Acoustic Impedance Sensor for Liquids — Potential and Limits for Industrial Applications

Niels Hoppe, Gerrit Schönfelder, Peter Hauptmann
Otto-von-Guericke-University Magdeburg, Institute for Micro- and Sensor Systems,
P.O.Box 4120, 39016 Magdeburg, Germany

Abstract— **Acoustic impedance measurement offers new possibilities to get more information about liquid mixtures in industrial applications. In contrast to speed of sound measurement the investigated media have not to be ultrasonically permeable. This strongly increases the number of materials which can be examined successfully.**

In this work we discuss problems such as chemical stability of sensor materials, long term stability of the sensor signal, temperature behaviour of the sensor in the static and dynamic case and influences of error sources like thin deposits and gas bubbles.

I. Introduction

The acoustic impedance Z can be determined by measurement of the reflection or transmission coefficient of an ultrasonic pulse. Different sensors which use this acoustic principle have been introduced. A short description is given in [1]. These sensors determine the acoustic impedance through a pulse-echo-technique utilising the amplitude of an acoustic pulse that is back-reflected from the interface between a liquid and the reference material of known impedance.

Under process conditions in industrial applications the acoustic impedance has to be determined with a small relative error. This requirement can only be met with special electronics and sensor configurations. Effects like chemical stability of the sensor material and long term stability of the sensor signal in a wide temperature range are studied. Furthermore, the temperature dynamic behaviour of the sensor and influence of error sources like deposits on the sensor surface and gas bubbles in the liquid are discussed.

II. Acoustic impedance measurement of liquids

A specific sensor construction is given in Fig. 1. Both the piezoceramic transducer (lead-metaniobate) and the buffer rods of reference material have cylindrical shapes. The buffer rods are made of zerodur ($Z_0 = 16.4$ MRayl). Since the lengths l_1 and l_2 are different, the reference A_{ref} and measurement echoes A_{meas} are received at different times. The measurement is done by determining the acoustic impedance Z_l with the help of the sound reflection coefficient R:

$$R = -\frac{A_{meas}}{A_{ref}}\frac{1}{k}, \quad (1)$$

$$Z_l = \rho_0 c_0 \frac{1+R}{1-R} \quad (2)$$

with $\rho_0 c_0 = Z_0$ and a calibration factor k related to the acoustic losses in the buffer rods. The value of k is determined with Equation (1) in a calibration measurement with air substituting the liquid, when R is -1 (ideal case). The speed of sound of the reference material c_0 is measured by the arrival times t_{ref} or t_{meas} according to $c_0 = \frac{l_1}{t_{ref}} = \frac{l_2}{t_{meas}}$.

To calculate the density of the liquid $\rho = Z/c$ the liquid speed of sound c_l is determined with the c-sensor as a

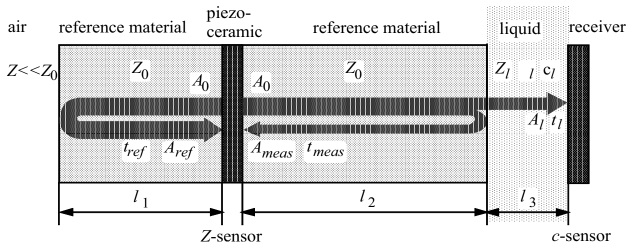

Fig. 1. Acoustic impedance sensor in combination with a speed of sound sensor.

separate receiver. The relation of c_l and the arrival times t_l and t_{meas} is given by:

$$c_l = \frac{l_3}{t_l - \frac{1}{2}t_{meas} - t_{offset}}. \quad (3)$$

Here, t_{offset} is a value that includes time delays of the electronic system. It is determined in a calibration procedure with a liquid of well known acoustic parameters, usually water. With Z_l and c_l the density is calculated by:

$$\rho_l = \frac{Z_l}{c_l}. \quad (4)$$

III. Influences under industrial conditions

Chemical stability of the sensor is an important prerequisite for the use in industry. As given in [1] glass materials are good reference materials for the sensor. To assess the chemical stability we investigated the reaction of borosilicate glass, quartz glass and zerodur to a concentrated acid and base. Because of the high acid resistivity class of all glasses no material erosion was detected. But in the reaction with a base all glasses are corroded. Zerodur was the material with the best properties. The material erosion was only 40 % of the borosilicate and 80 % of the quartz glass level. In contrast to the others zerodur had a very regular and smooth surface after the reaction. Thus applying this as a reference material in the Z-sensor the reflection at the interface to the liquid is not influenced. The measurement accuracy of the acoustic impedance sensor will be stable for erosions up to 200 μm.

Long term stability is necessary for reproducible results over the life time of a sensor. A measure of it in case of the Z-sensor is the calibration factor k which was determined in air over a wide temperature range. In a time of more than 6 month the calibration factor k changes less than ± 0.15 % (Fig. 2). This result was obtained after extensive tests with different silicone, cyan acrylic, epoxy and high temperature glues. Epoxy glues gave the best reproducibility.

