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Comparison of methods for measuring ultrasonic velocity variations during ageing or fermentation of food materials

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Abstract: A comparison of methods for measuring time-of-flight (TOF) variations of ultrasonic waves travelling through food materials is presented. Six commonly used methods for the TOF determination were taken into account, four in the time domain and two in the frequency domain. First, methods were briefly described and then tested using simulated ultrasonic waves. Factors such as signal-to-noise ratio (SNR), attenuation and delay between signals are taken into consideration, whereas the root mean-squared error (RMSE) and execution time are used as parameters for comparison. Of the six methods, the one operating on the basis of phase shift proved to be the most robust and provided excellent levels of resolution and optimum performance across a wide range of SNR values. Experiments were subsequently conducted in a real process, which corroborated the results obtained during the theoretical study. The ability to accurately measure TOF variations of ultrasonic waves makes it possible to detect more precisely velocity variations, which is the most commonly used parameter to determine and acoustic monitor physicochemical changes and properties of food materials.

1 Introduction

In low-intensity ultrasound, the ultrasonic wave parameters generally measured include the velocity of propagation, the attenuation coefficient of the acoustical wave travelling through the sample and the acoustic impedance of the material. These parameters can be used to measure and/or control process variables or to obtain information about different physicochemical properties of foods such as air bubbles in aerated foods, ratio of fat in meats, vegetable and fruit characterisation, quality of eggs, cracks in cheese, texture of biscuits, milk coagulation, wine fermentation control or dough characterisation among others [1–10]. From these three parameters, the ultrasonic velocity is generally more widely used to evaluate the properties of food materials.

Ultrasonic velocities are generally determined from measurements of the time-of-flight (TOF) of ultrasonic waves, which is the time it takes an ultrasonic wave to travel from the transmitter to the receiver transducer. If the distance d travelled by an ultrasonic wave is constant, its velocity c can be calculated by dividing the distance travelled by TOF

$$c = \frac{d}{\mathrm{TOF}} \tag{1}$$

Therefore to monitor the evolution of a process or characterise the changes that occur in a determinate medium using ultrasound velocity, such as ageing or fermentation of food products, it is enough to simply obtain the TOF variations over a certain period of time [11, 12]. The precision of the information required will directly depend on the level of accuracy attained in obtaining the TOF variations between waves that are gathered as they interact with the medium or process under test conditions.

To date, there are a number of different methods that can be used to calculate TOF variations between signals, whether in temporal or frequency domains [13]. Some of these methods are not sufficiently accurate in measuring TOF; for example, the threshold method that provides an overestimation of the TOF. However, this and other easily implementable methods can remain valid for determining TOF variations.

This paper has been divided into five sections, the first being the introduction. Section 2 gives a brief description of six TOF measurement methods considered in this study, along with a modification that can be applied to two of them. Section 3 provides the materials and methods used and Section 4 analyses the performance of each method in determining TOF variations. First, a theoretical study will be carried out that simulates groups of signals that are strategically delayed and have different signal-to-noise ratios (SNR). Then, an experimental study will be conducted on a set of waves gathered during the monitoring of a real fermentation process. Finally, Section 5 presents the main conclusions from this study to aid in the selection of the most suitable method to apply to processes that evolve relatively slowly.

2 Review of methods

In the time domain, the threshold is the simplest, fastest and most widely used method [14]. In this method, the TOF is estimated as the time at which the amplitude of the ultrasound signal at the receiver transducer first exceeds a preset threshold level (see Fig. 1). According to its principle of operation, the main limitation of this method is that the TOF is overestimated since the threshold level must be high enough to eliminate false detections.

Nevertheless, taking into account that the key issue in this study is the TOF variation between consecutive signals, determining the exact moment at which the wave arrives becomes of secondary importance, because the level of overestimation of the variations would be compensated by obtaining the difference between TOF values for consecutive signals. Moreover, it will be possible to establish a higher threshold level to prevent better from noise and to work within more internal and more stable areas of each signal.

The maximum detection and the zero-crossing methods are two variants that bear a relation to the threshold method, as can be seen in Fig. 1.

The resolution of these methods is often limited by the sampling period of the signals, but can be improved by using interpolation tools in the areas of interest [15]. Fig. 2 shows the capture of five samples in the neighbourhood of the maximum peak of an ultrasonic wave (max1), along with the curve obtained by carrying out a parabolic interpolation using 51 points. In this example the location of the real peak of the wave is improved (max2) by a difference of approximately half the sampling period.

In the same way, by carrying out linear interpolation between to consecutive samples around a zero crossing, positive and negative amplitude values (point 2 in Fig. 1), it will be possible to increase the resolution in this small area.

