Development of a multiple-scattering acoustic sensor for process monitoring

Application to monitoring milk coagulation

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Abstract—**Diverse industrial processes can be monitored by tracking changes in a fluid media. Having inline nondestructive information about the state of the process permits to have optimal results at reasonable costs. The suitability of low-power-ultrasound techniques has been widely investigated. However, sometimes this techniques have a poor signal-to-noise ratio or excessive sensitivity to temperature changes. In the present work, multiple-scattering of an ultrasonic signal is generated to enhancing the process-tracing ability. A pulse-echo system is used. The acoustic signal travels through a rod array, which is immersed in the changing medium. Useful information is taken from the echoes correlation. As a test case, this system has been proved for tracing milk coagulation, which is necessary in the cheese- manufacturing process.**

Keywords—ultrasound; acoustic; sensor; correlation

I. INTRODUCTION

In industrial processes that involve consistency changes of a liquid, it is useful to monitor evolution in order to be aware of points of interest. In the cheese-manufacturing process there is an ideal time to cut the curds at the end of milk coagulation,
which is actually acknowledged by craft techniques, being automatization therefore interesting as a study field.

In this report, a novel online noninvasive method for monitoring initially-liquid media going thorough texture-changing processes is presented. We are thus developing a new sensor, based in the multiple scattering of acoustic waves. Milk coagulation is used as a test case, which has been already approached by different authors [1][2]. A new low-power-ultrasound configuration is presented. A precedent on altering the mechanical configuration of traditional ultrasonic systems with similar purposes is [3]. There are several acquiring and signal-processing techniques which have been formerly aimed at the Conference [4][5][6]. The technique development and associated best-results-throwing processing are specifically detailed, whereas alternatives are mentioned.

We use an ultrasound pulse-echo system with a rod-array structure immersed in the changing medium. The novelty here is that the addition of the rods generates multiple scattering, in opposition to the traditionally used reflection plane. The advantage is that the waves strike the receptor in different angles, have various reflections and travel considerably longer paths, all of this resulting in the amplification of the medium-structure-change sensitivity of the pulse-echo technique.

II. THEORY

A. Cross-correlation

Cross-correlation is a useful function in order to quantify signals' similarity, as in [7]. It can be either calculated in time or frequency domain, as in (1), where $\mathcal{F}$ represents the Fourier transform and the asterisk represents the conjugated of a complex value.

$$\begin{aligned} r_{y_1,y_2}(t) &= \int_{-\infty}^{+\infty} y_1(-\tau)\, y_2(\tau - t)\, d\tau \\ &= \mathcal{F}^{-1}\{Y_1^{*}(f)Y_2(f)\} \end{aligned} \tag{1}$$

A property to be considered during this paper is that the closer the signals are, the more symmetric that the central lobe of the correlation will be. As the signals differ, it gets distorted, having a minor maximum and losing the symmetry.

Several characteristics of the correlation's central lobe can be used to detect changes in the process. For instance, the energy concentrated in it, the value of the maximum or the time at which it occurs. As measure of asymmetry, the difference between the lateral minimums can be considered. For the test case, we chose the delay time of the maximum, but other characteristics might be better for other cases.

B. *Finding a maximum with high precision*

At the point of the processing where a maximum occurrence- time (MOT) is to be determined, the temporal resolution we have is inferior to the needed one. This resolution is typically determined by the sampling frequency. If the bandwidth of the experiment is less than half the sampling frequency, a usual way to avoid this restriction is to interpolate.

Interpolating numerically augments data density, so the MOT can be found more precisely, but the processing speed is proportionally lowered.

An alternative solution is finding the zero-crossing corresponding to the function derivative at the MOT. Therefore, the Hilbert transform, which away from the data edges adjusts the derivative, is used. A straight-line approximation through the zero-crossing nearest points allows to interpolate with an analytical expression, which is computer wise the most efficient. Hence, the resolution is significantly improved, keeping the processing speedy. The accomplished resolution is given by the machine epsilon of the processing computer.

