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Air-coupled Transducers for Quality Control in the Food Industry.

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Abstract*—Food industry is continuously innovating its capability of analysis by incorporating new technologies aimed to meet increasing quality and safety requirements, concurrence and consumers demands. In this context, non-destructive and non-invasive techniques are demanded in different stages of the production chain for quality control and verification. Air-coupled ultrasound is a fully non-invasive and non-destructive technique that has already been successfully implemented in other industries (aeronautical, aerospace, etc.) with fast scan velocities, and compatibility with industrial environment. This technique is capable to determine mechanical and viscoelastic properties of different materials as well as the presence of discontinuities, cavities, and foreign objects. Clearly, these capabilities are extremely interesting for inline quality control in the food industry. Being the main challenge of air-coupled applications the performance of air-coupled transducers (bandwidth and sensitivity), the objective of this work is to show a transducer design approach to simultaneously optimize both sensitivity and frequency band that make possible to operate in through transmission. In addition, food industry requirements in terms of materials and working conditions are also reviewed and included in the transducers design. Transducers with centre frequency at 300 and 500 kHz has been designed, built and tested. A first verification of the use of this technology in food products is shown revealing the possibility to measure transmitted signal above the noise level.

***Keywords*— Transducer optimization, food industry, air-coupled ultrasound, air-coupled transducers, quality control, NDT.**

I. Introduction

Low-intensity ultrasound to characterize food stuff was first realized around 1930 but the full potential of this technique began to be studied in more detail in the late 80s [1]. There are several ultrasonic parameters that correlate with physicochemical properties of the food matrix [2] and can, therefore, be used for the analysis of food materials. Moreover, previous works (Refs. [3], [4] and [5]) have shown a close relation between physicochemical and sensory properties with ultrasonic parameters (mainly ultrasound propagation velocity and attenuation coefficient) of different food matrix as meat, milk, cereals, fruits and vegetables, fats, and aerated foods, that support the use of ultrasonic techniques as analytical tool in the food industry. However, it could be difficult to implement inline due to the operation conditions and restrictions that apply to the food industry.

The present work proposes two prototypes of air-coupled ultrasonic transducers (at 300 and 500 kHz), that could operate inline, provide a full non-invasive and non-destructive efficient analytical technique and are completely compatible with the food industry requirements. The proposed prototypes adapt the existing technology of air-coupling transducers presently available at CSIC to be compatible with food industry requirements while preserving the bandwidth and sensibility figures present in conventional designs.

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II. Methodology

A. Transducer design, optimization and manufacturing

The air-coupled transducers were designed to optimize, simultaneously bandwidth and sensitivity which are key parameters for this type of applications where it is necessary to transmit ultrasonic signals through solid plates in air and may be required to perform spectral analysis of the transmitted pulses in order to extract some valuable information about the material under inspection (like ultrasound propagation velocity, attenuation coefficient and their variation with frequency). Therefore, the optimization criteria, or figure of merit (FOM), employed in this work is defined as the product of peak sensitivity and bandwidth at -20 dB loss from the sensitivity peak. Sensitivity (*SNS*) is defined according to Eq. (1), where *FFT* denotes the fast Fourier of the electrical signal generated at receiver terminals (Rx), after applying a voltage signal: Tx at the transmitter terminals. Transducers are positioned facing each other and separated by a small air-gap (typically 10-20 mm).

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$$SNS(dB) = 20llog_{10}\left(\frac{|FFT(R_x)|}{|FFT(T_x)|}\right) \qquad (1)$$

Once the transducer design is decided and all material parameters are known, the FOM is calculated using a 1D transducer model where field equations are solved by using continuity conditions (strain and stress) at each boundary in the layered structure.

The transducer design consists of a piezoelectric element operating in its thickness mode, a stack of impedance matching layer and a low impedance backing block. Outer matching layer is a resonant layer tuned to the piezoelectric element resonant frequency and having the lowest feasible acoustic impedance (< 0.05 MRayl) and losses (< 1000 Np/ @ the transducer centre frequency). In particular, this material is selected according to Refs. [6], [7], with the main difference, compared to conventional designs, that only hydrophobic materials are allowed as outer matching layers due to operation restriction in the food industry.

