DESIGN FOR SELF-CALIBRATION OF INSTRUMENTATION

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Abstract: Self-calibration is one of most important methods for improving the measuring accuracy and system reliability with lower costs. The applications of the self-calibrated measuring methods is based on the design for self-calibration of instrumentation. In this paper a self-calibration orientated design of measuring instruments and systems are proposed to simplify and optimize the development and applications in the practice. System structures and design criteria are proposed to improve the error correct-ability of the measuring systems. Self-calibrated measuring systems for measurement of electrical and geometric quantities are given as examples in details.

Keywords: Self-calibration, System design, Fault-tolerant measurement

1 INTRODUCTION

Recently, Self-calibrated Measuring Methods (SCMM) have been developed to improve the measuring accuracy and system reliability with relative low costs [1 to 11]. These methods can be applied not only to the measurement of electrical quantities but also to measurement of mechanical and geometric quantities and so on. They are one of the best solutions of the problems between the measuring accuracy, system reliability, and manufacturing and use costs. Therefore more attention must be paid for the further development and applications of these measuring methods.

A very important development for the applications of the SCMM is the Design for Self-Calibration (DFSC) of instrumentation. Measuring instruments and systems should be designed according to the principle of the self-calibrated measuring methods, so that the self-calibration of the measuring systems can be easily realized in the practical uses.

For this purpose system structures must be modified to fulfill the requirements of the self-calibrated measuring methods. New design criteria are needed to optimize the measuring systems.

2 DESIGN FOR SELF-CALIBRATION

A self-calibration orientated design, by which a measuring system is constructed according to the principle and criteria of the self-calibrated measuring methods (SCMM) [1,4,5], can be defined as Design for Self-Calibration (DFSC).

In a self-calibrated measuring method the input/output relation of a measuring system is directly determined by the *self-calibration algorithm* with the use of the *internal reference quantities and elements*, and the measuring errors are self-corrected by the corresponding *signal and data processing algorithms*, and the system and functional faults are self-detected by the *self-diagnosis*, so that the measuring system is made *tolerant* towards the errors of the system components [1,4,5].

The design for self-calibration aims at the structure guarantee of the system fault detect-ability and diagnostic ability on one side, and self-compensation of systematic and random errors on other side. The self-calibration algorithms are supported by special hardware components (low-cost reference elements [4,5]).

The self-detection enables the measuring systems to self-detect system faults before and during the measurement and to fulfill the condition for further self-localization of the system faults. A system self-calibration is carried out only when the measuring system is faultless. Therefore the self-detection of system faults forms the fundamentals for ensuring the reliability of the self-calibrated measuring systems. The fault detection is normally realized by software with the use of the measurement of a reference quantity and the self-calibration data.

The random errors of measuring systems can be reduced only by effective data processing methods, e.g., averaging and smoothing, etc. Therefore the measuring systems have at least a short-term stability for the data acquisition. The signal-noise-ratio must be improved by the design. One of methods is using the addition structure and a offset quantity or elements [1,4,5,9,11].

The short-term stable systematic errors are self-compensated by the self-calibrated measuring methods with the use of long-term stable reference quantities and special algorithms. For the design the selection of reference quantities and elements and self-calibration methods and algorithms plays an important role for realizing a high measuring accuracy.

The following criteria characterize the Design for Self-Calibration:

- using standard measuring instruments to reduce the costs of measuring systems
- using the same kind of simple references to simplify the calculation and to reduce the costs
- using linear measuring circuits to obtain a high measuring accuracy easily
- simplifying the system structure to improve the system reliability and repeatability
- using more signal and data processing, etc.

Figure 1 shows a self-calibrated measuring instrument. For system calibration the reference quantities X_{rk} (k=1, 2, 3) are selected. The selected signal is added with the offset quantity X_s and the noises X_n. The combined quantity X_i is sampled by the data acquisition unit. The sampling data are processed by averaging and smoothing, etc., to reduce the noises. After the data processing the measuring values are calculated by corresponding model. The measuring values X_{osrk} (k=1, 2, 3) consist of the measuring values X_{ork} of the references and the measuring value X_{os} of the offset.

