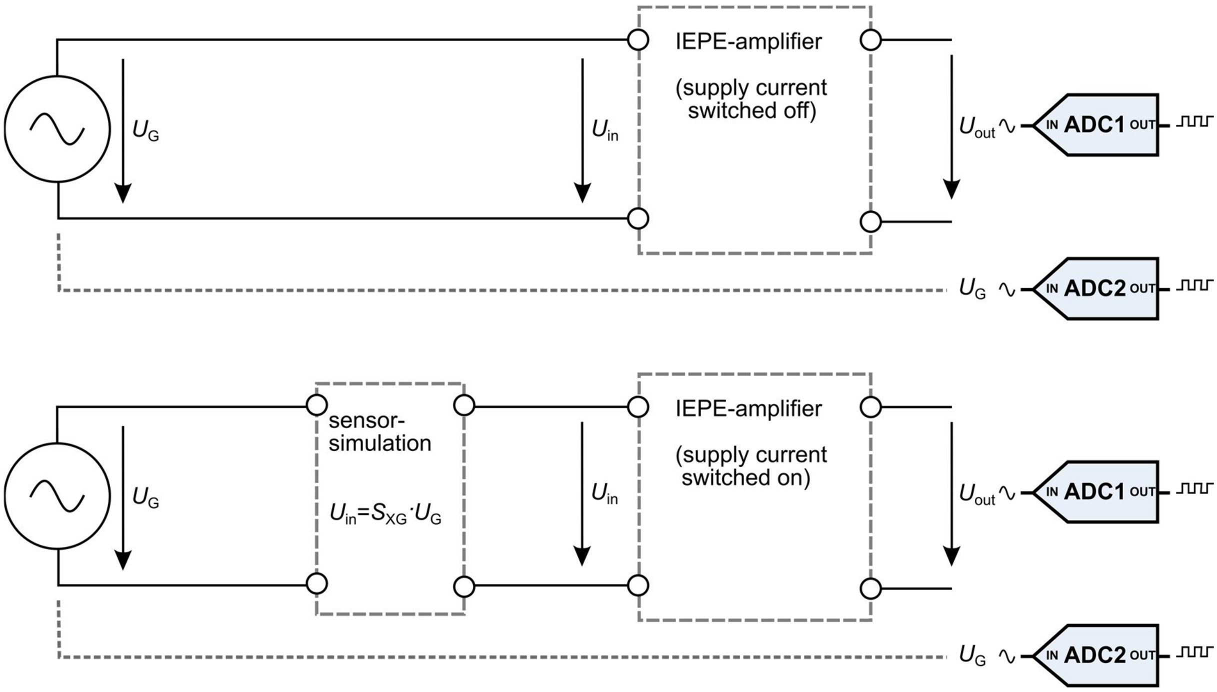

Figure 14: Calibration arrangement for IEPE amplifiers without bias current (top) and with bias current and corresponding sensor simulation (bottom)

Figure 14 shows the calibration arrangements for amplifiers having a supply current with cut-off option (top) or with persistent supply current and corresponding sensor simulation.

In a simplified case, the following applies to the arrangement with switched-off supply current:

$$X_{\mathrm{in}} = U_{\mathrm{in}} = U_{\mathrm{G}} \tag{44}$$

Considering the impedance ratios at the amplifier input, this becomes:

$$X_{\text{in}} = U_{\text{in}} = U_{\text{G}} \cdot \left(1 + Z_{\text{s}} \left(\frac{1}{Z_{\text{in}}} + \frac{1}{Z_{\text{C}}}\right)\right)^{-1} \quad \text{(cf. Figure 6)} \tag{45}$$

If the amplifier does not offer a cut-off option for the sensor supply current, a corresponding sensor simulation with the transfer function S_{XG} is to be connected between generator and amplifier. Hence, the following applies in the simplified case:

$$X_{\text{in}} = U_{\text{in}} = S_{\text{XG}} \cdot U_{\text{G}} \tag{46}$$

Considering the impedance ratios at the amplifier input, the following applies:

$$X_{\text{in}} = U_{\text{in}} = S_{\text{XG}} \cdot U_{\text{G}} \cdot \left(1 + Z_{\text{s}} \left(\frac{1}{Z_{\text{in}}} + \frac{1}{Z_{\text{C}}}\right)\right)^{-1} \quad \text{(cf. Figure 6)} \tag{47}$$

A 4.3 Examples of IEPE sensor simulations

A 4.3.1. *Use of a 1st order high-pass filter*

An RC circuit creating a first-order high pass is inserted between generator and amplifier input, see [13]. Figure 15 depicts its realisation.

