Characterization of milk coagulation based on the velocity of backscattered acoustic waves

Jaafari Nidae [1], A.Amghar [1] and F.Bakkali [1]
[1]Laboratory of Metrology and Information Treatment, faculty of science,
Ibn Zohr University, BP 8106, 80000 Agadir, Morocco
[a] Corresponding author's Email: nidae.jaafari@edu.uiz.ac.ma

Abstract. Sereval techniques based on ultrasound have been proposed for quality control of food products. They have shown that the use of ultrasonic techniques is very useful for quality control of certain food products and can be automated to allow rapid measurements while ensuring high accuracy. In this paper, we investigated three signal processing methods to calculate the group velocity of the acoustic wave: The Cross-correlation, Spectrum Ratio, and Smoothed Pseudo-Wigner-Ville transform to evaluate the use of ultrasonic measurements allow to characterize the milk coagulation process by correlating acoustic properties and coagulation process characteristics.

Keywords. Ultrasonic, velocity, cross-correlation, ratio of spectra, smoothed Pseudo-Wigner-Ville, milk coagulation.

1 INTRODUCTION

The use of ultrasound in the characterization of the elastic properties of samples plays a fundamental role in scientific and industrial fields. It provides important information on the mechanical characteristics and elastic properties of the samples, in a fast and accurate way. Ultrasonic sensors have the ability to propagate through non-transparent materials [6]. In addition, their advantages of non-contact measurement makes applications with high hygiene requirements possible. Ultrasonic measurements are therefore appropriate for monitoring and evaluating the progression of milk coagulation.

Ultrasonic velocity is a very valuable and important tool in the field of ultrasonic characterization to study the physical properties of the material [21,22]. Velocity measurement has been used to simultaneously evaluate the acoustic and geometric properties of homogeneous viscoelastic plates [7]. Broadband characterization of a viscous liquid [8]. Measurements are reported on the velocity of propagation of ultrasound in muscle tissue [23]. Refs, [2, 3] used ultrasonic measurement to determine the coagulation time and the characterization of syneresis by measuring the ultrasonic phase velocity.

This paper proposes to study the ultrasonic reflected waves using signal processing methods, including cross-correlation, spectral ratio, and smoothed Pseudo-Wigner-Ville.

The remainder of the paper is structured as follows: Section 2 describes the materials used in our study. Section 3 discusses the measurement technique. Section 4 presents the obtained results. Finally, we give a conclusion.

2 MATERIALS

2.1 Sample Preparation

We performed our experiments with skim milk. This milk was prepared by mixing 13 g of a milk powder in 90 g of water and heated to the fermentation temperature. After a slight agitation (to avoid the creation of bubbles), it was poured into a container which was placed in a thermostatically controlled water bath at the same coagulation temperature for 30 min to allow temperature equilibration of the system. The enzyme ferment was diluted with distilled water and mixed with the milk.

The mixture is stirred for 30 s to homogenize it. The enzymatic ferment used is called " Caille-lait universel 0,22 g/l ", is sold in pharmacies which is a product of the company COOPER Morocco.. In this work, we chose to work under the standard temperature 37°C and standard rennet recommended by the supplier.

2.2 Ultrasonic system

The configuration in which we used is represented on figure 1. The measurement system operates in transmit-receive mode: Only the transmitter transducer (5 MHz, 0.5 crystal diameter, model A309S-SU, Panametric, Olympus) immersed in water is used as a receiver. The transducer is connected to a pulse generator (DPR300-Pulser/Receiver, JSR Ultrasonics instrument) in a transceiver configuration. The backscattered signal on the interfaces is routed to a digital oscilloscope. (VirtualBench, National Instruments) which integrates perfectly with the LabVIEW platform.

The coagulating milk is enclosed in a Plexiglass container with parallel sides. We are interested in a longitudinal plane wave at normal incidence. This longitudinal wave is reflected and refracted between the different interfaces. All the reflections involved are taken into account providing echoes noted E_n. This wave is reflected on the first plate of the container generating three reflected waves (E1 to E3) and a longitudinal wave transmitted in the milk through plate 1, which is itself reflected on the second plate also generating three reflected waves (E4 to E6), and returns to the same transducer used as a receiver.