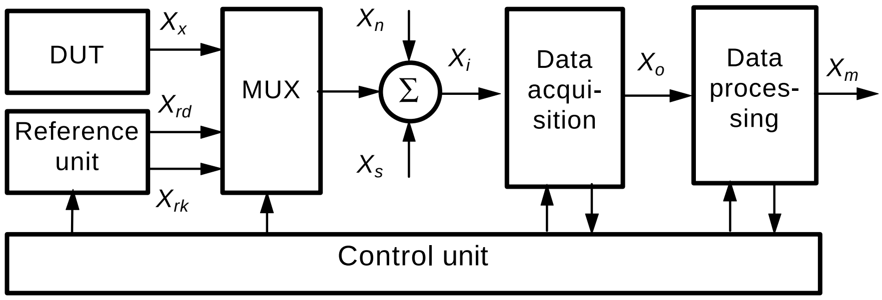


Figure 1. Self-calibrated measuring instrument (DUT: Device Under Test, MUX: Multiplexer)

For measurement the measuring quantity X_x is switched to the addition circuitry. The combined quantity with the offset and noises is measured in the same way. Similarly, the measuring value X_{osx} is composed of the measuring value X_{ox} of the measuring quantity and the value X_{os}.

The measuring result X_m can be then calculated by corresponding self-calibration model using the reference data X_{rk} and the measuring values X_{osrk} and X_{osx}. The *linear interpolation* can be used for the calculation of two references self-calibration, while the *quadratic interpolation* is suitable for the three references self-calibration [1,4,5,8], so that the offset value X_{os} can be compensated automatically (see Table 1).

Table 1. Linear and quadratic interpolated self-calibration

Methods	References	Measured values	Calculation models	Conditions
Linear Interpolated Self-Calibration (LISC)	X_{r1}, X_{r2}, X_s	X_{osr1}, X_{osr2}, X_{osx}	$X_x = W_{12} X_{r1} + W_{21} X_{r2}$ with $W_{ij} = \frac{X_{osx} - X_{osrj}}{X_{osri} - X_{osrj}}$ i,j=1,2, i^1j	$X_{r1} \le X_x \le X_{r2}$ $X_s < X_x$
Quadratic Interpolated Self-Calibration (QISC)	X_{r1}, X_{r2}, X_{r3} X_s	X_{osr1}, X_{osr2}, X_{osr3}, X_{osx}	$X_x = W_{123} X_{r1} + W_{231} X_{r2} + W_{312} X_{r3}$ with (i,j,k=1,2,3; i^1j, i^1k) $W_{ijk} = \frac{(X_{osx} - X_{osrj})(X_{osx} - X_{osrk})}{(X_{osri} - X_{osrj})(X_{osri} - X_{osrk})}$	$X_{r1} \le X_x \le X_{r3}$ $X_{r1} < X_{r2} < X_{r3}$ $X_s < X_x$

Any system faults are detectable in the self-calibrated measuring system [1,5,10]. This function is realizable by the diagnosis channel. The signal noise ratio can be improved by adding the offset quantity X_s, especially for measuring quantities with small value.

Figure 2 shows a further example of self-calibrated measuring system. This system is designed on the base of a computer-controlled measuring system composed of N standard measuring instruments. The principle is the same like the self-calibrated measuring instrument shown in Figure 1.

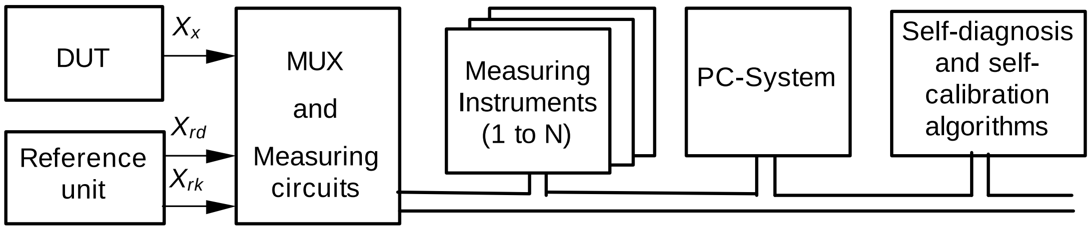


Figure 2. Self-calibrated measuring system based on a computer-controlled measuring system

