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THE INFLUENCE OF SOURCE IMPEDANCE ON CHARGE AMPLIFIER

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Abstract: This contribution discusses the influence of the source impedance on the complex sensitivity of a charge amplifier (CA). During calibration of a CA with varying source impedances deviations at higher frequencies were observed, which if not properly taken into account may generate systematic errors beyond the limits of the measurement uncertainty budget. The contribution discusses a model to describe the effect as well as an extension to established CA calibration procedures which allow to quantify and correct the effect.

Keywords: charge amplifier, calibration.

1. INTRODUCTION

The calibration of charge amplifiers is usually performed with a setup similar to figure 1.

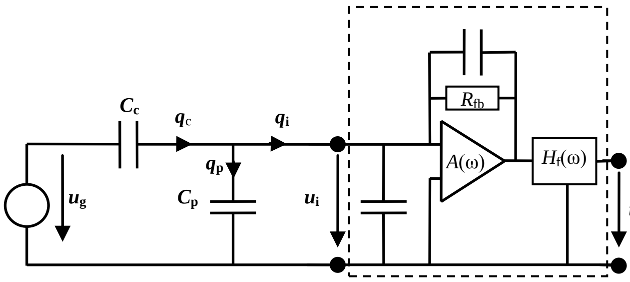

Figure 1: Schematic of a charge amplifier calibration setup

The sensor is replaced by voltage source generating $u_g(t)$ and a standard capacitor of a well known value C_c. By assuming u_i to be negligible, paralleled capacities C_p are ignored and the input charge is $q_c = q_i = u_g \cdot C_c$, resulting in the formula for the complex transfer function:

$$S_{uq}(\omega) = \frac{u_a}{u_g C_c} \qquad (1)$$

Calibrations at NMIs and accredited laboratories of charge amplifiers performed with different standard capacitors $C_{c1,2,\ldots,x}$ in a range from 10 pF to 2000 pF showed up significant systematic differences of $S_{uq1,2,\ldots,x}$ with increasing frequency and lead to the general conclusion, that at higher frequencies the burden voltage u_i could no longer be ignored and the total source impedance build by the sensor or calibration setup including cables as seen by the charge amplifier have to be regarded. The diagram 1 show the relative amplitude error and absolute phase error for six

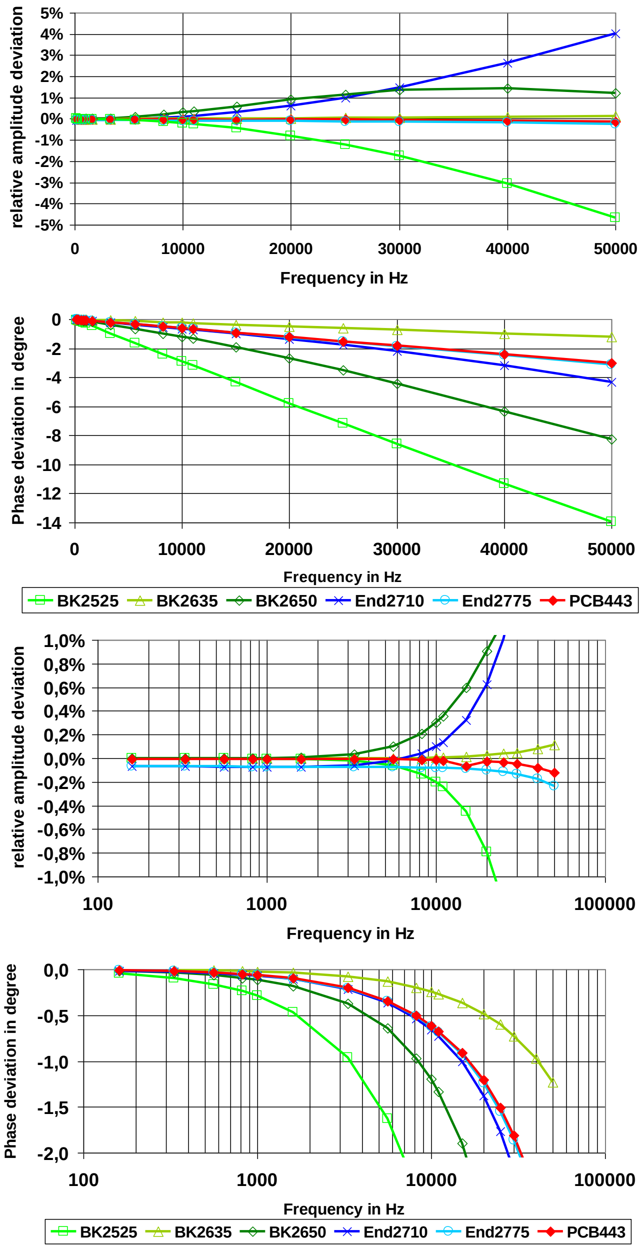

Diagram 1: Relative amplitude error and absolute phase error of the sensitivity $S_{uq}(\omega)$ for different charge amplifiers calibrated with C_c+C_p =100 pF+120 pF and sourced with a impedance of C_s = C_c+C_p =1920pF. The two lower graphs show the same data in different scaling.