Figure 3 shows an example of the experimental backscatter signal of the milk during the coagulation process. The data are then processed to follow the evolution of the milk velocity.

3 Measurement technique

3.1 Cross Correlation

One of the most reliable techniques to measure the ultrasound velocity is to calculate the propagation time between the two signals, comparing them globally to limit small dispersion effects [7].

Here, a single transducer is used in a transceiver configuration and we consider only the two echoes E2 and E4. As shown in figures 2 and 3, which are reflected respectively at the interfaces: plexiglass/milk at an instant t1 and milk/plexiglass at an instant t2

The time lag Δt is the delay between the arrival of the echo E2 and the echo E4 in a return path received at distance 2d= 2cm.

$$\Delta t = t_4 - t_2 \quad (1)$$

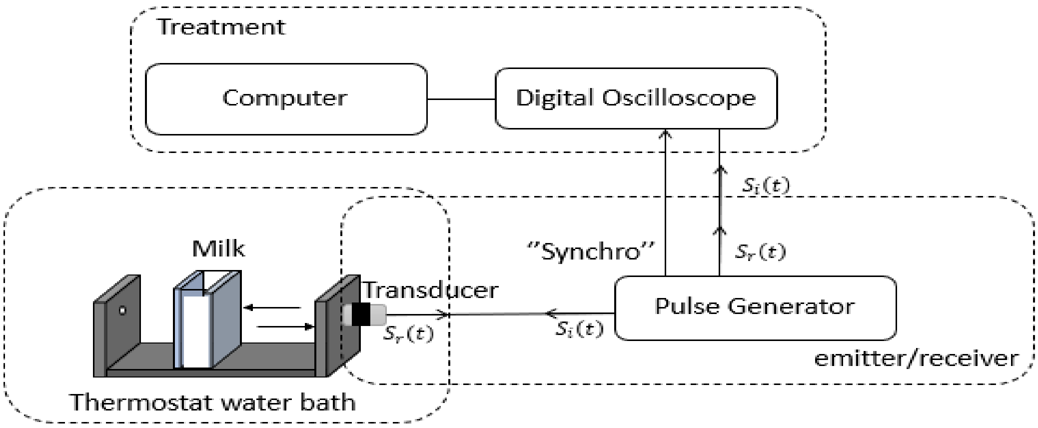


Fig 1. Experimental device for reflection measurement, by immersion in water.
$S_i(t)$: incident signal, $S_r(t)$: reflected signal

