Investigations on measurement control and signal processing for the pressure reciprocity calibration of microphones

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Introduction

The realization of the unit of sound pressure is done by determining the open-circuit pressure sensitivity of laboratory standard microphones using the reciprocity technique with microphones coupled in pairs by means of cylindrical couplers. If the transmitter microphone *i* is acoustically coupled to the receiver microphone *j*, the product of their open-circuit pressure sensitivities $M_i \cdot M_j$ will be

$$M_i \cdot M_j = \frac{U_j}{I_i \cdot Z_{ac}} \tag{1}$$

where

Z_{ac} is the acoustical transfer impedance of the coupling,

U_j is the open-circuit output voltage of the receiver microphone, and

I_i is the current through the transmitter microphone.

The ratio between U_j and I_i is called *electrical transfer impedance.* [1]

$$Z_{e_{ij}} = \frac{U_j}{I_i} \tag{2}$$

Measurement of electrical transfer impedance

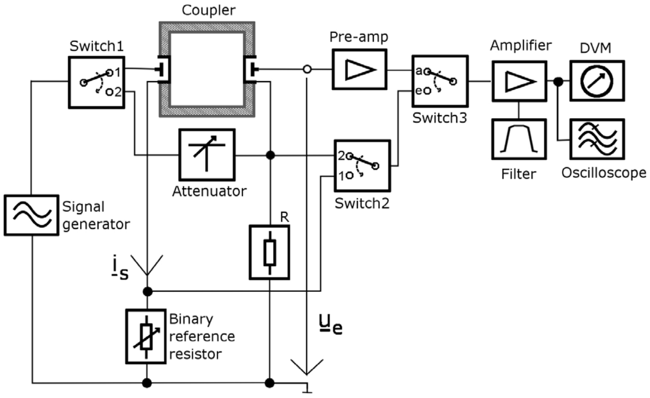

Figure 1: Schematic diagram of the set-up for measuring the electrical transfer impedance of a microphone-coupler-microphone system [2].

The set-up for the measurement of the electrical transfer is shown in Figure 1. A computer-controlled binary step-by-step resistor is used as reference. This resistor is adjusted by means of a four-step procedure such that its resistance is approximately equal to the electrical transfer impedance [2].

It can then be calculated as

$$Z_{e_{ij}} = R_{ref} \cdot \frac{u_1 \cdot u_3}{u_2 \cdot u_4} \tag{3}$$

where

R_{ref} is the resistance of the reference resistor after the adjustment, and

u_x are the voltages measured by the digital voltmeter during the four steps.

The quotient in eq. (3) expresses the quantization error of the attenuator and the resolution of the binary reference resistor.

Each step requires an alternating voltage to be measured as precisely as possible with a minimal input of time. An important prerequisite for this is a reliable and robust detection of signal stability. The voltages are affected by acoustical and electrical interference as well as by drift and transients.

Signal stability check

Existing concept

A five-element ring memory was used for the evaluation of voltage readings from the digital voltmeter (DVM). After the memory had been initially filled in the beginning of an averaging series, the following stability criteria were continuously checked:

- "No drift": Four consecutive readings are not strictly monotonically decreasing/increasing
- The relative standard deviation of the arithmetic mean of the readings is within the limit of 0,01 %.

As soon as these criteria were met three times, the measurement was considered as valid and the mean value of the five ring memory elements was defined as the result of the voltage measurement.

A detailed analysis of the performance of this concept revealed several problems of the algorithms used. Especially drift detection with noisy signals and identification of global stability did not work out as well as reliably as desired. Furthermore, certain conditions could lead to lock-out state and endless averaging loops which could only be manually stopped by the operator.

Optimized concept

Therefore, new improved criteria were developed in order to

- detect transients and drift, even with noisy signals,

- exclude instable readings from averaging, and
- reliably detect global stability.

For the detection of noise and other stochastic interference the relative standard deviation of the mean has proven to be a robust and reliable criterion. Therefore, it was maintained in the optimized concept.