3 EXAMPLES

Example 1 is related to the design of a self-calibrated measuring system for small capacities (Figure 3) [1]. Two reference capacities C_{r1} and C_{r2} are used for the self-calibration of the measuring system. If the transfer functions G_{r1}, G_{r2} and G_x are measured by a digital oscilloscope (e.g. hp 54601A), the capacity values C_{or1}, C_{or2} and C_{ox} can be determined according to the measuring values of the transfer functions. The measuring result of the capacity C_x of the DUT is calculated by using the linear interpolation (see Table 1):

$$C_x = \frac{G_x - G_{r2}}{G_{r1} - G_{r2}} C_{r1} + \frac{G_x - G_{r1}}{G_{r2} - G_{r1}} C_{r2} \tag{1}$$

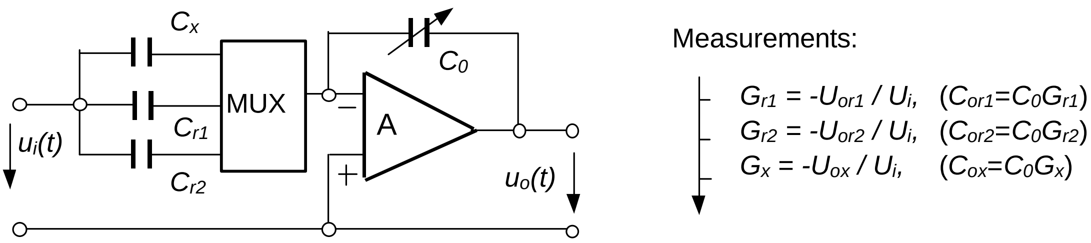
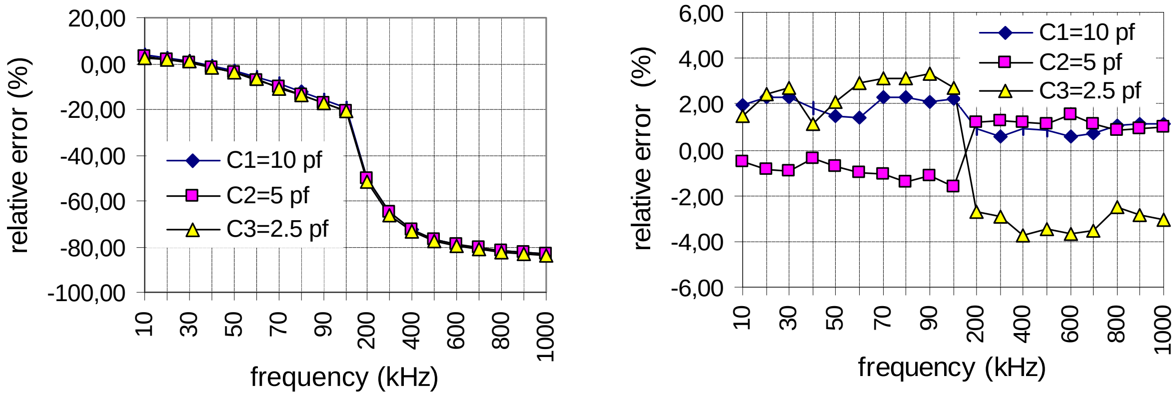


Figure 3. Small capacity measuring system using the Linear Interpolated Self-Calibration (LISC)



(a) original measuring error (b) measuring error after self-calibration

Figure 4. Accuracy improvement of small capacity measurement using the LISC

Figure 4 shows clearly an improvement of the capacity measuring accuracy using the LISC method according (1). Without the self-calibration the original measuring system has a frequency dependent phase measuring error caused by the reduced input impedance of the voltmeter in relative high frequencies. Therefore the capacity measuring values are deviated strongly from the nominal values. The errors are considerably reduced by the self-calibration using two reference capacitors. A measuring error < ± 4% is realizable for measuring small capacities in pf-range.

Example 2 shows admittance/impedance measurement of dielectric materials under high electrical intensities [1,4,9]. For generating a high measuring voltage a amplifier is used in the measuring system (Figure 5). The offset resistor R_s serves for the system safety in the case that the impedance Z_x of the DUT is too low and the test voltage is too high. A adapter is composed of two resistors R_s and R_0. An excess voltage can be reduced by the adapter in order to avoid the damage of the used voltage measuring instrument.