Several intermediate matching layers (up to four) are introduced to further optimize transducer FOM. The search of the optimum number of matching layers to use and the properties of these layers (namely, acoustic impedance and resonant frequency) is performed by a Simulated Annealing (SA) algorithm [8], [9], implemented in Python, and the impedance and frequency detuning method proposed in Ref [10]. The SA algorithm is essentially metaheuristic approach based on a Monte Carlo method where the space of search is sampled by using Markov chains and the acceptance probability is given by the Metropolis algorithm. The Metropolis algorithm acceptance criterion is make more restrictive as the search advances, which simulates the temperature cooling in the annealing process.

Actual restrictions in transducer manufacturing (as materials available, how different materials are attached together, etc.) are introduced in the search algorithm by using an adaptive penalization in the FOM function, where adaptive means that it becomes more restrictive as the search gets closer to the solution. Required impedances for the intermediate matching layers and backing range from 4 MRayl to 0.4 MRayl. To produce materials with the required impedance epoxy resins with the different loads (powders of different density) have been used.

Two different piezoelectric elements were considered for the transducer design, optimization, and fabrication, both 50% volume fraction dice and fill composite disks poled in the thickness direction. In one case made of PZT5A and in the other of PZT5H (Smart Materials). In both cases diameter is 25 mm and tuned to two different frequencies: 300 and 500 kHz.

As the transducers are intended to have wide band there is no need to tune transmitter and receiver to the same frequency, so both, transmitter and receiver employed the same optimized stack of matching layers. The use of two different piezoelectric elements provides some additional degree of freedom to tune in different ways transmitter and receiver to a different electrical impedance value which can provide some benefits in terms of peak sensitivity. Unlike other transducers previously produced by our group [11], and to comply with food industry requirements housing was made of stainless steel with a double RF-shield structure to optimize the isolation of the transducers from the noise present in industrial environments.

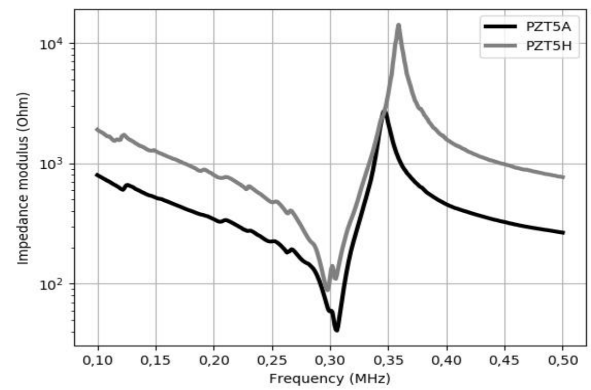

Fig. 1. Electrical impedance of the piezoelectric disks at 300 kHz mounted in the housing and before attaching matching layers and backing..

Electrical impedance around the piezoelectric disk first thickness resonance is measured with a BODE 100 impedance analyzer. Measured impedance vs frequency for the 300 kHz disks is shown in figure 1. It can be seen that same resonant frequency is used for piezoceramic disks used to make transmitter and receiver transducer but that different values of the electrical impedance will be achieved in the final transducer.

B. Experimental Set-up for transducer response characterization

To characterize the transducer response, the experimental set-up of Fig. 2 has been used.

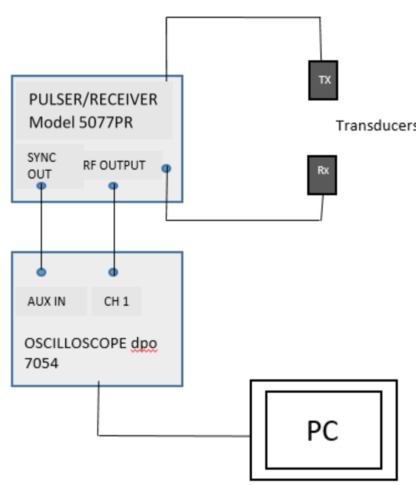

Fig. 2. Experimental set-up scheme for transducers characterization

The two transducers are placed in opposition and separated between 10 and 20 mm. They are operated in through transmission mode. Both transducers, transmitter and receiver were connected to a Pulser/Receiver Model 5077PR, the transmitter transducer (Tx) is driven by a semicycle of square wave tuned to the transducer centre frequency of amplitude between 100 and 200 V. The signal generated by the receiver (Rx) is sent to the receiver stage of the P/R and sent to a Tektronix Oscilloscope DPO7054, without applying any gain, and then transferred to a PC for further processing.

