Comparative Study of Different Methods to Assess Ultrasonic Velocities of Waves in a Liquid Medium

M. Montaña RUFO, Antonio JIMÉNEZ, Jesús M. PANIAGUA

GRnIIU Research Group, Polytechnic School, University of Extremadura; Cáceres, Spain
Phone: +34 927257598, Fax: +34 927257203; e-mail: ajimenez@unex.es

Abstract
This paper studies and compares the results from different methods to evaluate ultrasonic velocity (UV) of travelling waves during the coagulation process of renneted milk. The measurement of the time of flight (TOF) was always done from the beginning of the transmitter pulse to: (a) the beginning, (b) the time of maximum value of voltage and (c) the time of minimum value of voltage of each wave train belonging to the 1st, 2nd and 3rd echoes in the receiver’s A-scan. From the known distances that are travelled by the waves and the aforementioned TOFs between consecutive echoes, two different values of UV were calculated as: (1) averages and (2) fits by linear regressions. Moreover, by means of Fourier transformation (FFT), the influence of a periodic excitation (multiple echoes) allowed us to determine (3) the length of period, i.e. another measurement of TOF via cepstrum and consequently, another UV value.

Keywords: Ultrasonic velocity (UV), A-scan, time of flight (TOF), cepstrum, milk coagulation, ultrasonic process monitoring

1. Introduction

Several instrumental methods are used to assess liquids and gels, including foods. Ultrasound techniques are relatively cheap, simple and energy saving. In particular, low intensity ultrasound (LIU) has been successfully utilized for studying the physicochemical and structural properties of fluid foods, such as dairy products [1-8], oils [9], juices [10-12], wines [13-15], beers [16], honey [17,18], etc.

Ultrasonic characterization of fluid properties is mainly based on the physical measurement of the ultrasonic wave attenuation coefficient and/or phase velocity [19]. In basic research sound, velocity measurements are increasingly used; in addition, they are often employed in the process control of manufacturing procedures and also in a routine monitoring of quality changes of complex products during and after manufacture. Because of its outstanding sensitivity to liquid states, sound velocity is a favourable parameter for such applications [20]. In fact, in most applications, the determination of sound velocity is of key significance. Sound velocity measurements can be quickly performed and permit an examination of optically opaque samples. Nevertheless, most authors (with a few exceptions) rarely describe the methods used to determine sound velocity, in particular the technique for reading the time during which the sound wave travels through a given medium, so called: time of flight [21].

The purpose of this work was to identify the simplest and the most accurate of different methods for sound velocity determination in raw milk and its coagulation process. At the same time, we compared the results obtained by those methods.

2. Materials and methods

2.1 Materials

The experiments were performed with raw sheep milk collected from a local dairy processing centre (Hnos. Pajuelo SAT) on four separate days. These samples, 46 litres each, were used for both the characterization of the raw milk and the coagulation process. In particular, the numbers of inspections in order to monitor the coagulation process were 16, 16, 17 and 16 for
each of the four raw milks, respectively. The coagulation process generally follows the flow chart of Fig. 1. The separation of the curds and whey takes place in large vats and any impurities are eliminated here. When the milk reaches 28-32°C, the rennet is added, which, in our survey, is a liquid obtained from the pistils of the Cynara Cardunculus flower. Finally, when the curd is formed, it is broken into pieces of around the size of a grain of rice using fine metallic threads [22]. During the various inspections, the samples' temperature and pH were monitored constantly.

2.2 Immersion ultrasonic device

The raw milk and curd formation experiments were performed by immersion ultrasound. Total of 4 experiments were conducted in a laboratory environment at [31.7-33.0] °C, [31.2-32.0] °C, [31.1-34.5] °C and [32.5-35.0] °C, respectively. The device used consisted of a pulser-receiver (Panametrics, Model 5077), two pairs of transducers (Panametrics V318SU) whose main characteristics are listed in Table 1, and a digital storage oscilloscope (Tektronix TDS 1012B) connected to a PC incorporating the data processing software Tektronix OpenChoice Desktop v1.4. Immersion transducers are single element longitudinal wave transducers, whose wear face is impedance matched to water. The transducers were mounted on a custom-designed metal structure that ensured their perfect face-to-face alignment. Transducers were used in pulse-echo (P-E) mode. For the proposal, one of the transducers acted as a mirror which reflected the ultrasound waves. The test stand with samples is presented in Fig. 2.