Another method, very suitable for determining variations between signals, is based on correlation or cross-correlation

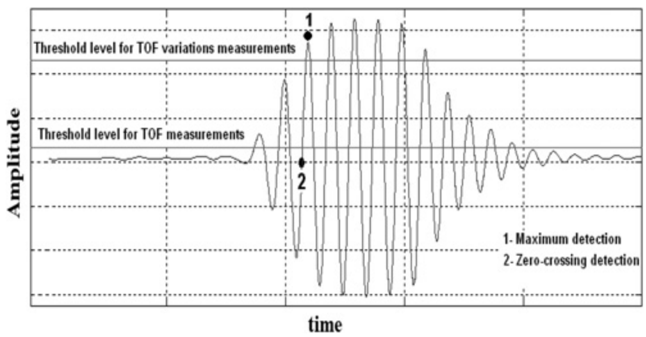

Fig. 1 *Threshold, maximum detection and zero-crossing detection methods for obtaining TOF variations*

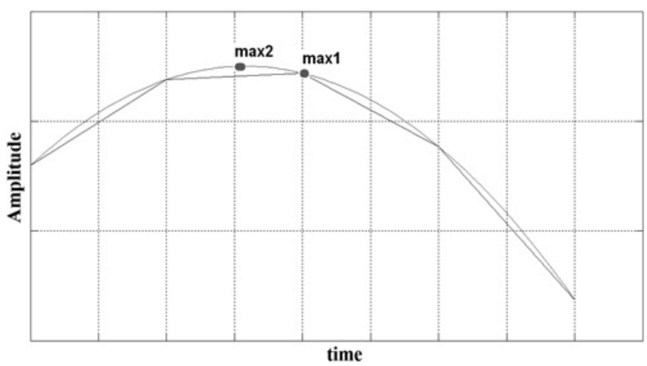

Fig. 2 *Original signal with five samples (max1) and interpolation curve with 51 points (max2)*

techniques [13, 16, 17]. This method has usually high execution times but is considered to work very well, as it uses all the information contained in the wave and is therefore a very thorough way of calculating TOF variations. In this case, the accuracy of the calculation depends principally on the sampling frequency and the similarity in wave forms.

In the frequency domain, one of the most common methods of calculating TOF variations is to use the phase variations between pairs of displaced signals [18]. This method is based on the time-shift property of the Fourier transform, which states that two signals $x_1(t)$ and $x_2(t)$ with a scale factor k and a time-shift difference $\Delta\tau$:

$$x_2(t) = kx_1(t - \Delta t) \tag{2}$$

have the following relationship between their respective Fourier transforms $X_1(f)$ and $X_2(f)$

$$X_2(f) = k\mathrm{e}^{-2\pi f \Delta\tau} X_1(f) \tag{3}$$

Therefore the phase spectrum $\varphi_2(f)$ of $X_2(f)$ can be computed by the formula

$$\phi_2(f) = \phi_1(f) - 2\pi f \Delta\tau \tag{4}$$

Finally, taking $\varphi_1(f)$ as the reference phase spectrum, the TOF variation between both signals can be computed from (4) as follows

$$\Delta\tau = -\frac{\phi_2(f) - \phi_1(f)}{2\pi f} \tag{5}$$

In other words, the TOF variation between two signals can be calculated if we can obtain the phase value for each of them at the resonant frequency of the transducer. However, it should be noted that the computed phase shift yields principal values between $-\pi$ and π, and needs to be first unwrapped by adding the adequate multiple of 2π where necessary.

When digitally processing signals to obtain these phase values, the computational tool fast Fourier transform (FFT) is normally used instead of discrete Fourier transform, as the former is a much faster algorithm. The only requirement of the FFT algorithm is that the number of points in the series be a power of 2. However, tools normally used to carry out the FFT algorithm allow the signals that have insufficient samples to fulfil this requirement by zero padding the input signal automatically.

Another technique, the phase-slope difference, consists of subtracting a specific section of the phase curve around the resonant frequency of the transducer between a reference signal and the shifted signal, thereby obtaining a straight line on the phase-frequency plane whose slope corresponds to the delay between both [19].

3 Materials and methods

In order to carry out the comparative analysis proposed in this study, the work has been divided into two main stages: the theory stage and the experiment stage.

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3.1 Simulation study

The performance, efficiency and competence of each of the above methods are studied with the help of Matlab software.