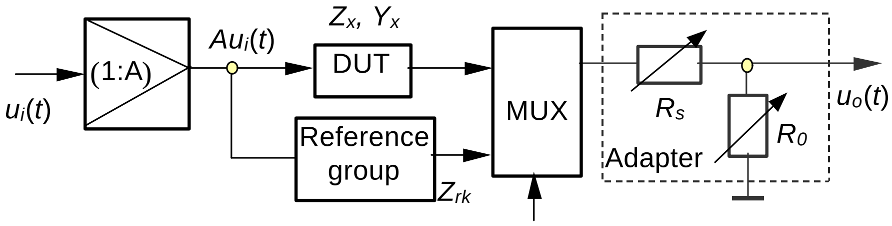


Figure 5. Measuring and safety circuit for admittance/impedance measurement under high electrical intensities using self-calibrated algorithm [1]

Two reference impedance (resistors or capacitors) Z_{rk} (k=1,2) are used for the self-calibration. The transfer functions for the self-calibration $G_{ork}(jw)$ and for the measurement $G_{ox}(jw)$ can be determined by the Fourier Series if the input and output signals $u_i(t)$ and $u_o(t)$ are sampled by a digital oscilloscope (e.g. hp 54601A). The corresponding impedance values are calculated by [1]

$$\begin{cases} Z_{ox}(jw) = \dfrac{AR_0}{G_{ox}(jw)} - (R_0 + R_s) \\ Z_{ork}(jw) = \dfrac{AR_0}{G_{ork}(jw)} - (R_0 + R_s) \end{cases} \qquad (k=1,\ 2) \qquad (2)$$

According to the linear interpolated self-calibration (see Table 1) the impedance $Z_x(jw)$ is written by

$$Z_x(jw) = \frac{Z_{ox} - Z_{or2}}{Z_{or1} - Z_{or2}} Z_{r1} + \frac{Z_{ox} - Z_{or1}}{Z_{or2} - Z_{or1}} Z_{r2} = \frac{G_{ox} - G_{or2}}{G_{or1} - G_{or2}} \frac{G_{or1}}{G_{ox}} Z_{r1} + \frac{G_{ox} - G_{or1}}{G_{or2} - G_{or1}} \frac{G_{or2}}{G_{ox}} Z_{r2} \qquad (3)$$

The offset error and constant relative error of the measurements can be self-compensated by (3) for calculating the impedance $Z_x(jw)$ of the DUT.

Example 3 deals with transfer function measurement by self-calibration. Figure 6 shows a self-calibrated measuring system using standard measuring instruments for the transfer function measurement of analog systems.

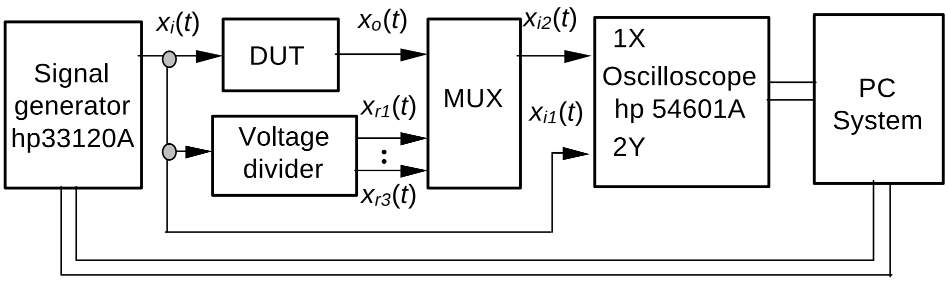


Figure 6. Transfer function measuring system using standard measuring instruments

Voltage dividers using precise resistors are used in this system for the self-calibration of the transfer function measurement. The signal generator provides the test signal $x_i(t)$ on one side and the reference signals by the voltage divider on other side. The signals are sampled by the oscilloscope.

Figure 7 shows an accuracy improvement of an analog circuit using the self-calibration compared with the *non-self-calibration* (NSC). The errors of the self-calibration is much less than the original errors.