The signal processing steps used in this example are (Fig. 1):

1. Numerically interpolate the function with five additional points between the measured ones, for having a better base for the analytical interpolation.
2. Apply Hilbert's transform to the function. It is important to compute it for the whole data and not only for those points close to the maximum.
3. Choose a window for which the only maximum is the one of the correlation's main lobe. Within this window, find the point p corresponding to the minimum of the absolute value of the derivative. The points p_{-1} and p_{+1} are those adjacent to p.
4. Being the straight line that goes through p_{-1} and p_{+1} of the form $y = mx + n$, the MOT is it's zero crossing, n/m.

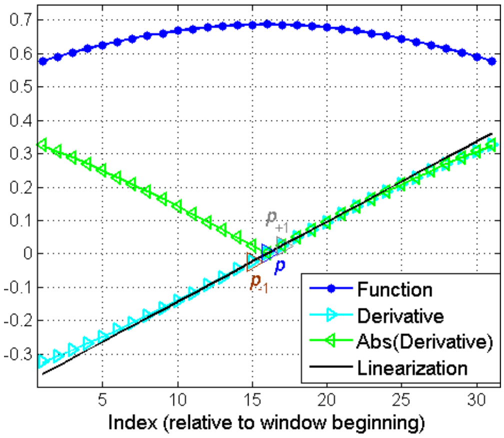


Fig. 1. Illustration of the procedure to find the maximum of a function.

III. MATERIALS AND METHODS

A. *Materials*

The materials that were used in the test case are listed below. The experiment is done in a thermal bath, where the milk is put for coagulating with the proposed sensor.

- Olympus 5072PR Pulser/Receiver + 15 MHz transducer
- Agilent 34410A multimeter + Fluke 80TK thermocouple
- Agilent DSO-X-2012A oscilloscope
- Cole-Parmer 01266-32 bath-temperature control
- Stainless-steel cell (With an aluminum alignable plate). (L x W x H): 11 cm x 10 cm x 10 cm
- Acrylic cell. (L x W x H): 30 cm x 20 cm x 18 cm
- Rod array
- Thermo-Scientific pipette, Finnpipette (100 - 1000 μL)
- Kern analytic balance, ABT 220-5DM model
- Calcium chloride, rennet, milk

B. *Rod array*

The system (Fig. 2) consists of 1.6-mm-diameter 8.5-cm-length copper rods. They are parallel placed using two acrylic spot matrices, with spot-centers 2-mm away from each other.

The amount of rods and the distance between them were varied, finding that the best disposition is formed by 60 rods distributed in 8 planes. The planes are separated two spaces from each other. The rods belonging to a same plane have also a two- space separation. From one plane to the other, the rods are shifted each time one position in the same direction.

A good signal penetration and enough reflections, as well as easiness to be cleaned were design necessities. The first item is related to the length of the rod-array-correspondent echo. Letting t_{end} be the time associated with the background-plane echo, we considered that the signal penetration is good if the rod echoes reach t_{end}. The second item is related to the echo form. Sharp peaks as the ones highlighted in red boxes in Fig. 3 correspond to planar reflections that happen directly against a rod plane, as in simple scattering. Signals associated to multiple scattering seem to be aleatory, but are constant within acquisitions and do not have particularly noticeable peaks. Multiple scattering reflections [8] [9] are more sensitive to changes in the fluid.

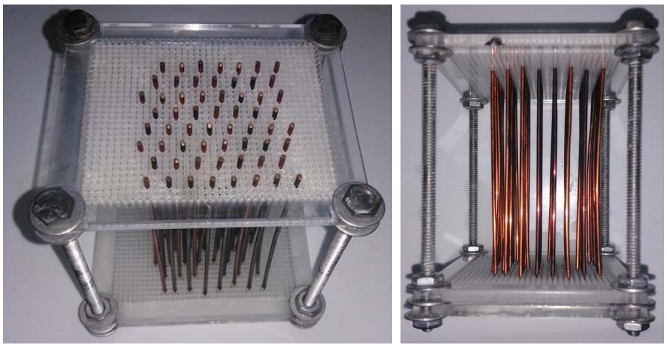


Fig. 2. Rod array.