The shape of the ultrasonic signal at the receiver transducer can be approximated with the following equation

$$s(n) = A(nT_s - D)^2 e^{-\beta(nT_s - D)} \sin(2\pi f(nT_s - D)) \quad (6)$$

where A is the envelope signal amplitude, T_s is the sampling period, f is the resonant frequency of the transducer, β is the damping coefficient of the wave and D is the time delay between ultrasonic signals. Values for these parameters have been selected in order to match, as far as possible, the shape, amplitude and duration of the simulated ultrasonic signals at the receiver transducer ($A = 1.3 \times 10^{10}$, $\beta = 5.5 \times 10^9$, $f = 1$ MHz and $T_s = 2$ ns). In addition, each waveform segment has a total of 15 000 points, approximately the same sampling points as the acquired experimental echo signals that will be processed during the second stage of this comparison.

For simulations, ten different delay values were cumulatively applied in groups of 50 waves: 0.8, 1.2, 1.5, 2, 3.8, 7.2, 11.6 15.3, 20 and 27.1 ns. The aim was to include differences that are lower than, near to and higher than those of the sampling period. Tests were conducted with the addition of two levels of Gaussian white noise, similar to that which is usually encountered in the experimental measurement of foodstuffs. SNR values of between 15 dB (dispersive and attenuating foods, such as bread dough) and 35 dB (liquid foods with little attenuation, such as milk or wine) are normally registered. Also, consideration was given to the loss of amplitude as a result of attenuation in the medium because of any changes produced in it as the process in question evolved (a reduction of 20 dB between the first and last signals, distributed evenly throughout the whole series). However, results were not affected by a little loss in amplitude with time and for this reason are not explicitly shown.

To obtain a broad view of the behaviour of the methods, each method was applied to two different contexts in which they could find themselves in practice:

1. Signals gathered and processed with their original noise level.
2. Signals gathered and passed through a filtering stage before being processed using the different methods.

To evaluate the performance of the different methods the root mean-squared error (RMSE) of the difference between the estimated TOF variation and the actual TOF variation as well as computing times of each method were obtained. With regard to particular aspects that apply to each of the methods, the following features must be mentioned:

For the threshold method, it has been established that the relevant time for each wave shall be the value whose corresponding amplitude first exceeds 60% of the maximum amplitude of the wave. The TOF variations were calculated between consecutive signals since it performed better results than doing so between the first (or reference) signal and the rest.

For the maximum detection and maximum detection with interpolation methods, the maximum detected immediately after exceeding a threshold level was used (60% of maximum amplitude). For the former, it is sufficient to record the time corresponding to when the maximum is reached. For the latter, the maximum, the preceding value and the subsequent value were used to execute a three-point parabolic interpolation. In this second method, it is important to take into consideration the extent to which the process is influenced by the amount of new points derived from the interpolation; therefore two tests were conducted with 11 and 51 points and as a result the initial resolution is reduced from 2 ns to, respectively, 0.4 and 0.08 ns. The TOF variations were also calculated between consecutive signals.

For the application of the zero-crossing detection and zero-crossing detection with interpolation methods, a technique was used whereby, in the half-cycle of the signal where a threshold level is first exceeded, the value is reduced until the positive amplitude value closest to zero has been located. For the first method, the time corresponding to this amplitude value is used whereas for the second, a linear interpolation is applied with the pair of points formed by the aforementioned amplitude value and the one preceding it. The new zero crossing can then be determined. As above, an interpolation with 11 and 51 new points is made and the results are compared; in this instance, resolutions of, respectively, 0.2 and 0.04 ns were obtained. The TOF variations were also calculated between consecutive signals.

For the cross-correlation method, preliminary tests were useful in determining that this method performed better when it was applied between the first received signal (reference) and each of the subsequent signals. On the contrary, when it was applied between consecutive signals, the method was negatively affected if TOF variations were in the order of the sampling period. This meant that the error was not only more significant, but also cumulative, given that the resolution of this method is limited to the sampling period.

The phase-shift method was applied between consecutive signals in order to avoid phase changes outside the established limits. As for the number of FFT points, it was decided that when working with windows containing 15 000 wave samples, it would be convenient to use the lowest number of points, that is, 2^{14} (16 384 points). In order to increase the resolution of this method, tests were also conducted with 2^{15} (32 768) and 2^{16} (65 536) points.

Finally, for the slope-difference method an attempt was made to ensure a similar treatment to that of phase-shift method, given that both methods are based on the use of the FFT. Tests were conducted with two different numbers of points: 2^{14} and 2^{15}. On this occasion 2^{16} was discarded, as preliminary testing revealed an excessive increase in execution time, whereas the results obtained were inferior to those obtained with 2^{15} points. The recommendations in the literature in relation to this method, namely to use an initial signal with zero noise [19], were taken into consideration.

3.2 Experimental study

An experimental set-up was prepared for the transmission, propagation and reception (in the form of echoes) of ultrasonic signals through a liquid medium (wine under fermentation). The arrival of time of these signals varies, owing to the changes that take place in the medium over time (see Fig. 3).

