

VECTORIAL IMPEDANCE METER FOR GAS CHEMICAL ANALYSIS

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Abstract: In this paper two digital correction techniques are presented aiming at enhancing the measurement accuracy of an electronic nose. The equipment operates as a vectorial impedance meter in the frequency range 0-15 MHz. The digital correction techniques allow compensating for the conditioning electronic response. Linear behaviour is assumed, cross-talk, amplitude and phase distortions are accounted for by a black box two-ports model. The model parameters are evaluated either with a set of measurements, spanning the whole frequency range, and by a single measurement by exploiting autoregressive (ARX) models.

Keywords: Impedance measurement, black-box model, Autoregressive model.

1 INTRODUCTION

Multisensor arrays are an emerging concept in the area of chemical sensors and analysis of gases and liquid solutions. Their working principle relies on the combination of several, e.g. 10, sensors, each one with a different response but with only a moderate selectivity toward the distinct chemical species to be detected. The pattern of the response signals, e.g. 10 different conductivities, is therefore characteristic for a given chemical species or mixture, and can be analyzed using modern processing techniques such as artificial neural networks. This approach has many advantages with respect to conventional chemical analysis, because a relatively small number of sensors can be used to detect an even unexpected large number of different compounds, and the proper analytical identification can be done by suitable signal processing and data treatment using computer programs.

Commercial and experimental chemical multisensor array systems are based on different kinds of chemical sensors such as metal oxide sensors, polymeric sensors etc.. Tin dioxide (SnO_2) sensors are a popular choice. These sensors change their conductivity at 200-400°C in the presence of volatile organic compounds (VOCs), give reproducible results over years, and are now widely used in gas monitoring applications. Their use in a multisensor array requires, however, an improvement of their selectivities. In the literature some innovative measurement techniques to obtain a selectivity enhancement have been recently proposed, among which the evaluation of sensor impedances [1, 2]. In fact it has been shown that by operating the sensors with different frequencies, different conduction mechanisms can be separated, hence the interaction with different chemical mixture results in different responses.

In the present contribution a multisensor electronic nose [3] that can operate as a vectorial impedance meter is presented. It allows to perform measurements with an array of up to 16 elements by evaluating sensors' impedances in a frequency range spanning from DC to 15 MHz. The system is fully software controllable and reconfigurable. The system accuracy is enhanced by digital correction techniques: to this purpose two different alternative approaches are exploited. The first one is a traditional approach based on the measurement of the instrument response at a set of different frequencies. This approach is very accurate but it is also time-consuming. An alternative approach, which results less accurate but faster, is the instrument response identification by injecting two broadband, uncorrelated stimuli, and by modelling the measurement system with an ARX model. In this paper the two different techniques are presented and compared.

2 SYSTEM OVERVIEW

A block diagram of the system is shown in fig.1. The headspace is designed to guarantee reproducible chemical conditions. The conditioning electronics performs amplification and multiplexing. Sensor signal acquisition can be performed either by a commercial acquisition board (National Instrument PCI-MIO16E1) or by a digital oscilloscope (Tektronix TDS754D with GPIB interface) depending on the frequency range selected for measurements. Sensor voltage excitation can be provided by the acquisition board or by a signal generator (HP 33120A with GPIB interface). Data processing is performed by the PC. Signal conditioning is performed by two different boards, one of which is placed in the headspace ('front-end electronics' in fig. 1). The second signal conditioning

board ('signal conditioning' in fig. 1) is interfaced to the DAC card, to the instruments and to the front-end card.

