# Ultrasonic Sensors for Process Applications - Sensor Design

Henning, Bernd; Rautenberg, Jens; Schröder, Andreas, Unverzagt, Carsten
University of Paderborn, EIM-E, Measurement Engineering Group (EMT)
Warburger Str. 100, 33098 Paderborn, Germany

## Abstract

Today, ultrasonic sensor systems are often applied in process technology. For the opening up of new industrial fields of application, such as the non-invasive process tomography, ultrasound sensors are necessary which are stable and adapted optimally under process conditions. Only with such optimized ultrasonic sensors the functionality of the sensor systems can be enlarged decisively with support of a complex measurement data evaluation. This contribution deals especially with the design process.

## 1. Introduction

Ultrasound sensors have a solid place in the process measuring technique today. Nowadays, established applications are the continuous measurement of flow, filling level, distance or the object detection. The use of ultrasound sensors is already a little less common to the concentration measurement or process monitoring [1]. There is a variety of process applications today at which the measured acoustic measurement quantities of liquid mixtures provide valuable process information about the concentration relationships or the course of a chemical process. A prerequisite for use of ultrasound sensor systems is the representative and reproducible significance of the measured acoustic measurement quantity and the sought-after process quantity. Due to the complex influence factors only the sound velocity is used as a measurand mostly. Generally it can be assessed that the special process application of an ultrasound measuring system is still difficult.

The rise of the efficiency of ultrasound sensor systems and its acceptance in the industry as well as the opening up of new application fields depend today to a high extent on whether it turns out well to determine the acoustic measurement quantities (sound velocity, acoustic impedance and sound absorption) simultaneously and precisely under the respective process conditions. The quality of the ultrasound sensors properties is decisive for it. Therefore current challenges are the essential improvement in the performance features of ultrasound sensor systems which include not only one acoustic measurement quantity. The development of implementable methods for a non-invasive process tomography with ultrasound sensors also requires exactly defined ultrasound sensor qualities. [2]

Starting-points are primarily an improved sensor design as well as a complex and efficient sensor signal evaluation. The pivotal role draws the specific improvement on the quality and stability of the ultrasound sensor properties. This seems only attainable about the realization of a more efficient design process which contains the following points:

- Modeling and numeric simulation
- Computer-assisted optimization
- Real-time measurement methods for the characterization and verification of the sensor qualities…

This contribution deals with this topic.

## 2. Ultrasonic sensor design

### 2.1 Modeling and numeric simulation

There is a variety of different methods for the description of sound propagation today. Analytical or half analytical procedures, such as global matrix/transfer matrix method, theory of thin shells and many others, deliver for simple models but exact results are, however, hardly suitable for a practical question due to the user defined restrictions (dimensionality, stationary consideration...).

For the computer-assisted simulation on the basis of the finite element analysis (FEA) there are several simulation tools commercially available (ANSYS, CAPA) today. These permit the examination of complex models and concrete 3D sensor constructions as well as the consideration of real operating conditions (e.g. at transient excitation...), but an enormous computation effort becomes partly necessary for it. Particularly if not only the ultrasonic sensor but also the complete measuring set-up shall be examined computational limits are reached fast. The way out frequently consists in a segmentation of the experimental set-up volume, diminution on axially symmetric 2 D models or the coupling of different simulation methods and tools (e.g. FEA and point source synthesis). [3]

The quality of the results of simulation is primarily determined by the material data, provided that one keeps the demands with regard to the spatial and temporal discretization into dependence of the wavelength conscientiously and consistently. The necessary acoustic material data for the different materials used in the sensor construction are only seldom available.

This applies particularly to the exceptionally diverse synthetic materials like polymers which are mixed for the adjusting of special qualities today or also filled with all sorts of aggregates (e.g. ceramic or metal powder, glass fibers). The acoustically relevant qualities themselves are in parts influenced by the manufacturing process (plastic injection molding, extrusion…) significantly.

In addition to that the acoustic qualities of synthetic materials change considerably with the temperature or also are influenced by the adjacent medium (humid air, solvents…). The estimate of the acoustic material data for example from the Poisson ratio often shows itself as completely unsuitable at synthetic materials since these material data are found out at special samples under partly quasistatic conditions in stress and compression tests.