The pulse-echo ultrasonic technique is used in this case, in which an ultrasonic transducer emits a signal that travels along the medium and is reflected at the bottom of the recipient or measurement cell. The reflected signal is then

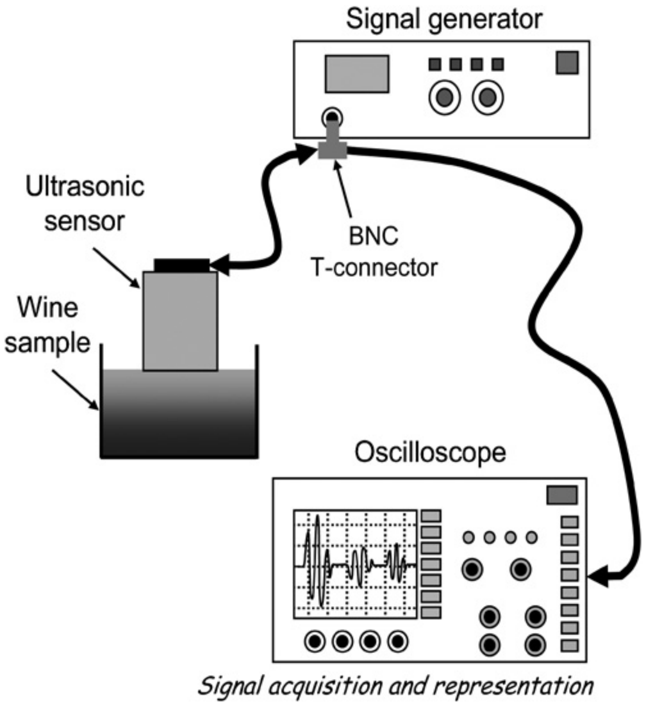

Fig. 3 *Experimental set-up*

detected by the same transducer. Here, the ultrasonic sensor is comprised of an ultrasonic transducer connected to a buffer rod which is the only element in contact with the wine sample. For that reason, the buffer rod material has been chosen carefully to be a plastic material suitable for food contact applications. By using an oscilloscope, an image of the received wave form can be obtained, as shown in Fig. 4. The wave marked as 'Initial' corresponds to the excitation wave, which travels through the buffer rod to the interface between the buffer rod and the liquid and returns to the transducer as Echo 1. The transmitted signal travels through the liquid, is reflected at the bottom of the recipient and returns to the transducer as Echo 2. The time elapsed between the arrival of Echo 1 and the arrival of Echo 2 is the time taken by the ultrasonic wave to travel a distance of $2d$ through the liquid (TOF). Echoes 3 and 4 are subsequent multiple reflections of Echo 2 at the transducer and at the interface between the buffer rod and the liquid. These echoes will always reach the transducer after the arrival of Echo 2, without ever interfering with the measurement in question.

The ultrasonic transducer, a PANAMETRICS ACCUSCAN with a resonance frequency of 1 MHz, is excited by a sine-wave burst of seven cycles and $10V_{p-p}$ of amplitude using an Agilent 33250A signal generator.

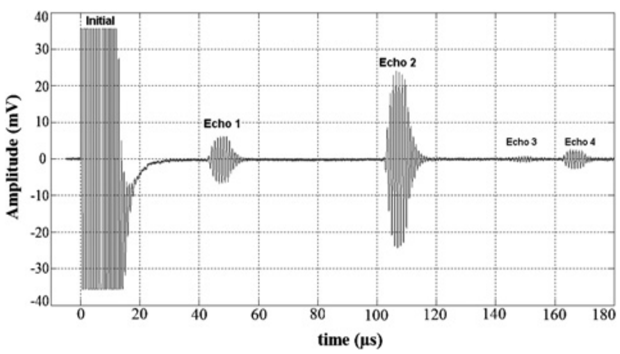

Fig. 4 *Signal transmitted and echoes received*

The received signals are stored by a Tektronix DP02024 oscilloscope, configured to an average of 128 and with a sampling frequency of 500 MHz.

The system took three consecutive samples (to be averaged out later) every 3 h. The resultant signal had an SNR of approximately 34 dB, which was then stored on a computer for processing.

The entire set-up is controlled by a Visual Basic application that enables complete manipulation and programming of the instruments' parameters via computer. Finally, MATLAB is used to automatically process all the stored samples and provide the results of the TOF variations for each of the techniques described above.

4 Results

4.1 Simulations

Tables 1 and 2 show computed RMSE values for case studies considered in Section 3. The results obtained with each method throw up a number of interesting remarks.