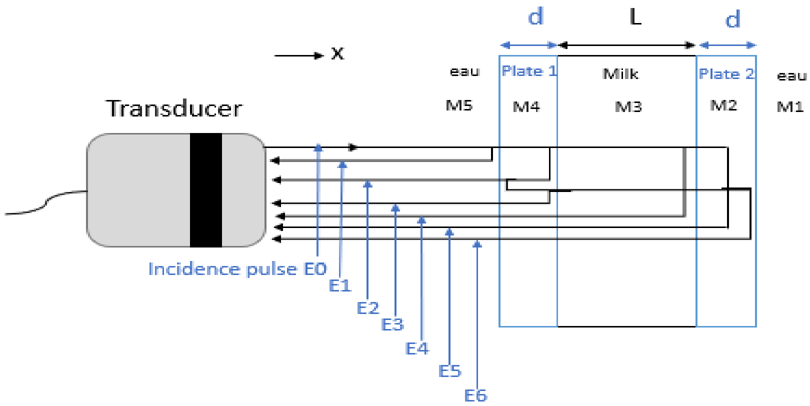


Fig 2. Illustration of different echoes reflected

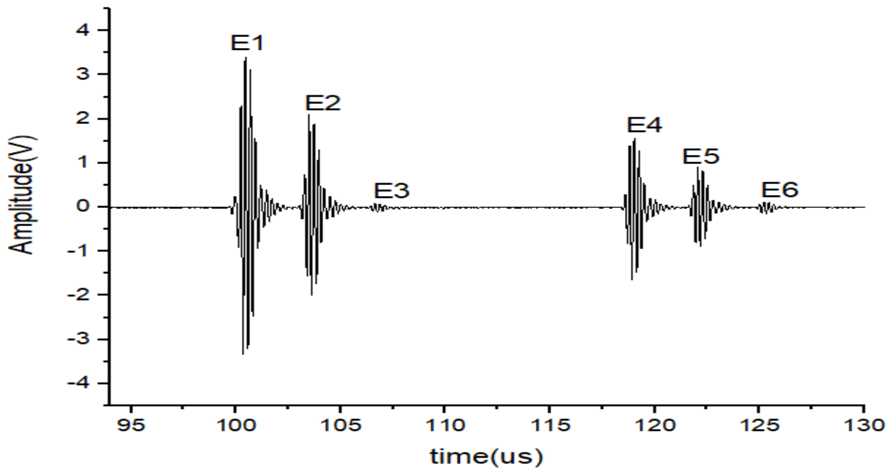


Fig 3. Experimental backscattered signal from the coagulating milk

In the case of a pure delay between the two echoes such that $E4(t) = E2(t - \Delta t)$, the cross-correlation function r_{E2E4} can be written as:

$$r_{E2E4}(t) = \int_{-\infty}^{+\infty} E2(\tau)E4(\tau + t - \Delta t)d\tau \qquad (2)$$

This function r_{E2E4} being symmetrical and maximal for a time t equal to zero. The maximum of r_{E2E4} is then reached for at time t equal to Δt.

During coagulation, the locations of the echoes with respect to time (x-axis) change and this is due to the change in the nature of the medium [5]. The abscissa corresponding to the peak of the maximum value of the function is the time of flight [12]. We calculated the cross-correlation function between E2 and E4 to derive the time of flight. Then, the velocity in the medium which corresponds to the ratio between the distance covered 2d by the pulse and the time of flight Δt:

$$V = \frac{2d}{\Delta t} \qquad (3)$$

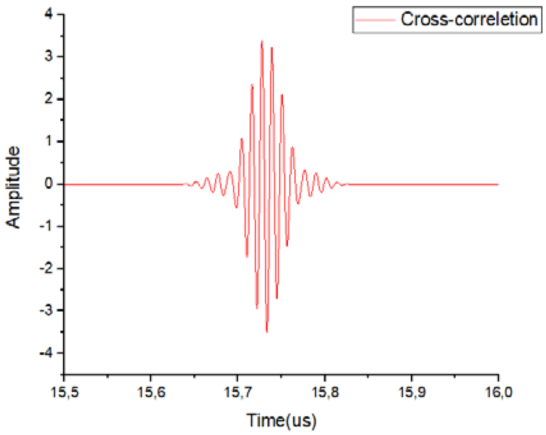


Fig 4. Cross-correlation function between echoes E2 and E4

The measured time resolution in the case of cross-correlation method is not sufficient for a precise measurement, because it allows to estimate the velocity only on a frequency band and therefore does not give access to the dispersion. The velocity calculated in this way corresponds to the velocity for a frequency near to the center frequency of the signal.

3.2 Ratio of spectra

Another technique for measuring the velocity is to compare the phase spectra of the E2 and E4 echoes to deduce the value of the phase velocity as a function of frequency. The Fourier transform of E2 and E4 is written, respectively as:

$$TF(E2) = A^{*}T_{54}R_{43}T_{54}e^{(-\alpha_{pg}(\omega)2d)}e^{-i\omega\left(\frac{1}{V_{pg}}2d+\emptyset_0\right)} \quad (4)$$

$$TF(E4) = A^{*}T_{54}T_{53}R_{32}T_{34}T_{45}e^{(-\alpha_{pg}(\omega)2d)} \quad (5)$$

$$e^{(-\alpha_{Milk}(\omega)2L)}e^{-i\omega(\frac{1}{V_{pg}}2d+\frac{1}{V_{Milk}}2L+\emptyset_0)}$$

where T_{ij} and R_{ij} are respectively the transmission coefficient and of reflection at the interface between the medium noted Mi and the medium noted Mj, α_{pg},and α_{Milk} are respectively the attenuation in the Plexiglas plate the attenuation in the milk. V_{pg} and V_{Milk} are respectively the longitudinal velocity in Plexiglas and the phase velocity in milk, and $\emptyset_0$ is the phase of the incident wave.