For this reason at the workgroup EMT a measurement approach and an experimental set-up to the simultaneous determination of transversal and longitudinal sound velocity as well as the frequency dependent absorption in the ultrasound frequency domain for isotropic solid materials was developed [4].

The determination of the material data proves to be similarly difficult for the used piezoelectric ceramics. Although the manufacturers of piezoelectric ceramics deliver reference values which, however, are not sufficient for a realistic simulation. After all, a full material data set has to be determined with 13 independent material and model properties (see figure 1).

- **Matrix of elastic stiffness constants at constant electrical field**

  $$c^E \Rightarrow c_{11}^E, c_{12}^E, c_{13}^E, c_{33}^E, c_{44}^E$$

$$c^E = \begin{pmatrix} c_{11}^E & c_{12}^E & c_{13}^E & 0 & 0 & 0 \\ c_{12}^E & c_{11}^E & c_{13}^E & 0 & 0 & 0 \\ c_{13}^E & c_{13}^E & c_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2}(c_{11}-c_{12}) \end{pmatrix}$$

- **Matrix of piezoelectric constants**

  $$e \Rightarrow e_{31}, e_{33}, e_{15}$$

$$e = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix}$$

- **Matrix of dielectric constants at constant strain**

  $$\varepsilon^S \Rightarrow \varepsilon_{11}^S, \varepsilon_{33}^S$$

$$\varepsilon^S = \begin{pmatrix} \varepsilon_{11}^S & 0 & 0 \\ 0 & \varepsilon_{11}^S & 0 \\ 0 & 0 & \varepsilon_{33}^S \end{pmatrix}$$

- **Density and Rayleigh-Damping parameter**

  $$\rho, \alpha_R, \beta_R$$

*Fig.1: Important material properties of piezoelectric ceramics for FEA-simulation*

The method which is used at the workgroup EMT shall be introduced in the following briefly. The comparison of the measured course of the electrical impedance of a piezoelectric ceramic with a course of the electrical impedance generated by means of a FEA simulation forms basis for it. For the first simulation step the material data of the manufacturer are used as default values. The weighted quality criterion is the deviation of the two impedance courses of each other.

Figure 2 shows the impedance courses from the FEA simulation with the material data from the manufacturer and the measuring before the optimization.