The threshold, maximum detection and maximum detection with interpolation methods require signals with a relatively high SNR in order to obtain similar errors to other methods. Indeed, it is recommended that digital filtering be carried out beforehand. In terms of the number of points used in the interpolation, it was observed that a greater number of points did not improve the results and that the experiment could be conducted quite comfortably with an interpolation of 11 points. However, with the addition of a filter stage the RMSE obtained was comparable with that of the sampling period or even lower when the original signals had a high SNR.

Compared with the three previous methods, the zero-crossing detection method is differentiated by the fact that signals with a high SNR can be applied without the need for a filter, providing some modest results. However, this one does not offer comparatively adequate performance with signals that have a low SNR (although results can be improved by using a filter). The modified version of this method, namely zero-crossing detection with interpolation, provides a clear improvement in the test with low SNR and a filter stage. It can therefore be concluded that this modified method is easy to apply and provide improved resolution and a lower level of error. Once again, it was established that an interpolation of 11 points is enough.

The cross-correlation method provides very precise results and can be applied with or without a filter, except in the case of signals with a low SNR, when the RMSE values remain in excess of the sampling period. Resolution is always limited by the sampling period.

The slope-difference method provides lower resolution than the sampling period only when the signals processed have a relatively (or very) high SNR, in which case filtering becomes unnecessary and it is sufficient to work with an FFT that uses the minimum number of points, that is, 2^{14}.

The most suitable of all methods seems to be the phase-shift method, which in general, can be used directly on the gathered signals. A filter stage is not necessary, even for low-SNR signals. However, it is important to note that the measurement resolution varies with the range of TOF variation being measured. In other words, the larger the TOF variation is, the lower the resolution readout will be. Thus, using an FFT with a quantity of points of 2^{14} (the

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Table 1 RMSE for signals with an SNR of 15 dB; delay variations, first value without filter stage and second value with filter stage

	RMSE, ns							
Delay, ns	Threshold	Maximum	Maximum interp	Zero-crossing	Zero-crossing interp	Cross-correlation	Slope-diff	Phase-shift
0.8	11.790_2.071	11.781_2.109	11.973_2.072	9.286_1.308	8.851_1.144	2.086_0.645	6.465_6.486	0.670_0.603
	–	–	11.885_2.112	–	8.829_1.175	–	7.450_7.510	0.617_0.556
1.2	11.760_2.176	11.718_2.241	11.931_2.121	10.521_1.380	10.045_1.115	2.298_0.632	6.410_6.413	0.740_0.667
	–	–	11.854_2.165	–	10.015_1.161	–	7.367_7.427	0.616_0.554
1.5	8.7524_2.183	8.812_2.219	8.9502_2.127	8.864_1.430	8.349_1.110	2.228_0.667	6.378_6.370	0.795_0.719
	–	–	8.897_2.158	–	8.320_1.156	–	7.298_7.360	0.615_0.552
2	8.9219_2.154	8.931_2.059	9.1426_2.032	9.695_1.327	9.310_1.126	2.098_0	6.348_6.326	0.890_0.808
	–	–	9.0615_2.092	–	9.276_1.166	–	7.169_7.242	0.612_0.548
3.8	8.6987_2.060	8.634_1.961	8.7913_1.970	8.603_1.455	8.3181_1.253	2.203_0.610	6.460_6.452	1.246_1.158
	–	–	8.7168_2.020	–	8.290_1.295	–	6.636_6.770	0.605_0.537
7.2	10.137_2.109	10.034_2.067	10.137_1.978	9.749_1.486	9.164_1.314	1.784_0.607	6.924_7.123	1.911_1.833
	–	–	10.058_2.004	–	9.129_1.363	–	6.249_6.379	0.590_0.536
11.6	12.123_1.980	12.129_2.032	12.323_1.965	9.718_1.507	9.289_1.319	2.098_0.620	6.591_6.834	2.598_2.538
	–	–	12.226_2.029	–	9.280_1.352	–	7.471_7.543	0.530_0.489
15.3	9.5451_1.875	9.535_1.981	9.790_1.926	9.266_1.498	8.854_1.324	1.854_0.702	6.640_6.789	3.393_3.336
	–	–	9.676_1.988	–	8.816_1.361	–	7.481_7.637	0.601_0.537
20	10.575_1.625	10.752_2.263	10.888_2.022	9.051_1.467	8.695_1.264	1.549_0	6.602_6.967	4.401_4.336
	–	–	10.812_2.106	–	8.6612_1.287	–	6.980_7.081	0.511_0.475
27.1	10.78_1.981	10.860_2.335	10.910_2.070	10.373_1.517	9.990_1.209	1.938_0.685	7.250_7.320	5.876_5.783
	–	–	10.846_2.123	–	9.963_1.238	–	6.554_6.646	0.505_0.496