<table>
<thead>
<tr>
<th>Transducer</th>
<th>f (MHz)</th>
<th>φ (mm)</th>
<th>λ (milk) (mm)</th>
<th>N (milk) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V318SU</td>
<td>0.5</td>
<td>19</td>
<td>3.0</td>
<td>30</td>
</tr>
</tbody>
</table>

**Table 1. Frequency f, diameter φ, wavelength λ, and near-field N, in milk of the immersion ultrasonic transducer used in the inspection of the milk and the coagulation process.**
2.3 Methods

Two methods for determining sound velocity were used. They were compared from the same ultrasonic signals captured in milk samples. We took account that the distance $d$ travelled by the ultrasonic beam before being reflected must be greater than the transducer's near-field length for the value of the velocity to be coherent [8]. That is why $d$ was within the range [30.3-30.8] mm for all samples.

2.3.1 Getting velocities via TOF

The velocity measurements were computed from the times $t_{i,j}$ obtained for $i$ consecutive echoes of the receiver's A-scan. These echoes are caused by reflections between the transducers facing each other. If we defined time considering the value achieved on the time axis at the point where the signal line intersects the “zero” level between the first negative peak and the next positive peak where the echo appears, $j=0$. If we defined time considering the value achieved on the time axis at the maximum and minimum values of voltage, $j=M$ and $j=m$, respectively. Since the transducers are separated by a distance $d$, the $(i+1)$ and $i$ echoes both are separated by twice that distance. Fig. 3 shows a typical A-scan of one of the inspections. We have marked the times of the trigger pulse ($t_{0,0}$) and echoes ($t_{i,j}$).

Thus, the determination of three different values for velocities was immediate from Eq [1] and [2]:

![Figure 2. Schematic and experimental set-up for the immersion measurements](image-url)
Figure 3. Example and characteristic points of the A-scan signal received by the Panametrics V318 transducer. After the trigger pulse, one observes the echoes of the ultrasound signal. Furthermore, another velocity measurement \( v_j \) was computed from the averages \( <v_{ij}> \) of the three mentioned values for velocities, as indicated by Eq [3]:

\[
v_j = \langle v_{0j}, v_{1j}, v_{2j} \rangle \quad (\text{for } j = O, M, m)
\]

Finally, this method allowed us to get another value to compute velocity \( v'_j \) from the slope of the linear regression fit corresponding to Eq. [4]:

\[
s = v'_j \cdot t_{i,j} \quad (\text{for } i = 0, 1, 2 \text{ and } j = O, M, m)
\]

where \( s \) are the known distances that are travelled by the waves corresponding to the first, second and third echoes.

All in all, this method provided 15 velocity values \( (v_{0O}, v_{0M}, v_{0m}, v_{1O}, v_{1M}, v_{1m}, v_{2O}, v_{2M}, v_{2m}, v'_O, v'_M, v'_m) \) from a single A-Scan for each test.

2.3.2 Getting velocities via cepstrum

By means of Fourier transformation it is possible to decompose a time variable signal into the frequency components contained in it. This transform gives a frequency domain representation of the amplitude and phase of a continuous signal acquired in the time domain. Direct calculation of the Discrete Fourier Transform would be computationally very intense, but there are various algorithms that speed up the process. Among them there stands out the FFT presented by Cooley & Tukey in 1965 [23]. Today, there are signal processing devices which allow the rapid calculation of the FFT, as was the case used in the present study. The procedure used to calculate and plot the FFT identifies the frequency range covering the
received ultrasonic pulse signal and the centre frequency (that of maximum amplitude). By way of example, Fig. 4 shows the FFT obtained from A-Scan in Fig. 3.