With such a long term stable sensor the static and dynamic temperature behaviour were studied. For examining the static behaviour the acoustic impedance sensor was

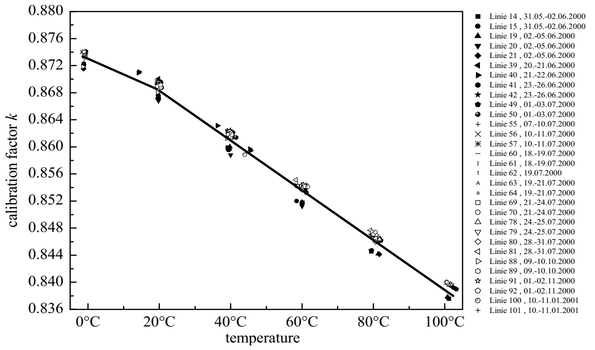

Fig. 2. Test of the long term stability of a sensor.

combined with a speed of sound sensor for density determination in order to compare the results with a reference densitometer. Over a temperature range from 0 °C to 100 °C and a density range from 0.75 g/cm^3 to 1.3 g/cm^3 the maximum error in density measurement in the static case was ±0.4 % (Fig. 3). For the dynamic case the material of the Z-sensor gives the strongest influence, because of its low heat conductivity. Respecting the thermal time constant in the dynamic calculation of the temperature dependent calibration factor k a maximum error of ±0.6 % in the impedance measurement can be reached. The sensor turns back to static behaviour after 30 minutes.

For sensors working with reflection techniques deposits on the reflecting surface are a severe problem. In [2] and [3] details for the impedance sensor are discussed. For industrial application of the Z-sensor possibilities of detection and correction of deposits are necessary. Because of the deposited layer a change in time of flight of the measurement signal in the buffer rod is detectable. The layer increases the length of the buffer rod. By comparing the speed of sound in the buffer rod for the reference signal and in the buffer rod for the measurement signal a layer detection is possible. After detection a sensor cleaning can be requested. An other possibility is the correction of the influence. For a small layer thickness $d_L (d_L \leq \lambda_L/50$, with $c_L = \lambda_L f)$ the product of acoustic impedance of the layer and time of flight through the layer, $Z_L t_L$, is constant:

$$Z_L t_L = \rho_L d_L = const. \qquad (5)$$

When the acoustic impedance of the layer is known, the error in impedance measurement can be predicted. This way a correction gets possible [3].

For ultrasonic devices gas bubbles in the liquid use to be problematic. Speed of sound sensors allow a detection of gas bubbles when signal attenuation is measured [4]. After detection a reaction to the bubbles is possible. An other way to solve the problem is sampling and reconstruction of the received signal [5]. After signal processing as described in [3] the correct speed of sound of the liquid can be determined. For the impedance sensor gas bubbles are a smaller problem. Because of the reflection technique and the use of a pulse-echo principle gas bubbles in the fluid interact only in a thin region near the sensor surface. For different liquids the minimum distances where no interaction occurs are given in Table I.

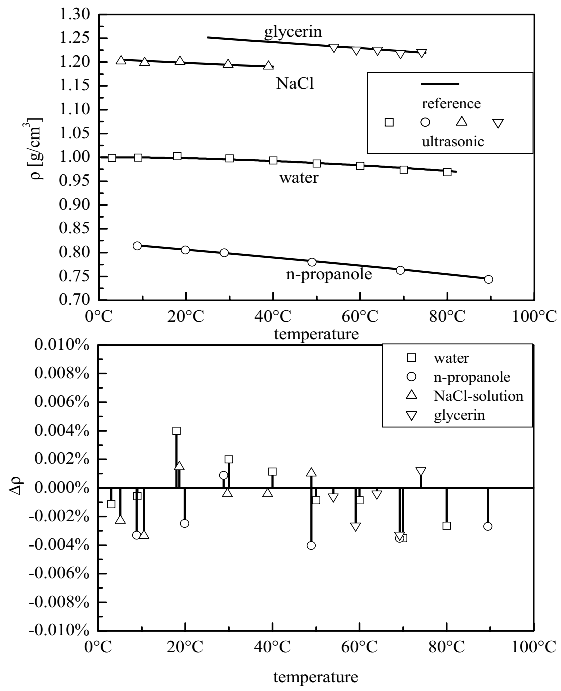

Fig. 3. Sensor behaviour over a wide temperature and density range.

TABLE I

Minimum distance of gas bubbles to the reflecting interface of the Z-sensor.

liquid	speed of sound m/s	minimum distance mm
galden	620	0.2
ether	985	0.3
water	1483	0.5
glycerin	1904	0.6

IV. Conclusion

The acoustic impedance sensor offers new possibilities to get more information about liquid mixtures. Intensive investigations of sensor material, sensor signal stability and sensor signal distortion through deposits on the sensor surface and gas bubbles in the liquid were done. The sensor is characterised by a high chemical resistance, low measurement error of ±0.4 % over a wide temperature range and the possibility to detect deposit layers and correct them.

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