Maximum interp and zero-crossing interp: first line = interpolation 11 points; second line = interpolation 51 points
Slope-diff: first line = FFT with 2^{14} points; second line = FFT with 2^{15} points
Phase-shift: first line = FFT with 2^{14} and 2^{15} points; second line = FFT with 2^{16} points

Table 2 RMSE for signals with an SNR of 35 dB; delay variations, first value without filter stage and second value with filter stage

	RMSE, ns							
Delay, ns	Threshold	Maximum	Maximum interp	Zero-crossing	Zero–crossing interp	Cross-correlation	Slope-diff	Phase-shift
0.8	4.310_0.903	7.486_0.876	7.474_0.188	1.798_0.955	0.992_0.150	0.566_0.566	0.644_0.647	0.202_0.193
	–	–	7.442_0.215	–	1.012_0.122	–	0.745_0.750	0.0539_0.0489
1.2	4.575_0.955	8.120_0.980	8.128_0.219	1.518_0.930	0.937_0.155	0.566_0.566	0.639_0.639	0.282_0.272
	–	–	8.113_0.230	–	0.938_0.121	–	0.737_0.742	0.0502_0.0461
1.5	4.167_0.982	9.289_0.962	9.051_0.227	1.626_0.941	0.874_0.156	0.604_0.604	0.636_0.635	0.342_0.333
	–	–	9.025_0.225	–	0.893_0.122	–	0.730_0.735	0.0479_0.0443
2	4.418_0.490	8.173_0.40	7.966_0.196	1.649_0	0.929_0.155	0_0	0.632_0.630	0.443_0.434
	–	–	7.956_0.222	–	0.943_0.123	–	0.717_0.724	0.0446_0.0421
3.8	4.501_0.982	7.737_0.949	7.687_0.206	1.794_0.940	0.996_0.167	0.583_0.583	0.645_0.643	0.813_0.804
	–	–	7.683_0.213	–	1.018_0.134	–	0.664_0.676	0.0395_0.0395
7.2	4.112_0.996	7.065_0.930	6.932_0.170	1.345_0.955	0.801_0.188	0.566_0.566	0.690_0.711	1.474_1.467
	–	–	6.907_0.212	–	0.802_0.153	–	0.625_0.637	0.0691_0.0734
11.6	4.536_0.972	7.133_0.955	7.097_0.179	1.357_0.955	0.793_0.217	0.566_0.566	0.660_0.682	2.174_2.1723
	–	–	7.076_0.207	–	0.808_0.178	–	0.747_0.753	0.2769_0.2808
15.3	4.103_0.906	7.976_0.928	7.911_0.201	1.720_0.906	0.942_0.204	0.570_0.570	0.662_0.676	3.019_3.016
	–	–	7.893_0.210	–	0.959_0.182	–	0.748_0.764	0.2950_0.2985
20	4.089_0.283	5.913_0.566	5.860_0.240	1.744_0	0.974_0.172	0_0	0.660_0.700	4.058_4.0525
	–	–	5.852_0.244	–	0.988_0.135	–	0.697_0.706	0.2736_0.282
27.1	4.449_1.014	7.411_0.910	6.937_0.227	1.396_0.936	0.787_0.163	0.570_0.570	0.725_0.728	5.4871_5.475
	–	–	6.888_0.240	–	0.795_0.131	–	0.656_0.667	0.3787_0.3826

Maximum interp and zero-crossing interp: first line = interpolation 11 points; second line = interpolation 51 points
Slope-diff: first line = FFT with 2^{14} points; second line = FFT with 2^{15} points
Phase-shift: first line = FFT with 2^{14} and 2^{15} points; second line = FFT with 2^{16} points

lowest possible), the RMSE values may even be higher than those obtained with the majority of the other methods.

The aforementioned effect can be mitigated by increasing the points of the FFT. When working with 2^{15} points obtained results are exactly the same as those with 2^{14} points. With 2^{16} points, it starts to become clear that this method provides the best resolution and that its RMSE values are a great deal lower than those of the other

Table 3 Computer times with the threshold method as a benchmark

Thresholding	1
zero-crossing detection	1.01
maximum detection	1.05
zero-crossing detection with interpolation	1.69
maximum detection with interpolation	2.11
cross-correlation	4.57
slope-difference	173.82
phase-shift	4833.9

methods, only improved by the results obtained with the cross-correlation method when the delays are similar to the sampling period or whole multiples of it. The price of this method depends on the computing cost, which is itself highly dependent on the order used in the FFT. It should also be noted that exceeding the 2^{16} points does not provide any significant improvement in results.

Finally, Table 3 provides normalised computer times regarding the time of the quickest method that turned out to be the threshold method. For the methods that involved interpolation 11 points were used, whereas 2^{14} points for the FFT was used for the slope-difference method and 2^{16} points for the phase-shift method.