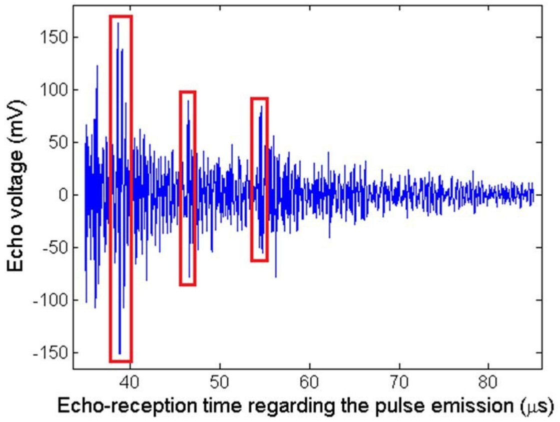


Fig. 3. Echo with sharp peak, which are associated to planar reflection.

The system easiness to be cleaned is crucial. On one hand, leftovers from one use to another would occupy the place of the changing medium among the rods, diminishing the process- monitoring resolution. On the other hand, there is a sanitary aspect, given that the sensor may be used in food manufacturing.

C. *Acquisition window selection*

Windows without predominance of planar reflections, have the most sensitivity towards medium changes. Therefore, such an acquisition window was sought.

Delayed echoes are preferable since they have a higher percentage of energy associated to multiple scattering than to planar reflections. The time in which the echo from the backplane is received is considered as the limit, therefore the chosen window must be completely held in a former period. We used a window that goes from 55 µs to 105 µs (Fig. 5).

IV. APPLICATION TO MILK-COAGULATION PROCESS

The milk coagulation in cheese-making is used as an example to test the proposed setup.

A. *Coagulation series*

Tests were made within two different coagulation conditions regarding different calcium chloride and rennet concentrations, as shown in table I.

B. *Acquisition procedure:*

System assembly is schematized in Fig. 4a. A picture of the physical mounting is shown in Fig. 4b.

1. Thermostatize the bath at 37 ºC ± 0.5 ºC.
2. Put the rod array and the stainless-steel cell into the acrylic cell so that they also get thermostated. The stainless-steel cell must be leaned so that the rod system exerts a tiny force on the transducer-containing side, avoiding the noise given by the system vibration.
3. Heat 650 mL milk in a microwave for it to approximate but not exceed 37ºC.
4. Let the system thermostatize before running acquisition program.
5. For every series the rod array is taken out of the milk for adding the rennet and agitating and put back in place at fixed times.
6. The acquisition begins for every series at a fixed time.

TABLE I. COAGULATION SERIES

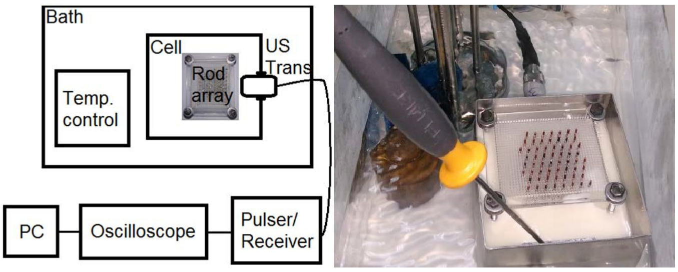
Series	Calcium chloride [g/L]	Rennet [µL/L]
1 to 12	0.07	670
13 to 15	0.035	270

C. *Basic signal processing*

The signals are processed in order to find patterns that may be used to follow the process. One characteristic is picked to continue working.

For each acquired signal:

1. Condition voltage data (Fig. 5) by eliminating DC value and applying fourth-order Butterworth high- and low- pass filters with cutoff frequencies of respectively 2.5 MHz and 25 MHz.
2. Compute the cross correlation between the actual signal and the initial one. The initial signal is the first one after the system has been stabilized.



a. Scheme of the system, without considering temperature acquisition.

b. Picture of the mounted experiment.

Fig. 4. Experimental setup in the actual example.

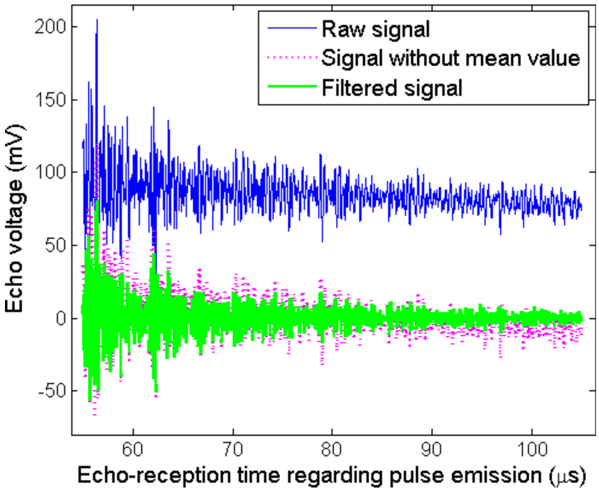


Fig. 5. Basic signal conditioning.