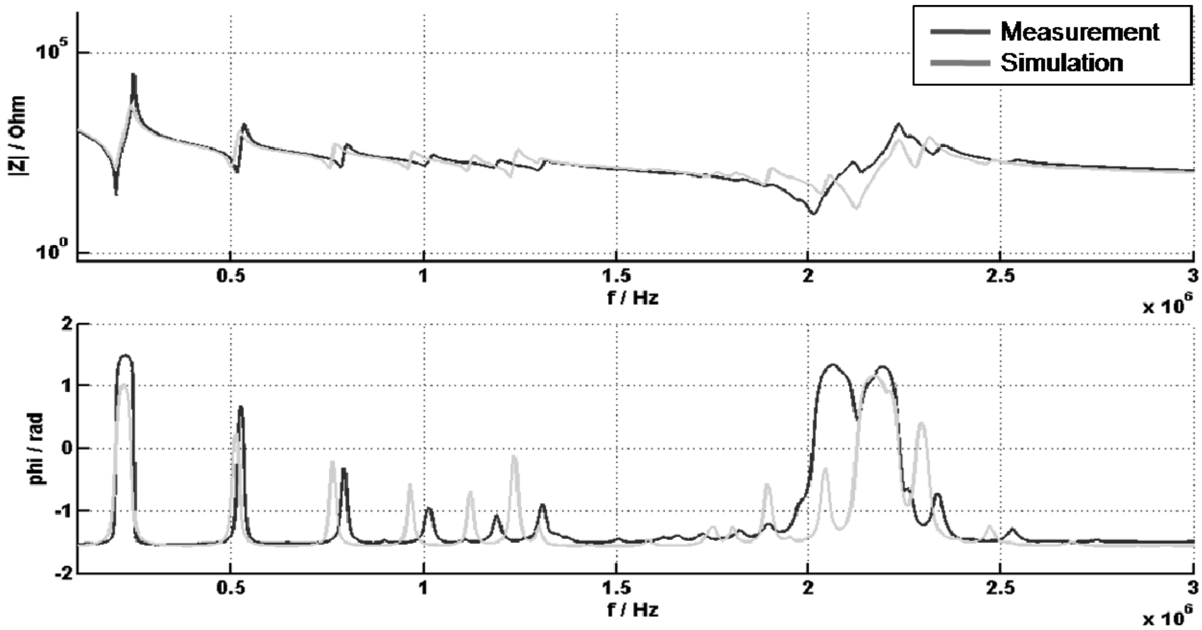


*Fig. 2: The electrical impedance courses measured and by means of FEA on basis of the material data of the manufacturer of the piezoelectric ceramic PXE5 (above: absolute value; below: phase)*

As represented into figure 3, the material data are varied to determine the material properties which have the greatest influence on the electrical impedance course firstly. All material data are then varied in an iterative process in certain limits to determine the deviation. Different algorithms, such as genetic algorithms, evolutionary computing [3] or also artificial neural nets, are suitable for it in principle.

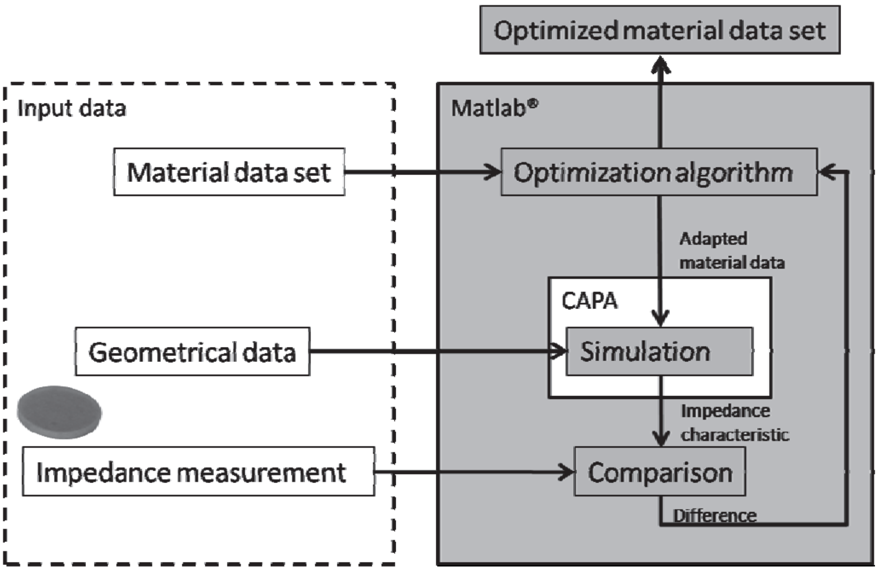


*Fig. 3: Approach to generate an optimized material data set of piezoelectric ceramics*

Finally the method of the minimum square deviation shows the best results. The material data are adequately particular well in this example after approx. 40 iterations. The program has been realized in Matlab®. The material data found out are subjected in addition to a consistency check according to DIN IEC 483. Only the data sets at which the consistency check less than 0.01% yielding deviations are valid explained. Figure 4 shows the electrical impedance course after the optimization in comparison to the measuring.