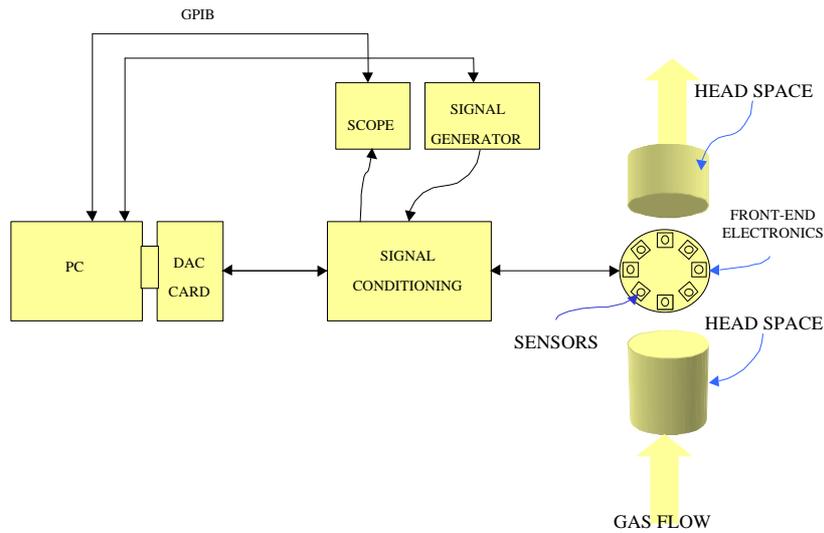


Figure 1. System block diagram

3 DIGITAL CORRECTION TECHNIQUES

A voltage divider is used to estimate Z_x (sensor impedance) from the ratio between the input voltage V_1 and the voltage V_2 across a reference impedance Z_p (see fig.2).

The sensor impedance Z_x can be obtained by the following relationship:

$$Z_x = R_x + j X_x = Z_p \cdot \left(\frac{|V_1| e^{j j_1}}{|V_2| e^{j j_2}} - 1 \right) = Z_p \cdot \left(\frac{|V_1|}{|V_2|} \cdot e^{j \Delta j} - 1 \right) \quad (1)$$

where j_1 and j_2 are the phases of V_1 and V_2 respectively, and $\Delta j = j_1 - j_2$.

V_{1m} and V_{2m} (see fig. 2) are the acquired signals at the output of the electronic conditioning system (grey box in fig.2). The two signal paths were designed to have an identical frequency response so that, nominally, $V_{1m} = K V_1$, $V_{2m} = K V_2$, and Z_x can be obtained by replacing V_1 and V_2 in eq.(1) with V_{1m} and V_{2m} respectively. Actually, the complexity of the system made it difficult to avoid both crosstalk and asymmetries, which produce performance degradation in the phase assessment when the described procedure is applied. Such degradation was recovered by a digital correction of the phase measurements. For this purpose a 'black box' model, based on the 'two port networks' theory, was preferred to a circuit model, which would have required the estimation of multiple non-independent parasitic parameters. The model used for the transfer function of the impedance meter between each sensor and the oscilloscope or the DAQ board is sketched in Fig. 2.

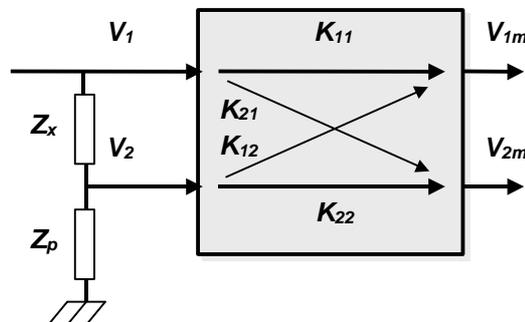


Figure 2. 'Black box' model

The digitized signals (V_{1m}, V_{2m}) can be seen as the outputs of a linear two port system where inputs are the signals (V_1, V_2).

The following linear relations model the system behavior in the frequency domain:

$$\begin{cases} V_{1m} = K_{11}V_1 + K_{12}V_2 \\ V_{2m} = K_{21}V_1 + K_{22}V_2 \end{cases} \quad (2)$$

Coefficients K_{11} and K_{22} account for the signal path asymmetries, and coefficients K_{12} and K_{21} account for the crosstalk between paths. The sensor impedance Z_x can be evaluated by using the following relationship:

$$Z_x = R_x + j X_x = Z_p \cdot \left(\frac{K_{22} \frac{V_{1m}}{V_{2m}} e^{jDj_m} - K_{21}}{K_{11} - K_{12} \frac{V_{1m}}{V_{2m}} e^{jDj_m}} - 1 \right) \quad (3)$$

where Dj_m is the measured phase difference between V_{1m} and V_{2m} .

3.1 Traditional Approach

Module and phase of parameters K_{ij} are evaluated by performing two measurements of V_1 , V_2 , V_{1m} and V_{2m} , in open circuit ($R_p=0$, $Z_x=\infty$, $V_2=0$) and short circuit ($Z_x=0$, $V_1=V_2$) respectively, for each frequency in a frequency range spanning from DC to 15MHz (V_1 sinusoidal burst).

Continuous functions for K_{ij} are obtained by interpolation.