charge amplifiers calibrated with a 100 pF standard capacitor and sourced with a 1920 pF impedance, quite well representing an Endevco Type 2270 transducer including the connecting cable. By using a 1000 pF capacitor for calibration the systematic deviation still will be about the half. [1]

The sensitivity to source impedance of a CA is mainly determent by the first amplifier stage, its feedback network and the surrounding input protection circuit.

2. MODELING THE CHARGE AMPLIFIER

For further analyses the charge amplifier with its unknown circuit details is regarded as a black box with an complex, frequency dependent input impedance $A_i(\omega)$ and charge coupled voltage source $S_0(\omega)$ as shown in figure 2.

$S_0(\omega)$ can be interpreted as the transfer function of the charge amplifier when driven by an ideal charge source.

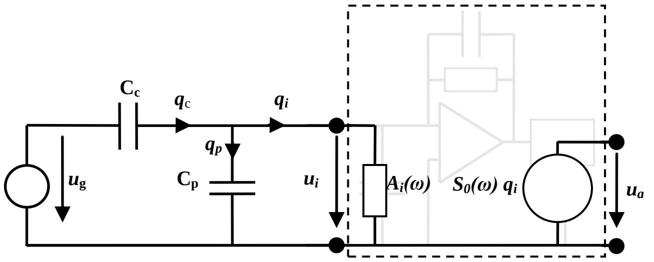

Figure 2: Simplified charge amplifier model

Where the output voltage is

$$u_a = S_o(\omega)\cdot q_i \qquad (2)$$

and the input burden voltage

$$u_i = A_i(\omega)\cdot \dot{q}_i = j\omega\cdot A_i(\omega)\cdot q_i\,. \qquad (3)$$

for $q_i = \hat{q}_i \cdot e^{j\omega t+\varphi_i}$.

Kirchhoff's laws leads to

$$q_c = q_i + q_p \qquad (4)$$

$$q_c = (u_g - u_i)C_c \qquad (5)$$

$$q_p = u_i C_p \qquad (6)$$

(5) ,(6) in (4):

$$q_i = u_g C_c - u_i(C_c + C_p) \qquad (7)$$

From the ‚traditional' calibration (1) we know :

$$u_g C_c = \frac{u_a}{S_{uq}(\omega)} \qquad (8)$$

With the total source impedance $C_s=C_c+C_p$ and including (2),(3) and (8) in (7) results in:

$$\boxed{S_{uq}(\omega) = \frac{S_0(\omega)}{1 + j\omega\cdot A_i(\omega)\cdot C_s}} \qquad (9)$$

One important conclusion of (9) is, that if the source impedance C_s is constant , the transfer functions S_{uq} will be the same, and for a given sensor-cable impedance a charge amplifier calibration setup can be matched by adding an appropriate C_p for a given (smaller) calibration capacitor C_c.

3. MEASURED RESULTS

To determine the characteristic values $S_0(\omega)$ and $A_i(\omega)$ of a charge amplifier, formula (9) is rewritten in the form:

$$\frac{1}{S_{uq}(\omega)} = \frac{1}{S_0(\omega)} + j\omega\cdot\frac{A_i(\omega)}{S_0(\omega)}\cdot C_s \qquad (10)$$

enabling a linear complex fit for measured S_{uqx} with varying C_{sx}.

C_{sx} was build from three different calibrated standard capacitors $C_{c1,2,3}$ of 10 pF, 100 pF and 1000 pF (GenRad Type 1404-A,B,C) and a variable capacitor GenRad Type 1422-D in parallel to the cable providing an adjustable C_p in the range of about 270 pF to 1400 pF .The total source impedance was measured by shortcutting u_g and measure C_s at the connector to the amplifier using a HP4274A LCR meter.

S_{uq} was measured using a PXI-System with an NI-PXI 5422 16 bit signal generator applying sine signals and a two channel NI-PXI-5922 24 bit digitizer with a NI-PXI-5900 differential preamplifier to simultaneous capture u_g and u_a. Each measurement was taken twice with swapped input channels to cancel differences in the channel amplification and group delay. The major remaining uncertainties in this setup are the nonlinearities of the PXI-5922/5900 at modulus frequencies for ratio measurements $u(u_a/u_g)<60$ ppm ([1],[2]), the uncertainty of the standard capacitor $u(C_c)<20$ ppm and the charge amplifier noise. The overall expanded uncertainty is estimated to be less than 200 ppm. The uncertainty of the total source impedance measurement $u(C_s)$ is less critical and the impact to the sensitivity uncertainty is about 2 orders smaller than $u(C_c)$. An uncertainty of $u(C_s) \leq 0.5\%$ is still sufficient for an $u(S_{uq}) \leq 200$ppm.