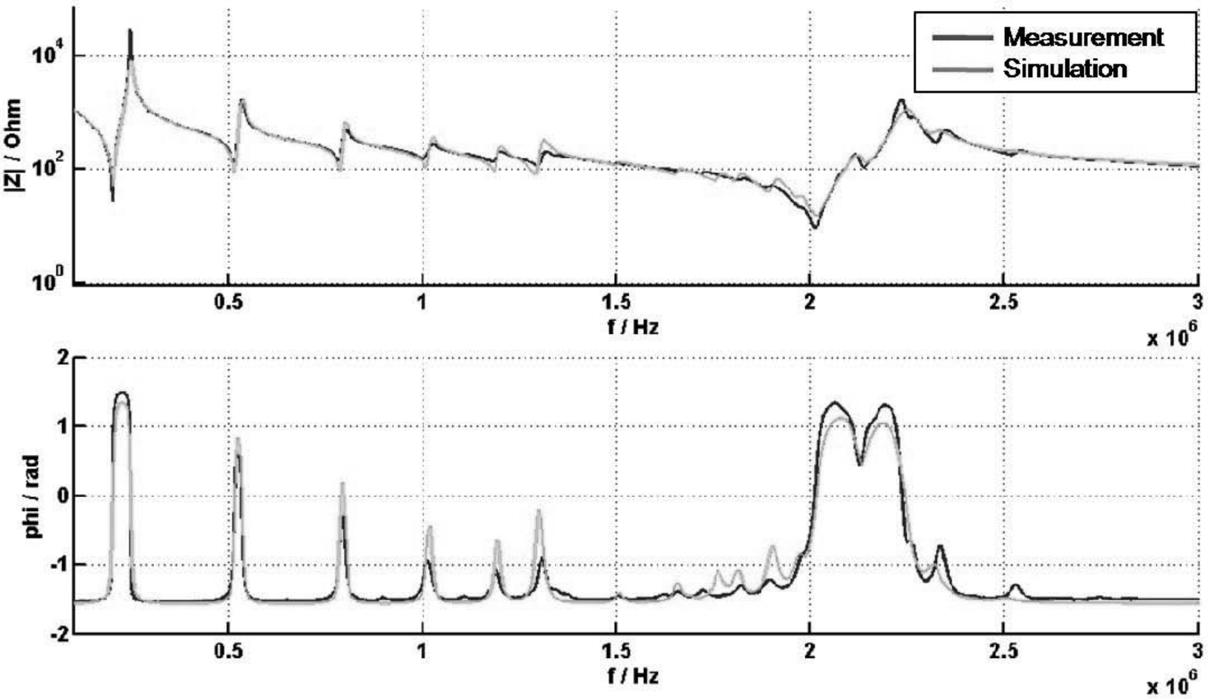


*Fig. 4: The electrical impedance courses measured and by means of FEA after the optimization of the piezoelectric ceramic PXE5 (above: absolute value; below: phase)*

## 2.2. Computer-assisted optimization

Another challenge consists in the realization of a computer-assisted optimization of the ultrasound sensor design. For this it is necessary to improve the pre- and post-processing. In this case the model generation must be carried out in a script, in which select model parameters (number of structural elements, geometric dimensions, material properties ...) are varied in a parameter area defined before. The variation of the model parameters can help to solve following problems:

- Examination of the qualitative influence of the individual parameters on the target design aims or sensor features (radiation characteristic, reach, focus depth, angle of beam...),
- Determination of optimal parameters at the redesign as well as
- Check of the robustness of the ultrasonic sensor qualities.

First of all the last point permits the weighting of the sensor qualities to be expected or resulted, e.g. at a change of the process or environmental temperature, the process medium to be measured or the material properties because of ageing (e.g. at synthetic materials) and other.

But also technological aspects can be examined specifically. So the permitted production tolerances of elements of the sensor construction or the replaceability by selected materials can be assessed previously.

If a computer-assisted sensor design is chosen the design engineer cannot bring in his expertise in the field of assessment of the simulation results any more. This means that suitable criteria which ensure an objective assessment with regard to the aim qualities of the ultrasound sensor must be defined. It is often not sufficiently to optimize only one property. For a multi-objective optimization the from time to time contrasting design aims must be weighted. In the literature different examples are described to reach this [5].

The method which is developed and used at the workgroup EMT shall be introduced here briefly [6].

The aim consists in determining an optimal cost function according to the desired target feature of the ultrasound sensor (frequency range, effective sound pressure distribution, angle of beam...). A simple axial symmetrical construction of an ultrasound sensor is shown in figure 5 consisting of four material layers (piezoelectric ceramic, two matching layers for the acoustic adaptation to the liquid to be measured and an absorbing layer).

The variable model parameters are the radii, the thicknesses and the material properties of the piezoelectric ceramic and of the two matching layers.

For the FEA simulation the program CAPA (www.wissoft.de) and for the automatic model generation as well as for the post-processing the program Matlab® are used. As already mentioned, it is important to find a representative result parameter for the simulation.