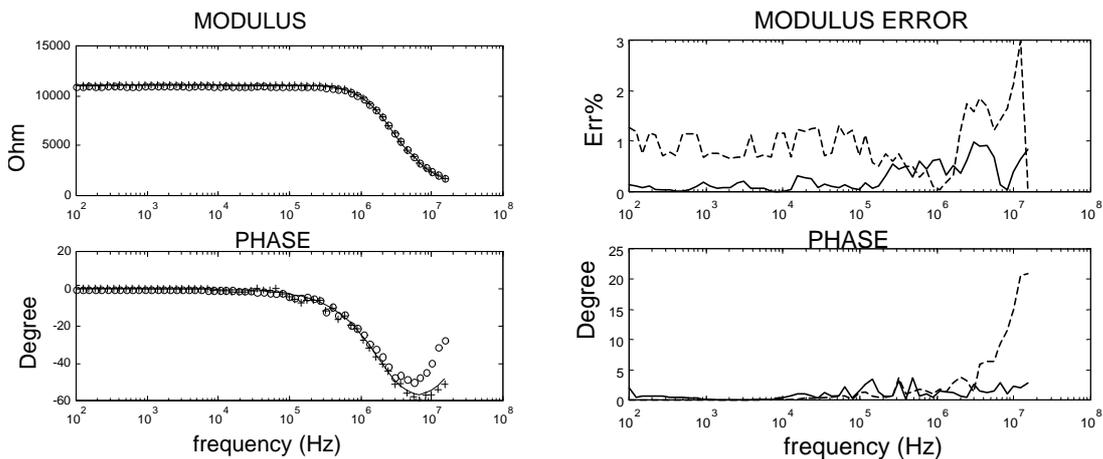


Figure 3. System improvement by using the traditional approach. Left plots: impedance modulus and phase. Continuous line: expected values; 'o': non corrected system; '+': corrected system. Right plots: modulus and phase errors. Continuous line: corrected system; dashed line: non corrected system.

As an example, in figure 3 the measured amplitude and phase with and without correction are reported for an 'a priori' characterised impedance. The used digital correction produces a significant improvement of the system performance. This can be especially noted as far as phase evaluation in the high frequency range is concerned. The maximum absolute phase error (see figure 3) was reduced from 22° to 3°. The measurements shown in figure 3 were obtained by using a reference impedance Z_p given by 10 k Ω in parallel with 10.5 pF, and with a 2 V amplitude sinusoidal signal as V_1 input. If Z_p is correctly tailored with respect to the expected range of variation of Z_x (SnO₂ sensor impedance typically present a maximum decrease of two orders of magnitude in presence of VOCs), the phase error can be maintained lower than 3° in the whole frequency range. Analogous considerations can be repeated for the amplitude of Z_x , whose relative percentage error can be kept near 1% from DC to 15 MHz.

3.2 ARX Approach

An alternative approach to the one presented in the previous subsection is based on the representation of the two-ports system of figure 2 with two multi-input single-output (MISO)

autoregressive models with exogenous inputs (ARX). This choice allows using an already established and efficient methodology for model parameter estimation.

In this context the input-output relationships can be represented in the time-domain by the following equations:

$$V_{1m}(t) = \sum_{i=1}^{p_1} a(i)V_{1m}(t-iT) + \sum_{i=0}^{z_{11}} b_1(i)V_1(t-iT) + \sum_{i=0}^{z_{21}} b_2(i)V_2(t-iT) + e_1(t);$$

$$V_{2m}(t) = \sum_{i=1}^{p_2} c(i)V_{2m}(t-iT) + \sum_{i=0}^{z_{12}} d_1(i)V_1(t-iT) + \sum_{i=0}^{z_{22}} d_2(i)V_2(t-iT) + e_2(t)$$
(4)

In eq.(4) two independent ARX models are used, each one characterised by two inputs. The coefficients $a(i)$ and $c(i)$ determine the system poles in the z-domain. While $b_{1,2}(i)$ and $d_{1,2}(i)$ determine the system zeroes; T is the sampling period.

As usual, the model order selection is a critical issue. In this paper the traditional 'optimum order' selection techniques (FPE and AIC) were applied. In this application models with 7 poles and 10 zeros give good results. Actually pole zero cancellations are present and this results in the two 'direct' and 'cross' K_{ij} coefficients having different poles.