As can be observed in Table 3, a method that provides extremely high resolution and excellent results, such as the phase-shift method with 2^{16} points for the FFT, also implies a high computing cost. In contrast, simpler methods such as maximum detection with interpolation or zero-crossing detection with interpolation are applications with a comparatively low computational cost and are efficient in relation to the results obtained, and may be suitable for use in a large number of applications.

4.2 Experiments

The experimental set-up, described above in the Materials and methods section, was used to monitor the TOF variations in a liquid medium (fermenting wine) caused by the physicochemical changes produced in it. Signals were gathered over the course of 11 consecutive days at 3 h intervals. Fig. 5 is a graph of the TOF variations obtained for the studied different methods.

In light of the simulation results, a filter stage was used which managed to increase the SNR to 48 dB, the curve obtained by the phase-shift method with 2^{16} points FFT was used as a benchmark (given that it was the method that generally produced the lowest level of error) and the RMSE for the other methods was calculated in relation to its results. Table 4 shows the RMSE obtained.

As was expected after analysing the results from the simulations, the cross-correlation method had the lowest RMSE. The zero-crossing detection with interpolation method also had an RMSE very similar to that of the cross-correlation method. In contrast, the worst result was obtained with the slope-difference method, despite the fact that signals were filtered beforehand: this was the method that presented the greatest difference between the results of the simulation and those of its direct use in a real application, partially owing to the difficulty of getting a reference signal without noise.

As a general result, for applications involving the monitoring of foodstuffs in a liquid state, such as the one employed herein, six of the studied methods were capable of producing an RMSE lower than that of the sampling

Table 4 RMSE using the phase-shift method as a benchmark

RMSE, ns	
thresholding	2.47
maximum detection	0.94
maximum detection with interpolation	0.85
zero-crossing detection	1.36
zero-crossing detection with interpolation	0.63
cross-correlation	0.62
slope-difference	9.92