3. Find and store in a vector the time (ns) at which formerly mentioned cross-correlation is maximal. This time shifts as the liquid's structure changes, as shown in Fig. 6.
4. Store in vectors the timestamp (min) associated to each signal and the temperature (ºC) measured during each acquisition

D. Observations on the example's results

Fig. 7 exemplifies the obtained results. The correlation-maximum-time curve has mainly three sections. The first section corresponds to the associated-to-enzymatic-casein-micelles stage, where an important temperature-influence is given and the behavior is variable. The second section corresponds to the associated-to-modified-micelles-aggregation stage, where a clear exponential fall takes place. The third stage corresponds to the time when the curds are already formed, where the behavior is dropping linear [10].

Fig. 8 shows the adequacy of an exponential adjustment for the second stage. The further signal processing was made in order to detect the first-transition time.

E. Further signal processing

The listed algorithms are applied in order, aiming to detect a transition point in the timestamp-dependent curve. This stage is extremely specific to the chosen-parameter curve and the particular study-case.

1. Apply the Napierian logarithm to the correlation-maximum-time vector.
2. Lines-of-fit for each L_1-length possible window are found. The adjustment error for each possible line of fit is computed as the mean square error.
3. Energy for each L_2-length window of the vector of error is calculated, until a window is found to have more energy than the previous one. If moreover the ordinate- difference between the window's first and last points is greater than D, then the previous L_2-length window is taken as the best one, otherwise the iteration continues. Call the time when the center of this window occurs C.

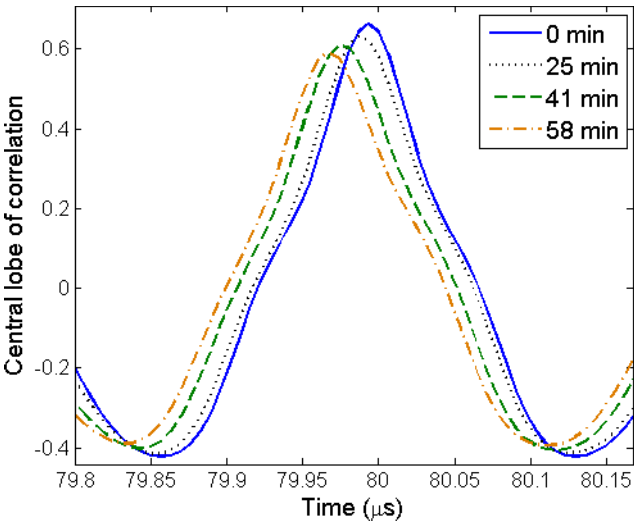


Fig. 6. Central lobe of correlation as coagulation goes by

4. Find the first-order function that adjusts in that best window, extending it to all the data.
5. The difference between this first-order function and the whole data vector is calculated within a window of two- times-L_2 length, up to C. Normalize the difference and find the first point in which it is low, for what a threshold is defined. This point is the sought time, found in an automatized way.

F. Results

In table II are presented the results obtained with the descripted further-signal-processing method for the considered series, labeled as *automatized*. These results are contrasted to the ones obtained by *eyeballing* all the analogue-to-figure-8 graphics.

The difference between the two methods is computed, resulting that the mean difference between the starting time found by simple observation of the curve against the one found by the further processing is of 0.9 min. This is a useful approach, which could be further improved.

V. CONCLUSIONS

The method of using low-power-ultrasound in pulse-echo mode against a rod-array has been proven to be useful in order to reveal structure-changes in the considered liquid medium.

The chosen signal processing is clearly adequate for roughly finding the transition time between the two first stages of the milk-coagulation process. The results obtained with a new instance of the physical device, which is made all out of stainless-steel, is to be surveyed. This has been constructed in order to make it robust against vibrations and eliminate problems related to border conditions.