The argument of the ratio of the complex spectra corresponds to the phase difference between the echoes E4 and E2, as:

$$Arg\left(\frac{TF(E4)}{TF(E2)}\right) = -\frac{4\omega L}{V_{Milk}} \quad (6)$$

The argument of a complex number is evaluated numerically by the Arctangent function which gives a discontinuous phase change, the result necessarily being between -π and π. However, it is necessary to eliminate phase jumps by addition or subtraction of 2π each time a discontinuity is detected, performed by the phase unwrapping method. A continuous phase spectrum is obtained which can be approximated by the equation of a line, to obtain the phase velocity.

$$\rho = a_0 f + 2\pi m$$

Where m is an integer. This line passes thr
at the origin $f = 0$ and its slope is equal (7)
term $a_0 f$, which is purely linear with respect to frequency, corresponds to an overall delay between the two signals that is independent of frequency. We then calculate by linear regression the value of $2\pi m$, which we subtract from the total phase so that the final phase is zero at the frequency origin [20,24,7].

$$\rho - 2\pi m = -\frac{4\omega L}{V_{Milk}}$$

The velocity V_{Milk} is written as:

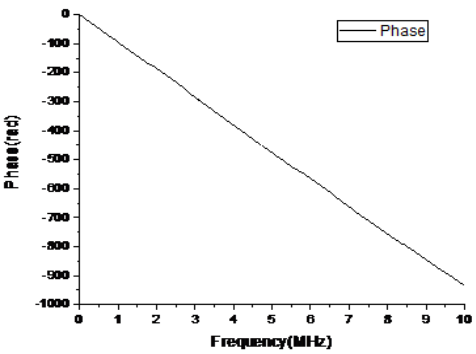
$$V_{Milk} = -\frac{4\omega L}{\rho - 2\pi m} \quad (9)$$

As shown in equation (9), the phase velocity of the sample is obtained by calculating the phase difference between the E4 echo and the E2 echo.

The ratio of the continuous phase spectrum is shown in figure 6a. The phase velocity as a function of frequency calculated from broadband pulses between 3MHz and 7MHz for milk is represented in figure 6b. The spectral method allows us to find the dispersion properties of the ultrasound velocity as a function of frequency [18,19]. Which can be seen in figure 6a, the small dispersion of the phase velocity with the frequency, is visible. Only the velocity relative to the center frequency is used to follow the evolution of milk during coagulation.

The frequency domain, obtained with the Fourier transform [13,14] allows us to know the different frequencies present in a signal, but it does not allow us to know at which instants these frequencies were emitted. So, it does not allow to know the temporal evolution of the frequency content of the signal. To overcome this limitation, we propose to use Time-frequency representation.

(a)



(b)

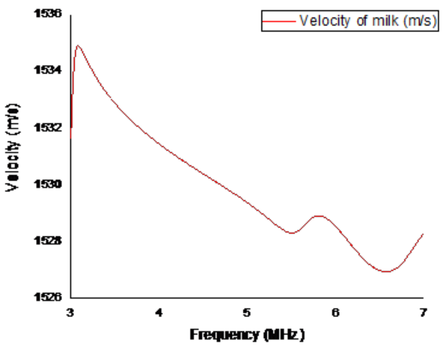


Fig 6. (a) Phase spectrum after unwrapping, (b) phase velocity in milk

3.3 Time-frequency analysis

The time-frequency representation allows to have the energy distribution of the information of the different components of a signal at given times. This distribution preserves the temporal and frequency supports of a signal and thus allows a precise localization in time and frequency.

3.3.1 The Smoothed Pseudo Wigner-Ville transform

The SPWV transform is a variant of the classical Wigner-Ville transform. It is proposed to minimize the interference terms between the internal components of the signal [11,25]. It uses two smoothing, temporal g(t) provided by the smoothing function, in order to reduce the undesirable effects of the cross terms and frequency h(t) by the sliding window as a function of frequencies, which aim to suppress the leakage effects [4, 26].
This distribution is expressed as follows [11]:

$$SPWV(t,f) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \left|h\left(\frac{\tau}{2}\right)\right|^2 \tag{10}$$

$$\left[g(t-\mu)x(\mu+\frac{\tau}{2})x^*\left(\mu-\frac{\tau}{2}\right)d\mu\right]exp^{-i2\pi f\tau}d\tau$$

The two quantities g(t) and h(t) can be set independently.