The capacitor C_1 (C1) is used to block the supply current from the generator, while the resistor R_1 (R1) adjusts the open-circuit voltage of approx. 10 V (for instance, 2,7 kΩ at 4 mA). The time constant of this RC circuit determines the lower limiting frequency of the calibration set-up. To obtain a low limiting frequency, a capacitor (electrolyte or bipolar electrolyte) of considerable capacity should be used. When using C_1 = 330 µF and R_1 = 2,7 kΩ, the limiting frequency is approximately 0,18 Hz. The proof voltage of the capacitor should be at least 30 volts.

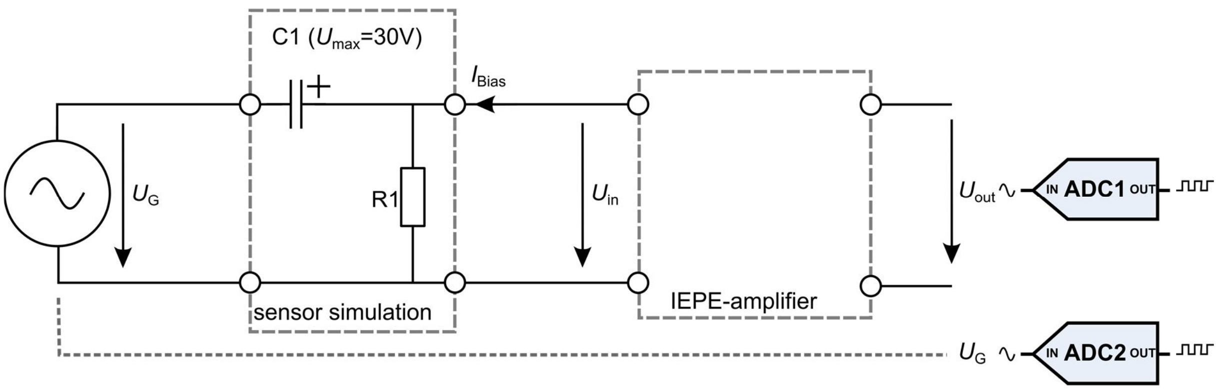

Figure 15: IEPE sensor simulation with high-pass filter

A 4.3.2. Use of a high-pass filter with impedance conversion

A high-pass filter of first order in sequence with a source follower as impedance converter is applied to decouple the generator from the amplifier. The components R1 and R2 as well as the field-effect transistor (FET, PMOS enhancement type) are used to adjust the open-circuit voltage (U_{BIAS}).