On order to detect drift, transients and similar disturbances, however, a CUSUM (cumulative sum) criterion was introduced which sums the differences between the recent mean value $\bar{x}_i$ and the recent reading x_i over all readings. This criterion mainly detects changes of the mean and does not regard stochastic interference. As soon as a systematic change of the signal occurs the CUSUM will differ from zero. Because the direction of this change is not important for a stability check, only the absolute value of the CUSUM is used. For better comparison with the relative standard deviation of the mean, the relative CUSUM according to (4)

$$CUSUM_{rel} = 100\,\% \cdot \left| \frac{\sum_{i=1}^{n} (\bar{x}_i - x_i)}{\bar{x}_i} \right| \qquad (4)$$

was chosen.

The five-element ring memory was replaced by a storage of a variable number of readings, the minimal number being five.

The two criteria were calculated, each over the whole number of stored readings, and evaluated by means of "control charts", as known from statistical process control [3] (see Figure 2). These charts contain two limits: a warning limit and an upper limit. Depending on the behavior of the criteria within the control chart ranges the averaging is controlled according to the following rules:

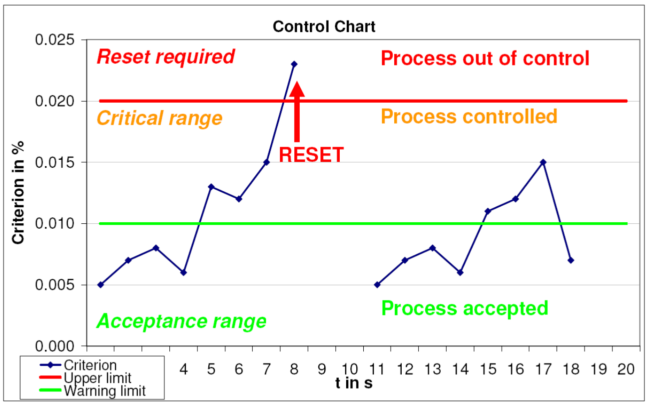

Figure 2: Control chart. The left part of the figure shows a process which initially enters the critical range and subsequently causes a reset of the averaging. In the right part the process returns to the acceptance range after having entered the critical range.

- Inside the acceptance range the process is considered to be stable and the averaging is completed.
- If the warning limit is exceeded, but the upper limit is not exceeded, the averaging is continued until the process returns to the acceptance range.
- If the upper limit is exceeded, i.e. the process is "out of control", the averaging is reset and restarted.

There are two independent control charts for the two criteria. Each of them can cause an averaging reset, and the averaging will be completed as soon as both criteria are within the acceptance ranges.

The control chart limits were determined by numerical simulation with real measurement data and were validated by check measurements (see Table 1).

	Relative CUSUM	Relative standard deviation of mean
Warning limit	0,01 %	0,01 %
Upper limit	0,03 %	0,02 %

Table 1: Limits for the control charts

Conclusions

The implementation of robust and stable signal statistics considerably enhanced the performance of the PTB measurement system for the electrical transfer impedance. By applying a multi-level adaptive statistical process control procedure, a fast assessment of the number of averages required for a given uncertainty and a reliable elimination of disturbances were achieved.

In addition, concepts for a modified reference resistor control were analyzed with respect to the resulting measurement uncertainty. These concepts aimed at a reduction of the reference resistor steps used for the measurement in order to minimize the traceability effort. By means of a GUM workbench [4] model it was discovered that the reduction of resistor steps resulted in a slightly increasing uncertainty. This investigation provided useful knowledge for further improvements of the measurement procedure.

References

[1] IEC 61094-2, Electroacoustics – Measurement microphones, Part 2: Primary method for the pressure calibration of laboratory standard microphones by the reciprocity technique, IEC, 2009.

[2] Wargowske, J., Fedtke, T., Richter, U., Ein rechnergesteuerter Messplatz zur Darstellung und Weitergabe der Schalldruckeinheit Pascal. DAGA 1995, 639-642.

[3] Bassville, M., Detection of abrupt changes – Theory and application. First edition, Prentice-Hall Inc., 1993.

[4] METRODATA, GUM Workbench, www.metrodata.de