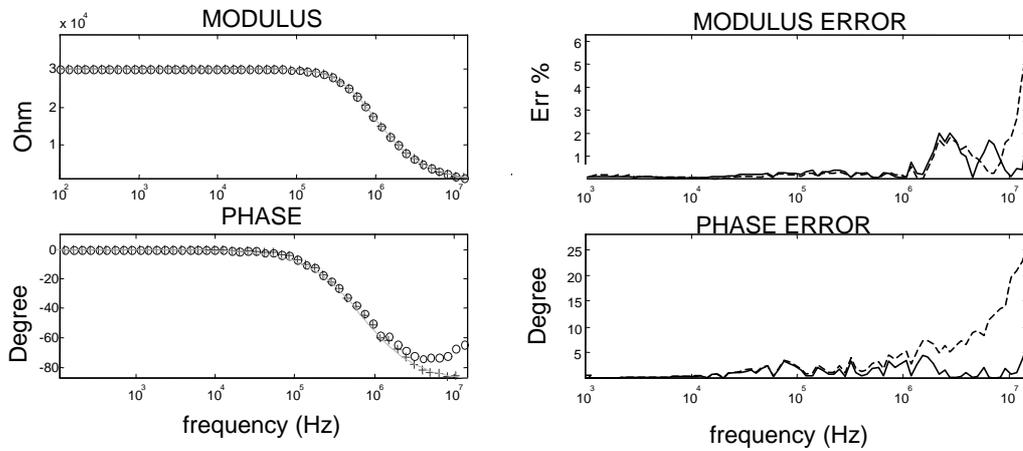


Figure 4. System improvement by using ARX correction. Left plots: impedance modulus and phase. Continuous line: expected values; 'o': uncorrected system; '+': corrected system. Right plots: modulus and phase errors. Continuous line: corrected system; dashed line: uncorrected system.

The coefficients K_{ij} describe the model behaviour in the frequency domain (see eq.2) and can be straightforward derived from the ARX parameters. For instance, for K_{11} the following equation holds:

$$K_{11} = \frac{\sum_{i=0}^{z_{11}} b_1(i)e^{-j2\pi fiT}}{1 - \sum_{i=1}^{p_1} a(i)e^{-j2\pi fiT}}$$
(5)

The system identification procedure consists in the simultaneous injection of two uncorrelated inputs and in the measurement of the system outputs. The four signals are acquired by means of a four channels scope (TDS754D). Finally the model parameters are estimated.

Similar results were obtained either by using white noise signals and frequency sweeps (V_1 characterised by an increasing frequency and V_2 by a decreasing frequency) as input stimuli.

The results in figure 4 show an example of the ARX approach performance. For the data presented hereafter two independent sources of white Gaussian zero mean noise were used. In particular, two HP33120A waveform generators characterised by a noise bandwidth of 10 MHz were employed. A sampling frequency of 50 MHz was used, and time windows of 1 ms were processed (50 ksamples).

4 CONCLUSIONS

Two digital correction techniques aiming at enhancing the measurement accuracy of an electronic nose operating as a vectorial impedance-meter are presented. The traditional approach provides better results, nevertheless the ARX approach gives acceptable results inside the input signals' bandwidth,

especially as far as the phase errors are concerned (see figure 5 for an example). It can be stated through tests on known impedances, and by comparison with the traditional method, that the modulus error remains in any case below 4% and that the phase error is lower than 5°. The worse results of the ARX method are explained by the fact that a lower energy is injected in the system to identify its behaviour (all harmonic components are simultaneously excited). In the very low frequency region (below 1kHz) a high uncertainty is expected due to the short observation time. Nevertheless the behaviour of the system in this frequency band is easily predicted and the digital correction becomes trivial (cross talk can be neglected and only the ratio of the two coefficients K_{11} and K_{22} has to be evaluated). It must be stressed that when the accuracy yielded by the ARX is sufficient (as is the case of the electronic nose), this method is preferable since it is extremely fast. In fact only one measurement is required to characterise the system behaviour in the whole frequency range.

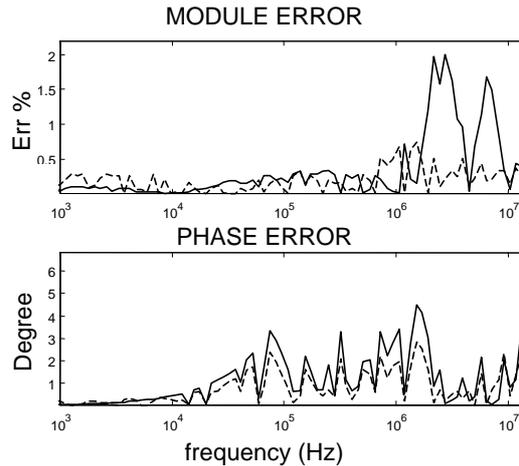


Figure 5. comparison of ARX and traditional correction techniques. Impedance modulus and phase errors. Continuous line: ARX correction technique; dashed line: traditional correction technique.

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