![FFT of the signals received by the Panametrics V318 transducer in the inspection showed in Fig. 3](image)

From the so generated spectrum we derived additional properties of the object under investigation. The influence of a periodic excitation (here multiple echoes) manifested as spectral maxima at multiple times of the fundamental frequency thus as multiplicative superpositions of the fundamental spectrum of the probe with an undulation in form of equidistant maxima in the spectrum. From the distance of maxima followed the time of flight between the reflexes. By means of the so-called cepstrum method the spectrum could be smoothed as well as the length of period be determined directly. The cepstrum arose by a FFT of the logarithmized spectrum [24]. As you can see in the example of Fig. 5, which shows the cepstrum created from FFT in Fig. 4, one reads directly from the first maximum a periodic time of flight $t$. In this way, the spectral evaluation methods provide further possibilities for velocity measurements. In particular, we computed another value for velocity $v$ from Eq [5]:

$$v = \frac{2d}{t}$$  \hspace{1cm} (5)
3. Results and discussion

For the four raw milks measured, the values of the velocity $v$ obtained with the V318 transducer in pulse-echo mode were: $(1530\pm20)$ m/s, $(1410\pm40)$ m/s, $(1438\pm18)$ m/s and $(1432\pm17)$ m/s. These results are coherent with the literature data. In particular, Donoso et al. report values of $v$ in milk with different fat contents of between 1500 m/s and 1540 m/s [25], and Taifi et al. and Bakkali et al. report values in the ranges $[1514–1597]$ m/s [6] and $[1517–1519]$ m/s [1], respectively, in reconstituted milk.

Analysis of the validation plots produced from the propagation velocities (including coagulation process) also confirmed the correctness of the data acquisition. This analysis has been evaluated by establishing a fit to the equation of a straight line between a velocity parameter and the remaining ones. Thus, Table 2 shows the coefficients $r$ of these linear correlations. As you can see, $r$ values were greater than 0.80 in practically all cases, verifying that no major errors were made during the data acquisition in the laboratory. In particular, the fits involving velocities obtained from all echoes showed a greater $r$. This aspect could be attributed to the path of the sound wave considered, which travels through the sample three times. On the contrary, those fits involving the velocities computed from the times at the maximum value of voltage showed a lower coefficient, around 0.5 or less. In any case, all fits showed an excellent statistic significance level with a $P$-value lower than 0.05, except those marked in red in Table 2, which exceeded that value. Figure 6 shows two examples of the validation plots obtained with (a) some velocities via TOF, and (b) some velocities via cepstrum.

**Table 2. Coefficients of linear correlations obtained when fitting the equation of a straight line for each velocity parameter with the others.**