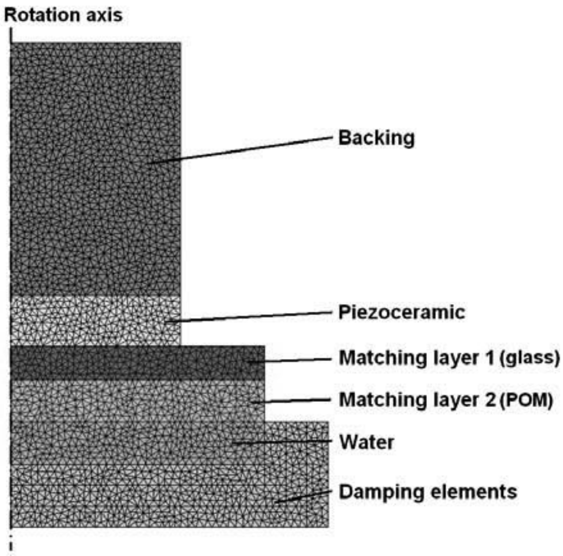


*Fig.5: Example of an axis symmetric transducer model generated by the Matlab® toolbox*

The out of plane displacement on the ultrasound sensor surface, the velocity potential at an adopted measuring point or the resulting receiver signal assuming an arrangement of two equal sensors which are arranged by a liquid separated opposite are suitable for this. The latter result parameter offers the advantage to compare the simulation results directly with measurement results using the experimental setup.

In figure 6 a) and b) the results are represented for the two cost functions "receiver signal" and "integrated surface displacement" at variation of the thicknesses of the two matching layers. Every point represents the result of a FEA simulation in the diagram.

The periodicity of the transmission at the multiples of half the wavelength in the respective material can be recognized very well. Figure 6 c) shows in addition the influence of the absorbing layer on the back.

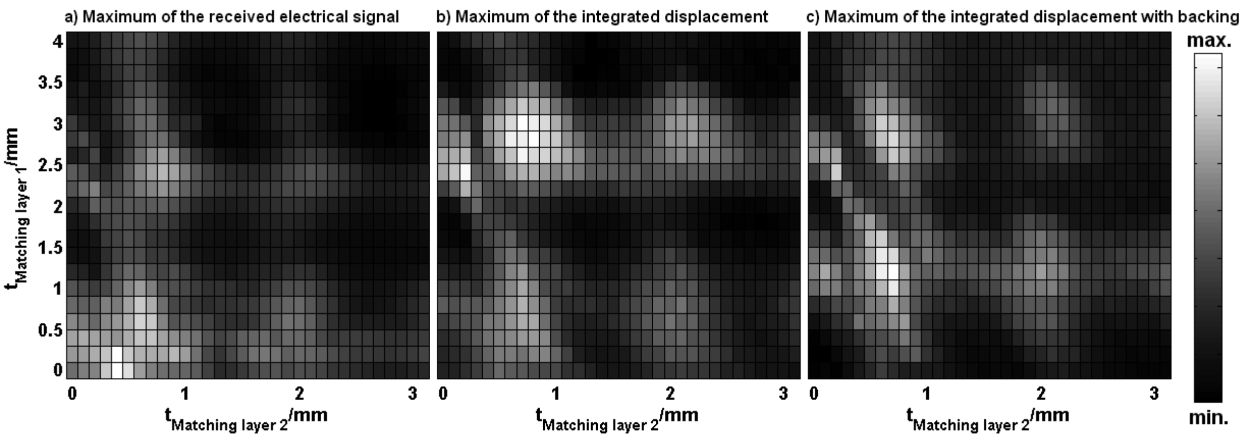


*Fig. 6: Visualization of different cost functions with variation of the thicknesses of the matching layers: a) Maximum of the received electrical signal, b) Maximum of the integrated out of plane displacement, c) Maximum of the integrated displacement with backing*

For example the radii of the matching layers and the piezoelectric ceramic were changed (in the same way) in figure 7. At a sensor operating in the thickness mode the influence of the radial modes overlapping can be examined specifically so. Since particularly the radiation characteristic is influenced through it, the used cost functions also distinguish themselves significantly.