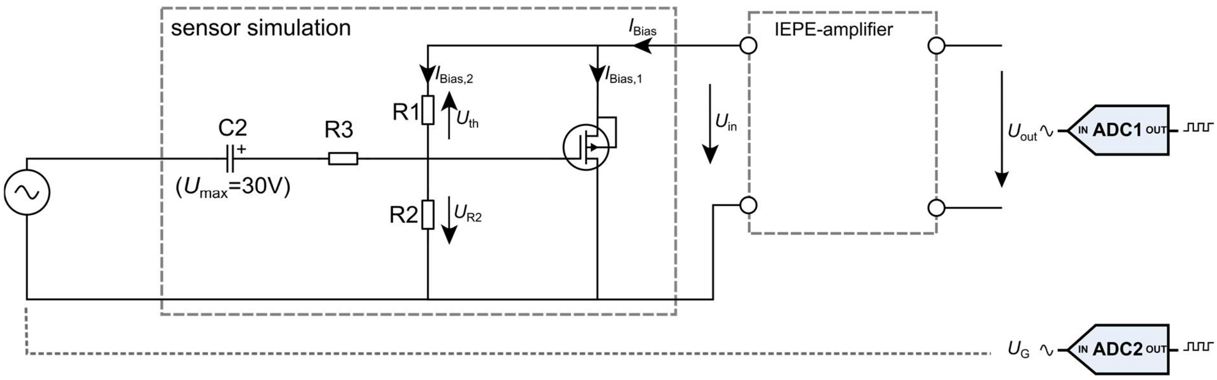

Figure 16: IEPE sensor simulation with high-pass filter and impedance matching

An advantage of this circuit is the almost constant bias voltage that is realized despite of different supply currents given by different amplifiers or settings. The IEPE amplifier is kept at a defined operating point. The setting of the bias voltage is realised merely via the threshold voltage (U_{th}) of the FET, and via the resistors R_1 and R_2. U_{th} is practically independent of the supply current and generates a current ($I_{\text{Bias,2}}$) which results in a voltage drop (U_{R2}) along the resistor R_2. For an open-circuit voltage of approx. 10 V and when using a FET, type NDS0610 with U_{th} = –1,7 V, the resistors are to be selected as follows: R_1 = 910 kΩ and R_2 = 4,0 MΩ. For other open-circuit voltages, the resistances can be calculated by converting the following equation:

$$U_{\text{Bias}} = \frac{R_1 + R_2}{R_1} \cdot U_{\text{th}} \tag{48}$$

The resistor R_3 = 10 kΩ protects the gate from excessive current pulses and may be omitted.

Because of the high-impedance resistor R_2, the lower cut-off frequency of the circuit can be set at very low frequencies. With a capacitance of approx. C_2 = 3,3 µF and R_2 = 4 MΩ, the cut-off frequency is approx. 0.01 Hz. Thus, this kind of the sensor simulation is also suitable for calibrations at very low frequencies.

A 5. Inline charge voltage converters

A 5.1 Properties of inline charge voltage converters

Inline charge-to-voltage converters supplement piezoelectric sensors with charge output by providing the electronics required for operation with an IEPE amplifier. Therefore, they can be considered as active charge-to-voltage converters supplied by a constant current.

A 5.2 Calibration of inline charge voltage converters

For calibration purposes, they may be regarded as an IEPE sensor simulation. As in section A 3, a charge source is required for the input and a known IEPE amplifier is required at the output to determine their complex transfer function (S_{UQ}) (cf. Figure 17).

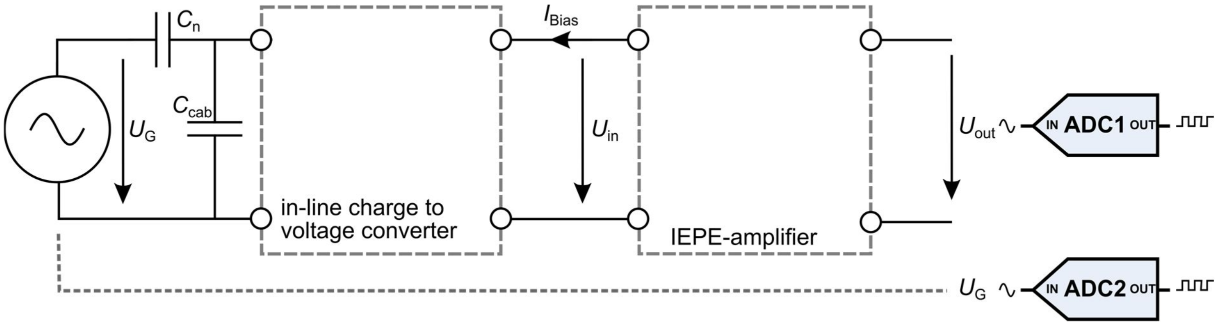

Figure 17: Set-up for the calibration of an in-line charge-to-voltage converter using a known IEPE amplifier

For the simplified case, the input quantity for calculating the transfer function is

$$X_{\mathrm{in}} = C_{\mathrm{n}} \cdot U_{\mathrm{G}} \tag{49}$$

For the consideration of all input and source impedances please refer to the section on charge amplifiers.

In this case, the output quantity for the transfer function differs from the previous considerations

$$U_{\mathrm{in}} = S_{\mathrm{UU}}{}^{-1} \cdot U_{\mathrm{out}} \tag{50}$$

with S_{UU} being the well-known complex transfer factor of the IEPE amplifier used. The transfer function is then calculated as follows

$$S_{\mathrm{UQ}} = \frac{U_{\mathrm{in}}}{C_{\mathrm{n}} \cdot U_{\mathrm{G}}} = \frac{U_{\mathrm{out}}}{S_{\mathrm{UU}} \cdot C_{\mathrm{n}} \cdot U_{\mathrm{G}}} \tag{51}$$

Its determination is possible both by measuring U_{out} by means of a calibrated IEPE amplifier and by direct measurement of U_{in}. In the latter case it should be noted that U_{in} is superimposed by a comparatively high bias voltage.

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