<table>
<thead>
<tr>
<th>$v_O$</th>
<th>$v_M$</th>
<th>$v_m$</th>
<th>$v'_O$</th>
<th>$v'_M$</th>
<th>$v'_m$</th>
<th>$v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.87</td>
<td>0.97</td>
<td>0.90</td>
<td>0.79</td>
<td>0.85</td>
<td>0.87</td>
<td>0.87</td>
</tr>
<tr>
<td>1.08</td>
<td>0.83</td>
<td>0.70</td>
<td>0.95</td>
<td>0.84</td>
<td>0.78</td>
<td>0.93</td>
</tr>
<tr>
<td>0.91</td>
<td>0.81</td>
<td>0.85</td>
<td>0.85</td>
<td>0.40</td>
<td>0.87</td>
<td>0.93</td>
</tr>
<tr>
<td>0.69</td>
<td>0.90</td>
<td>0.83</td>
<td>0.24</td>
<td>0.77</td>
<td>0.96</td>
<td>0.85</td>
</tr>
<tr>
<td>0.77</td>
<td>0.74</td>
<td>0.19</td>
<td>0.84</td>
<td>0.76</td>
<td>0.84</td>
<td>0.87</td>
</tr>
<tr>
<td>0.90</td>
<td>0.44</td>
<td>0.73</td>
<td>0.93</td>
<td>0.93</td>
<td>0.90</td>
<td>0.93</td>
</tr>
<tr>
<td>0.53</td>
<td>0.82</td>
<td>0.94</td>
<td>0.95</td>
<td>0.91</td>
<td>0.97</td>
<td>0.84</td>
</tr>
<tr>
<td>0.22</td>
<td>0.38</td>
<td>0.57</td>
<td>0.35</td>
<td>0.43</td>
<td>0.78</td>
<td>0.94</td>
</tr>
<tr>
<td>0.84</td>
<td>0.86</td>
<td>0.95</td>
<td>0.83</td>
<td>0.74</td>
<td>0.96</td>
<td>0.81</td>
</tr>
<tr>
<td>0.94</td>
<td>0.96</td>
<td>0.99</td>
<td>0.77</td>
<td>0.94</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>0.96</td>
<td>0.95</td>
<td>0.93</td>
<td>0.95</td>
<td>0.93</td>
<td>0.96</td>
<td>0.93</td>
</tr>
<tr>
<td>0.95</td>
<td>0.84</td>
<td>1.00</td>
<td>0.93</td>
<td>0.94</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>0.80</td>
<td>0.94</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>0.82</td>
<td>0.79</td>
<td>0.82</td>
<td>0.79</td>
<td>0.82</td>
<td>0.79</td>
<td>0.82</td>
</tr>
<tr>
<td>0.92</td>
<td>0.92</td>
<td>0.92</td>
<td>0.92</td>
<td>0.92</td>
<td>0.92</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The results computed by the methods which velocities were obtained from all echoes ($v_O$, $v_M$, $v_m$, $v'_O$, $v'_M$, $v'_m$ and $v$) are illustrated graphically in Fig. 7 for the four raw sheep milks. The location of mean values is represented by the point, and errors by the bars. According to the figure, one can’t infer a greater accuracy of results produced by any method. In fact, no significant differences were determined between the discussed methods. Therefore, it seems insignificant whether the determination of velocities by a method involves values corresponding to the points where the signal line intersects the “zero” level or time values corresponding to the maximum or minimum values of voltage. Nevertheless, error values suggest that cepstrum analysis is a more precise method, as with the other methods, the error...
bars are either wider or equal to any particular milk only. In this regard, it should be noted that the higher relative velocity errors corresponded to $v_O$, $v_M$, and $v_m$.

![Graphs](image)

Figure 6. Validation graphs of the velocity values obtained with (a) $v'_m$ vs. $v_O$ (both of them via TOF) and (b) $v'_O$ vs. $v$ (via TOF vs. via cepstrum, respectively)

4. Conclusions

This study compared different methods for evaluating ultrasonic velocity (UV) of travelling waves during the coagulation process of renneted milk as an example of liquid medium. On the one hand, some velocity values were obtained via TOF, considering the times of flight obtained for consecutive echoes of the receiver’s A-scan. On the other hand, other velocity values were obtained via cepstrum, determining directly the length of periodic excitation at multiple times of the fundamental frequency that appears in the FFT.

An analysis of the results delivered by all tested methods suggests that, firstly, the obtained velocity values were coherent with the literature data, showing also a high correlation coefficients when a fit to the equation of a straight line between each velocity parameter and the remaining ones was established. In particular, the fits involving velocities obtained from all echoes showed a greater correlation coefficient, due, in principle, to the fact that complete A-scans were considered in these cases.

Secondly, it seems insignificant whether the determination of velocities by a method involves values corresponding to the points where the signal line intersects the “zero” level or time values corresponding to the maximum or minimum values of voltage. Nevertheless, error values suggest that cepstrum analysis is a more precise method.
Figure 7. Sound velocity in the four raw milk samples computed with methods involving all echoes.

Acknowledgements

The collaborations of Hnos. Pajuelo SAT and Centro Tecnológico Agroalimentario Extremadura (CTAEX) are gratefully acknowledged for their participation in discussions and valuable inputs to this study, as well as the financial support from FEDER and Plan Nacional I+D (CIT-060000-2008-0008).

References