For each frequency the reciprocal measured complex S_{uq} is split into real and imaginary part and a linear least square fit with the total source impedance C_s as the independent variable was applied.

Diagram 2 shows the reciprocal real and imaginary of $S_{uq}(\omega)$ from the most sensitive to C_s amplifier (BK2525). Each line represent 8 measurements at one frequency. The relative mean squared errors of the fits are smaller than 10^{-5} indicating the validity of the proposed model.

Two measured $S_{uq}(\omega)$ where made at C_s=1300 pF .One used the C_{c1}=10 pF and the second used the C_{c3}=1000 pF. The resulting S_{uq} difference is shown in diagram 3. The increase to 50kHz indicate a slight mismatch of Cs of about 3 pF. For the BK2635 CA and PCB443 CA no differences greater the standard deviation of the measurements ($\sigma \leq 5\cdot 10^{-5}$) were observed and are another proof of (9).

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[1] The legend indicate brand and type of the CA investigated, however the results represent individual devices and might not be representative for the type of CA.

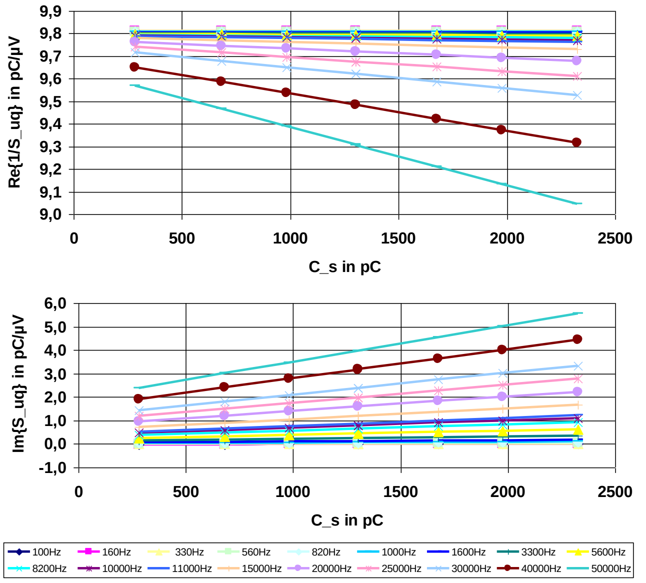

Diagram 2: The real and imaginary inverse of $S_{uq}(\omega)$ for various source impedances C_s

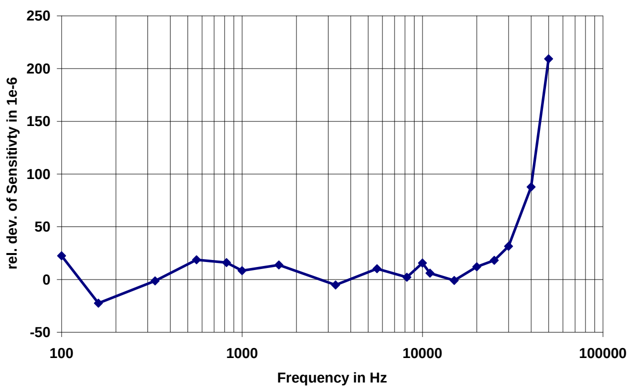

Diagram 3: Deviation of two calibrations with C_{c1}=10pF and C_{c3}=1000pF where the total source impedance is matched to C_s=1300(3) pF.

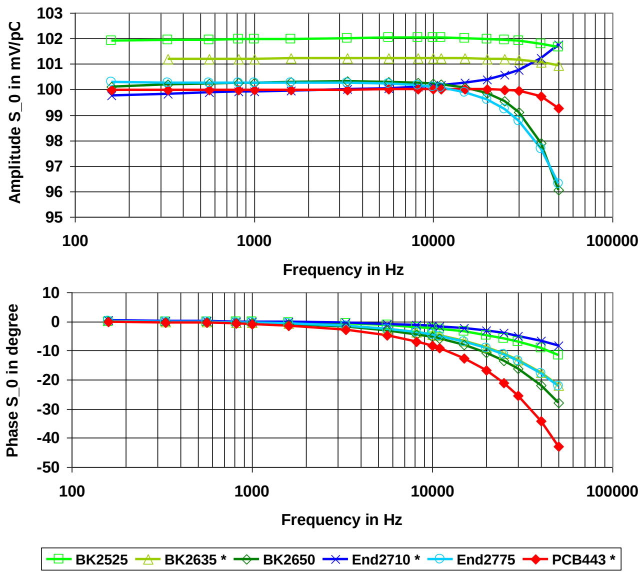

Diagram 4: Amplitude and phase of $S_0(\omega)$ of six CA. The phase of marked CAs is shifted 180° for comparision.