3.3.2 Time-frequency image

In the time-frequency image in Figure 7, we observe that the temporal echo terms (E2 and E4) are well localized. In what follows, we look for the temporal positions of the maximums at the center frequency of the transducer that represent the positions of the echoes. The celerity in the medium is the ratio of the distance traveled by the pulse in a round trip, and the time of flight which is the time of shift between echoes.

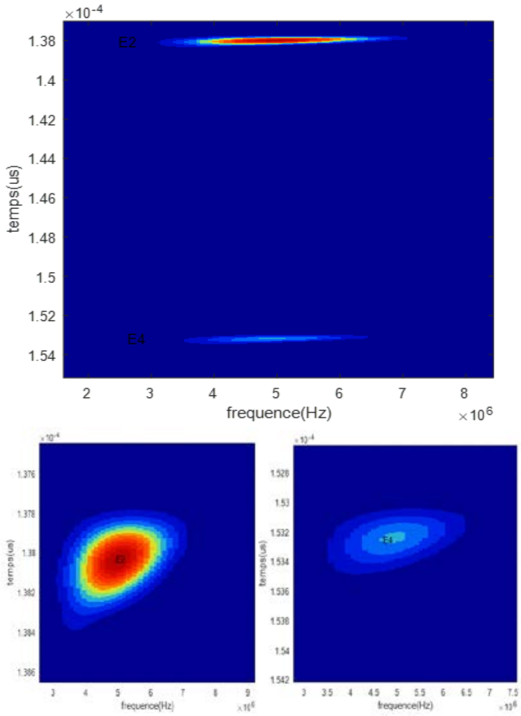


Fig 7. Time-frequency representation of the backscattered echoes E2 and E4.

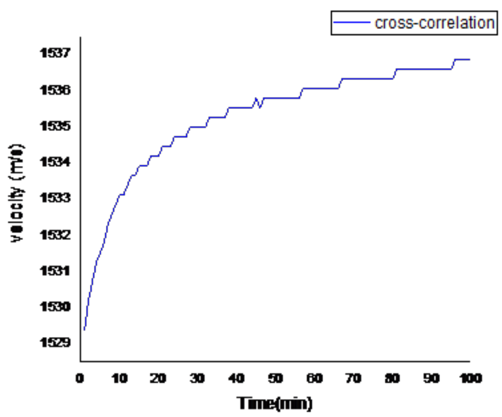
4 RESULTS AND DISCUSSIONS

4.1 Experimental results

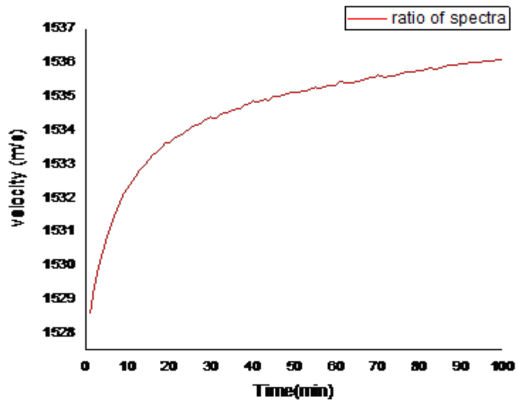
During the first 100 minutes of coagulation in the standard conditions of temperature and rennet, we have recorded the backscattered signals. It then. we determine the velocity in the milk at each moment, by the methods of Cross-correlation, ratio of spectra and the time-frequency method described above. Apparent velocity data obtained during coagulation are shown in figure 8.

Ultrasonic evaluation allows a quick and inexpensive determination of the milk state during the coagulation, thus meeting the requirements of today's dairy producers [10]. he evolution of the velocity during coagulation under standard conditions as a function of time (Figure 8) shows a steady increase. This is due to the nature of the coagulation process. [15]. However, the rate of change of velocity appears to have two main phases. In the first, there is a rapid increase in velocity after the addition of rennet (which may involve the enzymatic phase). followed by a slow change in velocity in the second phase which illustrates the physicochemical and aggregation phase [2]. Therefore, the transition point between these two phases has been designated as the clotting time [1].