The further aim is to have an automatic estimation of the transition time in accordance to the rheological results.

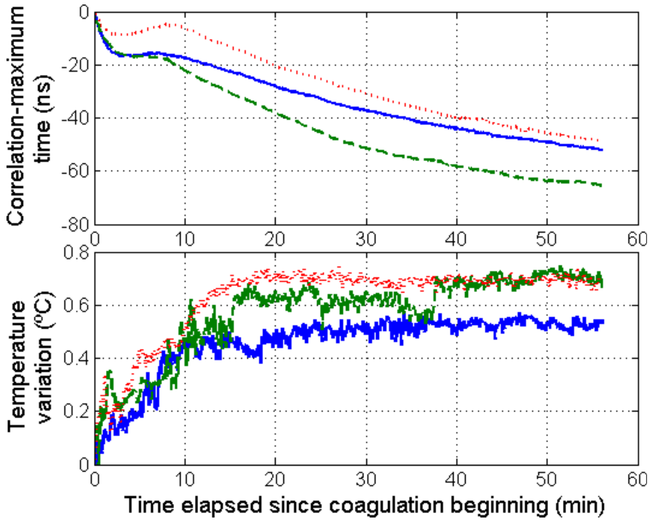
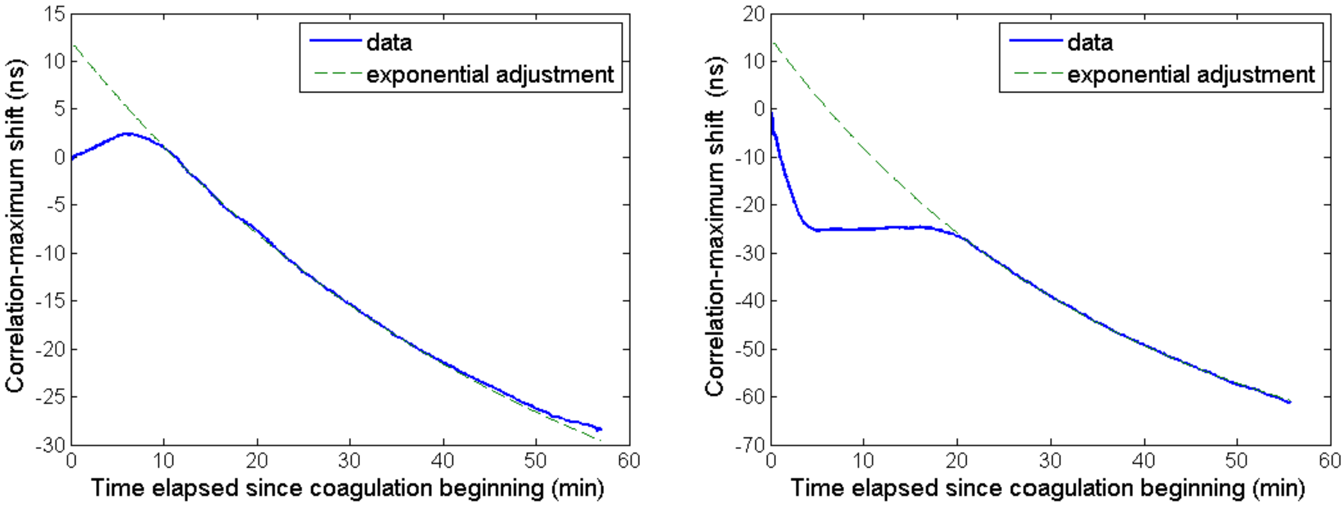


Fig. 7. Example of tracking results.



a. Series with more rennet.

b. Series with less rennet.

Fig. 8. Adjustment of the second stage by an exponential fall.

TABLE II. RESULTS

Series	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Eyeballing (min)	8.1	9.3	9.2	5.5	6.7	7.6	11.1	7.5	11.1	9.3	9.9	9.4	19.9	20.1	20.2
Automatized (min)	7.7	8.3	9.3	9.1	8.4	8.3	7.9	10.6	10.6	9.2	9.8	15.1	18.0	19.0	19.3
Difference (min)	0.4	1	0.1	3.6	1.7	0.7	3.2	3.1	0.5	0.1	0.1	5.7	1.9	1.1	0.9
Mean Difference (min)	0.9														

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