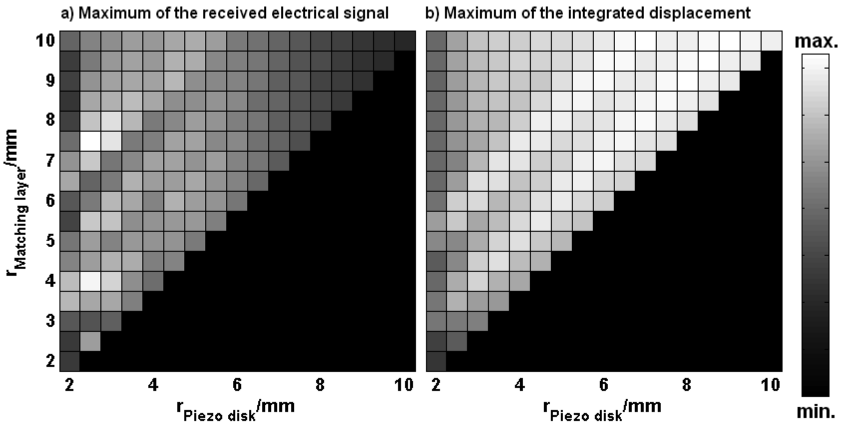


*Fig. 7: Visualization of different cost functions if the thicknesses of the matching layers are fixed and the radii of the matching layers and the piezoelectric disk are varied. a) Maximum of the received electrical signal, b) Maximum of the integrated out of plane displacement*

### 2.3 Real-time measurement methods for the verification of the sensor qualities

The simulation requires the permanent and precise verification by experiments. The measuring of the out of plane displacement is typically realized by the use of a laser vibrometer scanning the ultrasound sensor surfaces point for point and convert the results into a two-dimensional representation of the surface displacement. The often long measurement time (approx. 2 hours) is adverse. This technique can also be used for the measuring of the sound field with a low modification in a liquid. Since the distance to the transmitting ultrasonic sensor has to be taken into account the necessary measurement time rises considerably. It is prerequisite for good results that the measurement conditions remain constant during the complete measuring procedure.

An alternative offers the Schlieren method. This method for the sound field visualization already established for a long time, offers the advantage to pursue the sound propagation almost in real time. Therefore it will be possible to examine the effect of various influencing factors on the device under measurement immediately. An essential improvement is reached by a Digital Micro-Mirror Device (DMD) which makes it possible to manipulate the Schlieren picture in the Fourier plane directly (filtering and so on). The further developed method is described more in detail in [7].

# 3. Summary

The development of ultrasound sensors tailored to the application case optimally is decisive for the functionality and the reliability of ultrasound sensor systems today. For this, current demands for an improved quality and greater stability of the sensor properties at a minimum of product costs can be met.

The design tools available today offer good possibilities to improve the ultrasound sensors. More efficient design tools have to be developed or combined with each other skillfully due to the complex difficulties, the complicated sensor constructions and the coupled model parameters. Ultrasound sensors with defined qualities offer the prerequisite for a complex measurement data processing to meet the industrial requirements.

# 4. References

[1] Hauptmann, P.; Hoppe, N.; Püttmer, A.: Application of ultrasonic sensors in the process industry, Meas. Sci. Technol. 13 (2002) R73–R83

[2] NAMUR: Final Report Technology-Roadmap Process-Sensors 2005 – 2015, http://www.namur.de

[3] Weber, P. K.; Schmitt, D.; Weyland, J.: CATD – Computer Aided Transducer Design – Methods & Benefits, 17th CAD-FEM User's Meeting, Sonthofen, Germany, 6.-8.10.1999

[4] Rautenberg, J.; Henning, B.: Simultaneous direct and indirect measurement of sound velocities. Eurosensors XXII, Dresden, 07.-10.09.2008, Proceedings

[5] H. H. Hansen, Optimal design of an ultrasonic transducer, Structural Optimization 14, 150-157, Springer-Verlag, 1997

[6] Schröder, A.; Rautenberg, J.; Henning, B.: Evaluation of cost functions for FEA based transducer optimization, 2nd Int. Congress on Ultrasonics, Santiago de Chile, 12.-16.01.2009, proceedings

[7] Unverzagt, C.; Olfert, S.; Henning, B.: A new method of spatial filtering for Schlieren visualization of ultrasound wave fields, 2nd Int. Congress on Ultrasonics, Santiago de Chile, 12.-16.1.2009, proceedings