(a



(b)



(c)

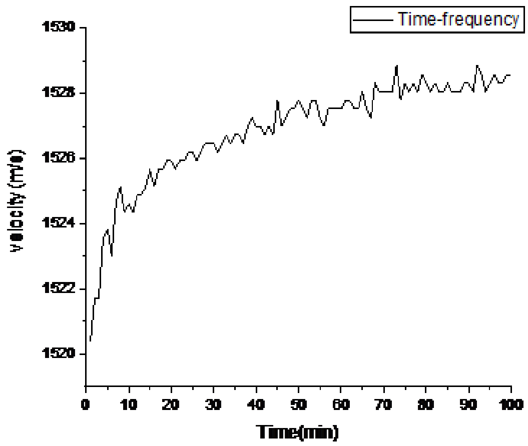


Fig 8. Evolution of the milk velocity obtained by: (a) Cross-Correlation, (b) ratio of spectra, (c) Time frequency

4.2 Discussions

We can notice at first that the evolution of the velocity during the coagulation is almost the same in the three methods of calculation used.

Comparing the results of the calculation with the temporal, spectral and time-frequency methods. The velocity values in a certain time are presented in (table 1). The velocity values obtained at a given instant by the three methods of calculation are very close, especially those found by the cross-correlation method and the spectral ratio. The velocity values obtained by time-frequency were slightly lower than the values found by ratio of spectra and cross-correlation.

Table 1. Values of the ultrasound velocity during coagulation by the three methods at different times.

Time(min) / Velocity(m/s)	t=0	t=20	t=40	t=60	t=80	t=100
Cross-correlation	1529,37	1534,18	1535,51	1536,05	1536,32	1536,86
Ratio of spectra	1528,58	1533,64	1534,86	1535,32	1535,77	1536,1
Time-frequency	1520,39	1525,93	1526,99	1527,52	1528,31	1528,58

The maximum relative difference between the results of the temporal and spectral methods is 0.79 m/s. The maximum gap between the spectral and time-frequency methods is 8.19 m/s.
Certainly, that temporal analysis is quick and easy to implement, but it does not give access to the dispersion of the signal. Spectral analysis is one of the most important tools available for signal processing, yet it is limited in the case of non-stationary signals [17], that is to say signals whose spectral characteristics evolve over time with other terms. With TF, we lose all information related to time [16]. It is therefore essential to implement specific tools to describe a temporal evolution of frequency characteristics.
The choice of a calculation method depends on the structure to be examined and the conditions under which the test will be performed.

5 Conclusion

In this article, we have used three representations of the backscattered from the coagulating milk signal: temporal representation, frequency and time-frequency. In general, the time domain is the first and most natural way to represent an acoustic signal. The frequency domain, obtained by the Fourier transform. The time-frequency image of the backscattered signal is a combination of the frequency content of a given signal in the time domain. In order to use each representation with the appropriate velocity calculation method, the principle of velocity measurement based on the methods of cross-correlation, spectrum ratio and Smoothed Pseudo Wigner-Ville transform is proposed, and its experimental analysis is performed during milk coagulation using the non-contact ultrasonic method.

References

1. AY, Chyung et GUNASEKARAN, S. *Ultrasonic attenuation measurements for estimating milk coagulation time*. Transactions of the ASAE, (1994), vol. **37**

2. BAKKALI, F. MOUDDEN, A. FAIZ, B. et al. *Ultrasonic measurement of milk coagulation time*. Measurement Science and Technology, 2001, vol. **12**.

3. TAIFI, N., BAKKALI, F., FAIZ, B., et al. *Characterization of the syneresis and the firmness of the milk gel using an ultrasonic technique*. Measurement Science and Technology, 2005, vol. **17**.

4. DARIOUCHY, Abdelilah, AASSIF, El Houcein, DECULTOT, Dominique, et al. Acoustic *characterization and prediction of the cut-off dimensionless frequency of an elastic tube by neural networks*. IEEE transactions on ultrasonics,

ferroelectrics, and frequency control, (2007), vol. **54**.

5. IZBAIM, Driss, FAIZ, Bouazza, MOUDDEN, Ali, et al. *Contrôle ultrasonore du processus de la fermentation du yaourt*. In : 10ème Congrès Français d'Acoustique. (2010).

6. Meng, Rui Feng, et al. *On-line monitoring of yogurt fermentation using acoustic impedance method*. Applied Mechanics and Materials. Vol. **101**. Trans Tech Publications Ltd, (2012).