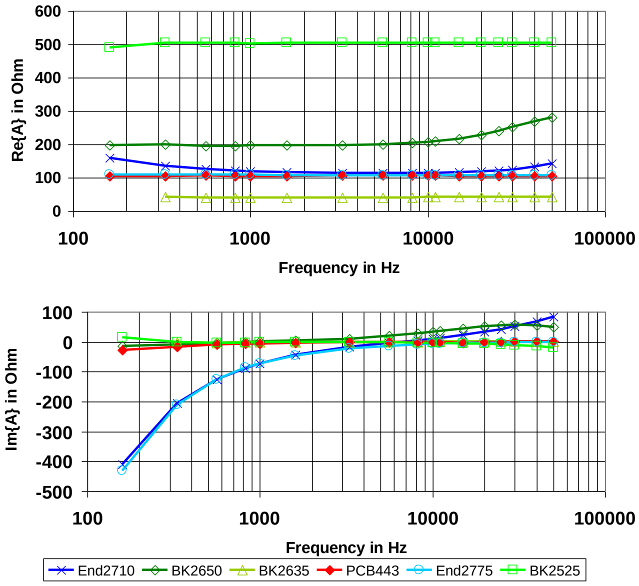

Diagram 5: Re{Ai}and Im{A_i} of the complex input impedance $A_i(\omega)$ of six different charge amplifiers.

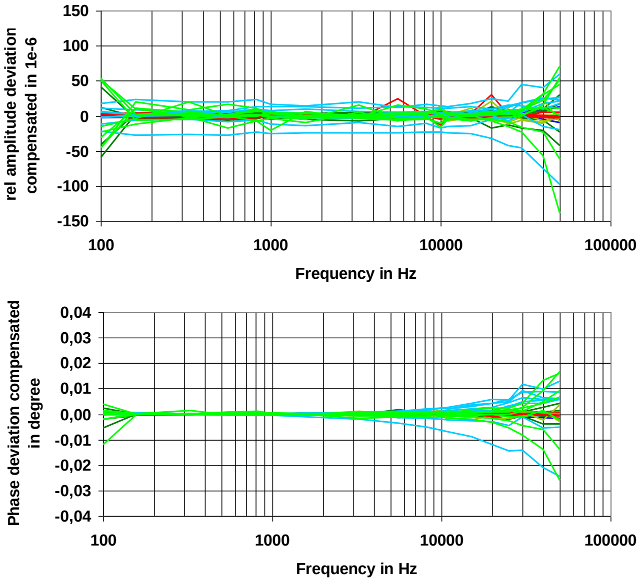

Diagram 6: Amplitude and Phase deviations of $S_{uq}(\omega)$ after compensation, All CAs, 280 pF ≤ Cs ≤ 2300 pF

Diagram 4 show the amplitude and phase of $S_0(\omega)$. Amplifiers marked with an asterisk are phase shifted by 180 degree for better comparison. The real and imaginary part of the complex input impedance $A_i(\omega)$ in Ohm for the CAs investigated are shown in diagram 5. While the ideal charge amplifier would have an input impedance of A_i = 0 Ohm, resulting in a independence of source impedance, the real world amplifiers investigated have input impedances ranging from 45 Ohm up to 500 Ohm. With $S_0(\omega)$, $A_i(\omega)$ and the known source impedance and applying formula (9) the influence of the source impedance to the transfer function $S_{uq}(\omega)$ can be compensated. Diagram 6 show the remaining deviations after compensation of all 6 CA with source impedances from 280 pF to 2300 pF, in a frequency range from 100 Hz to 50kHz, 648 measurements in total. The values underlay the conservative estimation of a u($S_{uq}(\omega)$)< $2\cdot10^{-4}$

4. CONCLUSION

The sensitivity of charge amplifiers to source impedance variations can be measured and explained with high confidence by the model in Fig. 2.

By characterising the charge amplifier with the transfer function $S_0(\omega)$ and its input impedance $A_i(\omega)$ it is now possible to compensate this effect.

For calibrations of charged based sensors with lowest possible uncertainty the charge amplifier as the key linking element to the data acquisition is usually calibrated before and after the sensor calibration. To avoid systematic deviations these charge amplifier calibrations should be performed with a source impedance matching the sensor impedance. A procedure that is common practice in our laboratory now.

5. ACKNOWLEDGMENT

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6. REFERENCES

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