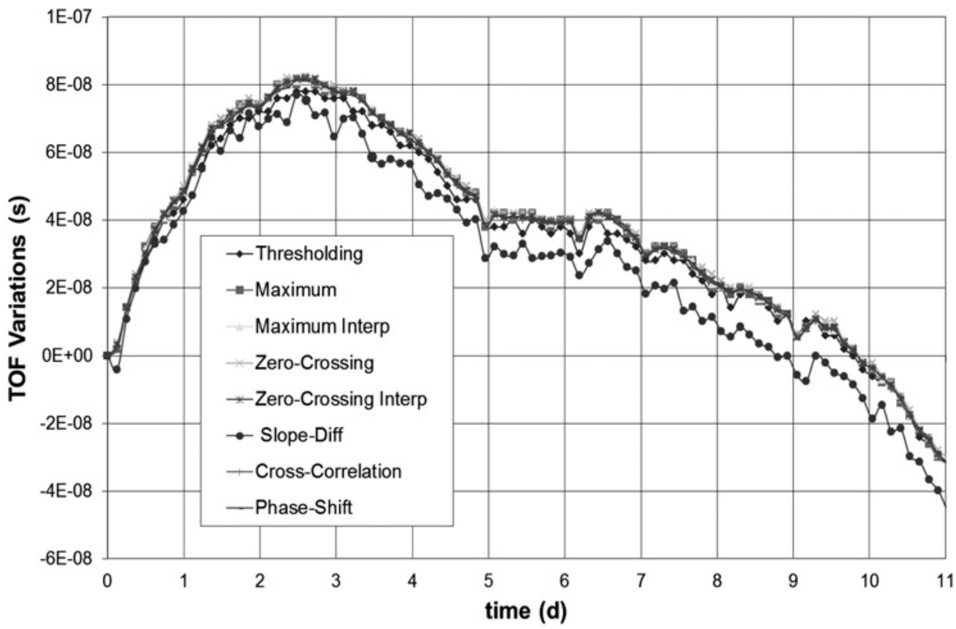

Fig. 5 *Cumulative TOF variations during the experimental application*

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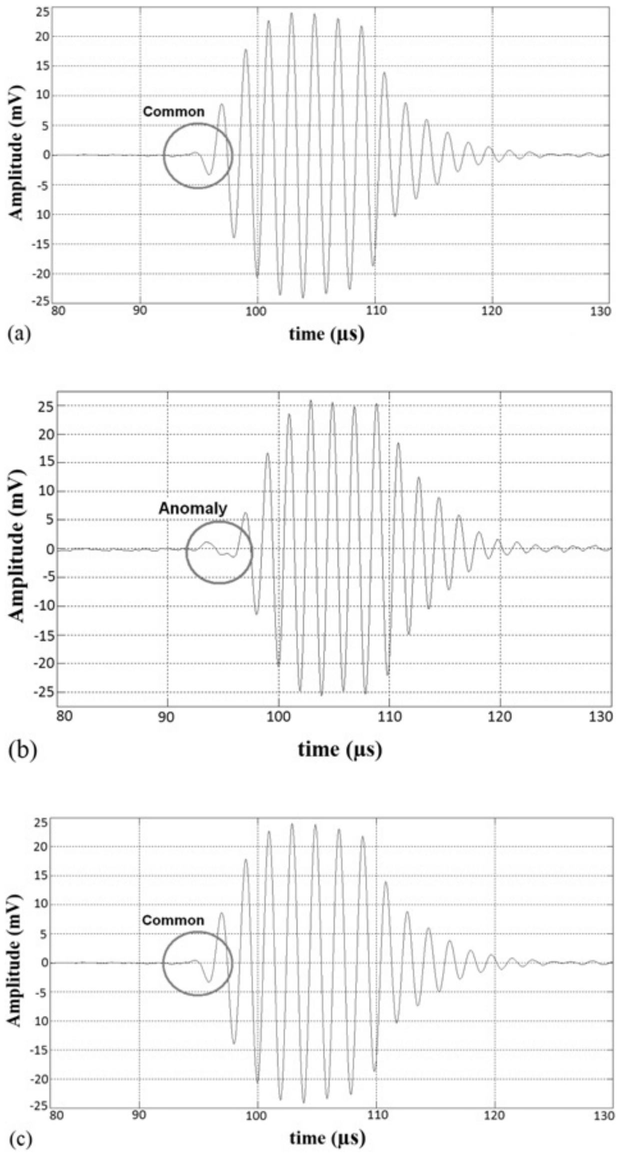

Fig. 6 *Three consecutive echoes*

a First echo was a common waveform
b Second echo showed an anomaly at the start of the waveform
c Third echo was a common waveform

period. Selecting one of them is therefore dependent on the resources available for the application in question.

A situation that arose whereas measurements were being taken during the experiments, and which had a dramatic effect on the obtained results in the time domain, occurred when one of the echoes received sporadically produced an anomaly at its moment of capture. Fig. 6 shows three consecutive signals in which the middle signal shows an alteration when captured, despite the fact that the other signals continue to be captured in the normal way.

In order to determine how this anomaly affects the functioning of the methods, nine test signals were emitted in sequence, with the fifth signal consisting of the anomalous signal shown in Fig. 6. As Fig. 7 shows, the methods that operate in the time domain are the ones most affected by the anomaly. They produce a displacement that cannot be attributed to the wave. Once again, owing to its robustness the phase-shift method produced the least-affected results.

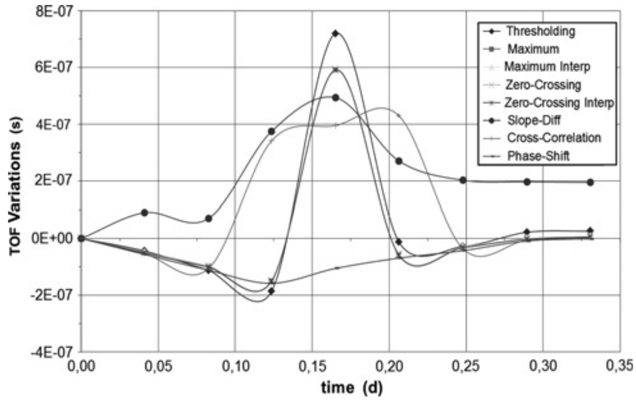

Fig. 7 *Results for the eight methods after exposure to a sporadic anomaly*

5 Conclusions

In the time domain, the cross-correlation method always provided the best results. In addition, its computational cost is not considerably high and it can be applied directly to most signals without the need for prior filtering, with the exception of signals with very low SNR. The zero-crossing detection with interpolation method provides an attractive compromise between measurement accuracy in terms of RMSE and low computational cost, being and an interesting option to be considered because of its good results and simplicity.

In the frequency domain, the phase-shift method presents the best results in any situation which are also superior to that provided by the methods operating in the time domain. This method is also the most robust and provides excellent levels of resolution, optimum performance across a wide range of SNR values, greater effectiveness in the face of unanticipated anomalies and the possibility of being used without a prior filtering stage. However, the price paid for this exceptional performance is the comparatively high computing cost this method demands and which would make it more difficult to implement using low-cost portable electronic equipment for the online monitoring of production processes for foodstuffs. Nonetheless, this caveat is not a factor that would imply a limitation in the use of this method in laboratory-based measurement systems.

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