7. Abdelhak El Mouhtadi. *Ultrasonic Characterization of Homogeneous and Composite Viscoelastic Plates*. Acoustics [physics.class-ph]. University of Le Havre, (2011). French.

8. GHODHBANI, Nacef, MARECHAL, Pierre, et DUFLO, Hugues. *Ultrasonic broadband characterization of a viscous liquid: Methods and perturbation factors*. Ultrasonics, (2015), vol. **56**.

9. ELHANAOUI, Abdelkader, AASSIF, Elhoucein, MAZE, Gérard, et al. *Acoustic scattering by a two-layer cylindrical tube immersed in a fluid medium: Existence of a pseudo wave*. Ultrasonics, (2016), vol. **65.**

10. JIMÉNEZ, Antonio, RUFO, Montaña, PANIAGUA, Jesús M., et al. *Contributions to ultrasound monitoring of the process of milk curdling*. Ultrasonics, (2017), vol. **76**.

11. AGOUNAD, S. AASSIF, El Houcein, KHANDOUCH, Younes, et al. *Characterization and prediction of the backscattered form function of an immersed cylindrical shell using hybrid fuzzy clustering and bio-inspired algorithms*. Ultrasonics, (2018), vol. **83**.

12. SUN, Sihao, LI, Shiyang, LIN, Luan, et al. *A novel signal processing method based on cross-correlation and interpolation for ToF measurement.* In: 2019 IEEE 4th International Conference on Signal and Image Processing (ICSIP). IEEE, (2019).

13. PROSSER, W. H., SEALE, Michael D., et SMITH, Barry T. *Time-frequency analysis of the dispersion of Lamb modes*. The Journal of the Acoustical Society of America, 1999, vol. **105**.

14. SESSAREGO, J. P., SAGELOLI, J., DEGOUL, P., et al. *Analyse temps-fréquence de signaux en milieux dispersifs. Application à l'étude des ondes de Lamb*. Nous, 1990, vol. **1**.

15. GUNASEKARAN, Sundaram et AY, Chyung. *Milk coagulation cut-time determination using ultrasonics*. Journal of Food Process Engineering, (1996), vol. **19**.

16. BOUCHEFIRAT, Messaoud et DIB, Samira Encadreur. *Analyse spectrale en contrôle non destructif par ultrasons*. (2019). Thèse de doctorat. Université de Jijel.

17. FLANDRIN, Patrick. *Représentations temps-fréquence des signaux non-stationnaires*. (1987). Thèse de doctorat. ANRT.

18. SAMET, Naïm, MARÉCHAL, Pierre, et DUFLO, Hugues. *Ultrasonic characterization of a fluid layer using a broadband transducer*. Ultrasonics, 2012, vol. **52**, no 3, p. 427-434.

19. PETERS, François et PETIT, Luc. *A broad band spectroscopy method for ultrasound wave velocity and attenuation measurement in dispersive media*. Ultrasonics, 2003, vol. **41**.

20. JEONG, Hyunjo et HSU, David K. *Experimental analysis of porosity-induced ultrasonic attenuation and velocity change in carbon composites*. Ultrasonics, 1995, vol. **33**.

21. STRELITZKI, R. et EVANS, J. A. *On the measurement of the velocity of ultrasound in the os calcis using short pulses*. European Journal of Ultrasound, 1996, vol. **4**.

22. TAKEDA, Yasushi. *Development of an ultrasound velocity profile monitor*. Nuclear Engineering and Design, 1991, vol. **126**.

23. MOL, Chris R. et BREDDELS, Paul A. *Ultrasound velocity in muscle*. The Journal of the Acoustical Society of America, 1982, vol. **71**.

24. MOBLEY, Joel, MARSH, Jon N., HALL, Christopher S., et al. *Broadband measurements of phase velocity in Albunex® suspensions*. The Journal of the Acoustical Society of America, 1998, vol. **103**.

25. BOUBAL, O. et OKSMAN, J. *Application de la distribution de pseudo Wigner-Ville lissée réallouée à la détection de cliquetis*. TS. Traitement du signal, 1998, vol. **15**.

26. ANDRIA, Gregorio et SAVINO, Mario. *Interpolated smoothed pseudo Wigner-Ville distribution for accurate spectrum analysis*. IEEE transactions on instrumentation and measurement, 1996, vol. **45**.