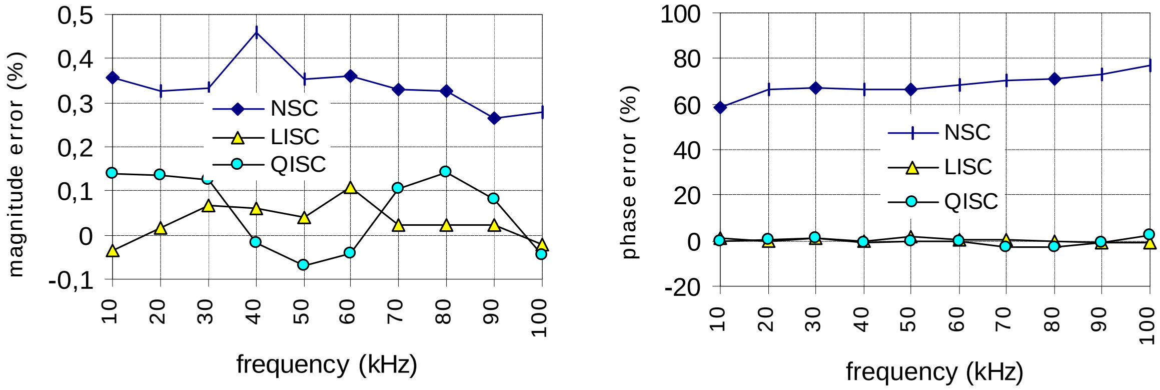


Figure 7. Measuring errors of the self-calibration compared with original errors (NSC)

Example 4 shows a self-calibrated measuring system (Figure 8) for examining length and distance transducers (e.g. optic, inductive and magnetic transducers).

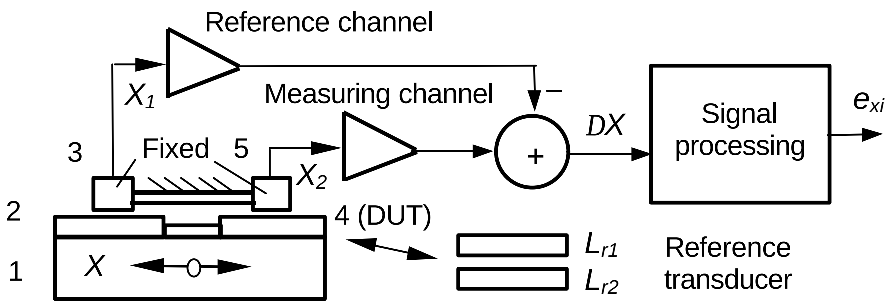


Figure 8. Measuring system for examining length and distance transducers (1: movable table, 2: transducer I, 3: detector I, 4: transducer II (DUT) , 5: detector II)

In this measuring system reference and measuring channels are used to realize a difference measurement between transducer system I (2 and 3) und transducer system II (4 and 5). The distance X of the moving table is measured by the reference and measuring channels at the same time. The two signals X_1 und X_2, which depend on X, form a difference signal DX_{oi} at the *i-th* sampling point

$$DX_{oi} = X_{2i} - X_{1i} \qquad (i=1, 2, \ldots, N) \qquad (4)$$

where N denotes the number of measuring points. From this difference signal the errors of the measuring transducer are derivable.

To compensate the errors of the measuring system two reference transducers L_{r1} and L_{r2}, the errors e_{r1i} and e_{r2i} of which are measured by a laser interferometer in advance, are used for the self-calibration. The errors of the measuring transducer can be determined by the linear interpolation:

$$e_{xi} = \frac{DX_{oxi} - DX_{or2i}}{DX_{or1i} - DX_{or2i}} e_{r1i} + \frac{DX_{oxi} - DX_{or1i}}{DX_{or2i} - DX_{or1i}} e_{r2i}, \quad (i=1, 2, \ldots, N) \qquad (5)$$

where DX_{oxi} and DX_{orki} are measured values of the measuring transducer (DUT) and reference transducers L_{r1} and L_{r2}. Both reference transducers should be so selected that their errors e_{r1i} and e_{r2i} are obviously different each other in order to avoid the case DX_{or2I} -DX_{or1i}=0. This can be realized by using transducers from different classes.

4 CONCLUSIONS

The design for self-calibration is applied to the measuring accuracy improvement of electrical and geometric quantities. From the analysis and measured results we can draw the following conclusions:

- The Design for Self-Calibration (DFSC) of Instrumentation is very useful for applications of the self-calibrated measuring methods to practical measurements.

- The measuring accuracy and the system reliability can be easily improved by the DFSC. The costs of the measuring instruments and systems can be reduced by the DFSC using standard self-calibration hardware and software.
- The development of standard reference quantities and elements supports the DFSC. A successful design for self-calibration is based on achievable, technical easily realizable and cost-favorable reference quantities and elements.
- Fast signal sampling and data processing methods and systems should be developed for the DFSC in order to reduced the measuring time in the self-calibrated measuring systems.

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