C. Experimental Set-up for food measure.

As an example of application, two different food products where an inline quality assay can be of interest are selected to test the possibilities of the transducers developed in this work: one extruded which main ingredient is corn and the other baked which main ingredient is cornmeal.

The ultrasonic system employs a through transmission configuration with the transducers previously described. To simulated the process of ultrasonic measurements inline, a conventional ultrasonic scanning system was used. Several food products were placed along a bar. The scanning system performs a linear scan that simulates the passage of the samples between the air-coupled transducers.

The scanning system was developed by DASEL and the pulser/receiver employed was the DASEL AirScope. This generates a tunable semicycle of square wave. In these measurements pulse centre frequency was tuned to transducers centre frequency and amplitude was set to 400 V. Signal from the receiver was amplified up to 40 dB, with no averaging to simulate the situation in a fast scan system.

III. RESULTS AND DISCUSSION

A. Transducers results

Fig. 3 shows a picture of two pairs of the transducer prototypes produced (300 and 500 kHz), both cases with stainless steel housing, 25 mm flat aperture and straight back BNC connector.

Fig. 3. Picture of the prototype transducers produced according to this procedure.

Response of the two pairs of 300 kHz transducers (Tx: PZT5A, Rx: PZT5H and Tx and Rx made of PZT5A) is shown in Fig. 4. Fig 5 presents results for the 500 kHz pair of transducers (Tx: made of PZT5H, Rx: made of PZT5A). Measurements are obtained using an Olympus 5077 PR and a Tektronix 5054 DPO, digital oscilloscope. Pulser amplitude was set to 200 V and 100V for 300kHz and 500kHz respectively and receiver gain to 0 dB.

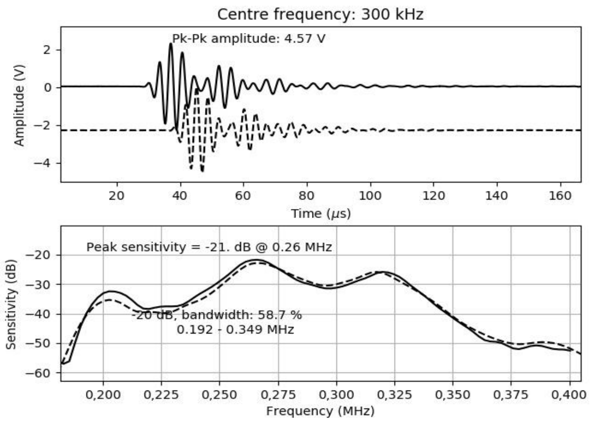

Fig. 4. 300 kHz transducers time and frequency domain response. Solid line: transmitter: PZT5A, Receiver: PZT5H, Dashed line: Transmitter and Receiver: PZT5A.

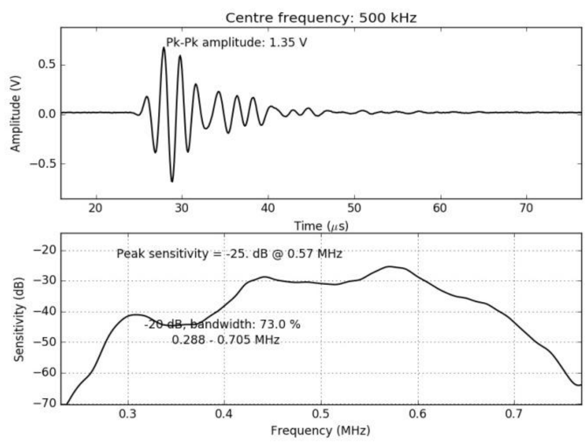

Fig. 5. 500 kHz transducers; transmitter: PZT5A, Receiver: PZT5H.

Table I summarizes the main properties of the transducers. The most interesting feature is the extremely high sensitivity obtained (-21dB and - 25 dB for 300 and 500 kHz transducers) that is achieved keeping a quite wide usable relative frequency band (measured at -20 dB), between 59 and 73%.

In addition, only slight differences are observed between the different combinations of the 300 kHz transducers (see Fig. 4).

TABLE I. PROPERTIES OF THE 300 AND 500 KHZ TRANSDUCERS

Nominal frequency (MHz)	Frequency of peak sensitivity (MHz)	Centre frequency (-20 dB band)	Relative -20 dB band	Peak SNS (dB)
0.30	0.26	0.27	59%	-21
0.50	0.57	0.50	73%	-25

B. *Results of measures in the food products.*

Figure 6 shows two representative examples of the transmitted signal in the food products considered (a: extruded corn, b: baked). First, the signal acquired at two random locations is shown and then the mean of seven signals transmitted at seven different locations in the same sample, just to show the dramatic variations of the variability of the signal when considering different products. In addition, as it can be observed in the example, the complexity of the matrix has a strong influence in the signal.

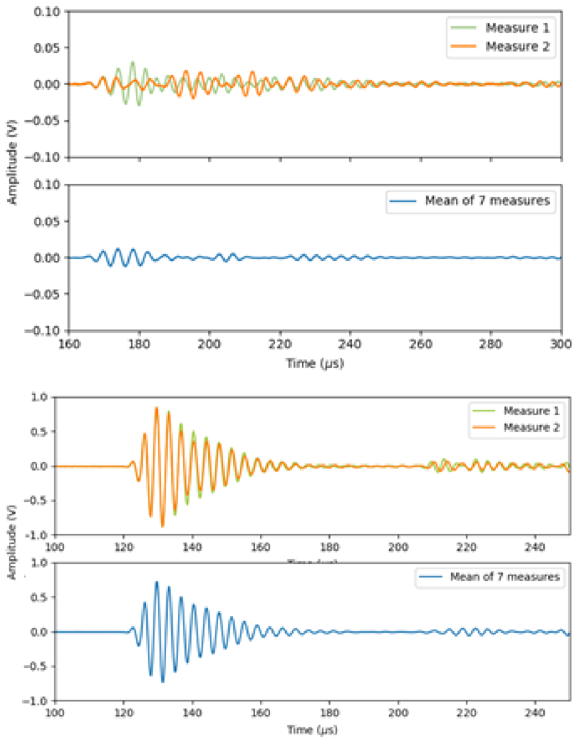

Fig. 6. Measurements at a single location and mean of seven measurements in the time domain performed in an extruded corn food (top) and a baked corn food (bottom). Through transmission, 300 kHz, PR: Olympus 5058, excitation: 900 V, gain in reception: 40 dB.

In addition to the observed variability, another significant difference between the two food products considered is the large difference in the signal loss after transmission of the airborne ultrasonic signal through both of them. In the case of the extruded corn (transmitted signal shown in Fig. 6, up), further calculations revealed a loss about -75 dB, while for the other product (transmitted signal in Fig. 6 bottom) the observed loss is only about -35 dB. The transmission coefficient losses measured in the extruded corn food is much larger than in baked product due to two main reasons: first, the larger surface irregularity and, second, the much higher porosity and larger pore size in the extruded corn food. In addition, variation in the signal loss with frequency is more pronounced in the extruded food product than the baked one, mainly because stronger scattering phenomena present in this material.

IV. CONCLUSIONS

A methodology to optimize air-coupled transducers based on a modified SA algorithm, a multi-layered structure and incorporation of materials compatible with its use in the food industry (namely: hydrophobic radiating surface, stainless steel housing and double RF shield) has been presented. Different prototypes transducers have been produced with 25 mm flat aperture, centre frequency of 300 kHz and 500 kHz, usable relative bandwidth about 70% and peak sensitivity between -21 and -25 dB. The relatively low frequency of these designs and the extremely high sensitivity are very attractive to food quality control where materials of interest use to present a complex structure and very high attenuation factors. Moreover, the large frequency band open up the possibility to perform spectral analysis of the food response which has the potential to provide valuable information.
Finally, the transducers have been tested to measure the signal transmitted in two different food products that are representative of the different range of materials of interest in the food industry. It was possible to obtain measurements in the frequency range 0.15 - 0.70 MHz, with losses in the material up to -90 dB, which reveals the potential of this transducer technology and show the possibility to extend this kind of measurements to a very wide range of food products.

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