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ULTRASONIC MONITORING OF FISH THAWING PROCESS OPTIMAL TIME OF THAWING AND EFFECT OF FREEZING/THAWING

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ABSTRACT

Introduction. Fish quality is traditionally controlled by chemical and microbiological analysis. The non-destructive control presents an enormous professional interest thanks to the technical contribution and precision of the analysis to which it leads. This paper presents the results obtained from a characterisation of fish thawing process by the ultrasonic technique, with monitoring thermal processing from frozen to defrosted states.
Material and methods. The study was carried out on fish type red drum and salmon cut into fillets of 15 mm thickness. After being frozen at –20°C, the sample is enclosed in a plexiglas vessel with parallel walls at the ambient temperature 30°C and excited in perpendicular incidence at 0.5 MHz by an ultrasonic pulser-receiver Sofranel 5052PR. the technique of measurement consists to study the signals reflected by fish during its thawing, the specific techniques of signal processing are implemented to deduce informations characterizing the state of fish and its thawing process by examining the evolution of the position echoes reflected by the sample and the viscoelastic parameters of fish during its thawing.
Results. The obtained results show a relationship between the thermal state of fish and its acoustic properties, which allowed to deduce the optimal time of the first thawing in order to restrict the growth of microbial flora. For salmon, the results show a decrease of 36% of the time of the second thawing and an increase of 10.88% of the phase velocity, with a decrease of 65.5% of the peak-to-peak voltage of the signal reflected, thus a decrease of the acoustic impedance.
Conclusions. This study shows an optimal time and an evolution rate of thawing specific to each type of fish and a correlation between the acoustic behavior of fish and its thermal state which approves that this technique of ultrasonic monitoring can substitute the control using the destructive chemical analysis in order to monitor the thawing process and to know whether a fish has suffered an accidental thawing.

Key words: ultrasound, non-destructive control, acoustic behavior, thermal state, optimal time of thawing, phase velocity, wave attenuation

INTRODUCTION

Overseas fish is either directly treated on boats before being frozen or directly frozen, then treated in the factory after being unloaded. At the factory, the thawing of that fish is an essential step in its transformation and treatment; the quality of the texture is directly related to the quality of thawing. During this

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process there is a risk of the growth of microbial flora and loss of liquid containing proteins, soluble vitamins and mineral; thawing must be carefully made to guarantee the quality of fish texture. For several industrialists, and given the results obtained from the existing processes of control, this operation remained still too delicate. Indeed, if the slow thawing in the open air (3°C) appears extremely respectful to the product quality, its excessive duration (between 24 and 72 hours) cannot satisfy the productivity requirements. Although the creation of the cabinet for thawing has become imposed in order to reduce the time of this cycle, the corresponding process, too fast (between 1 to 6 hours), also has inconveniences; Thawing through circulation of cold water (10°C) leads to an over consumption of water and an important crossed risks of contamination [Brent et al. 2004]. The fast thawing in warm pulsed air (between 25 and 35°C) fails to prevent the degradation of tissue component of the treated fish. Hence the industrialists have to find a technical solution, allowing to control and to well master the thawing process; that is, to determine the conditions and the optimal thawing time. Ultrasonic method is perfect to assure such control over many traditional analytical techniques [Awad et al. 2012]. The measurements are non-destructive, precise, fast and fully automated and can be made on-line. In addition, it is possible to analyse optically opaque samples without the need of extensive sample preparation [Bamberger and Greenwood 2004, Norlida et al. 2011, Dolatowski et al. 2007]. Low intensity ultrasound was used to provide information about the physicochemical properties of fish [Coupland 2004, Keshava and Ramana 2003]. Phase velocity and wave attenuation were used to characterise the structure and salmon composition [Shannon et al. 2004]. This study proposes the use of the ultrasonic analysis to characterise the evolution of thawing in order to deduce the optimal time and to monitor the effect of an accidental refreezing.

CONTROL METHODOLOGY

Experimental device

The experimental device (Fig. 1) consists of: An ultrasonic pulser-receiver Sofranel 5052PR. A broadband ultrasonic transducer (with a center frequency of 0.5 MHz and a diameter of 20 mm). A digital storage scope model HP54600B. A computer equipped with a card type Keithley GPIB IEEE-488 for acquisition of signals reflected by the fish during its thawing.

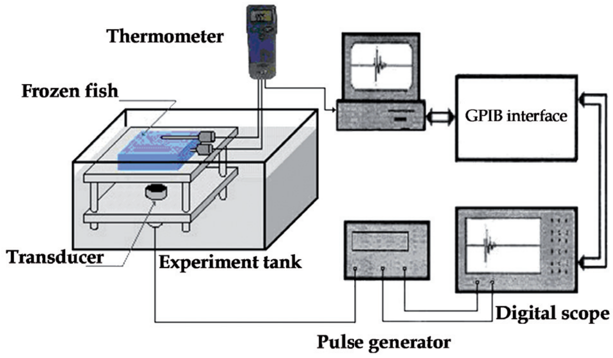

Fig. 1. Experimental device

An electronic thermometer connected to the computer allows to record the temperature at the center of the sample. A samples holder immersed in a water tank realizing the coupling between the transducer and the sample, without contact between fish and water.

Description of the measurement technique

The measurement technique used is based on a system-mode ultrasonic pulse echo at perpendicular incidence of a low intensity with a pulse width of 2 μs, repeated at 5 kHz, at an intensity of 30 mW·cm^{-2}. The transducer alternately acts as a transmitter and a receiver i.e. the monostatic method. The electrical signal of piezoelectric transducer is constituted of pulses generated with a repetition period adjustable by the pulse generator. This period is chosen to avoid overlap between the end of the response and the beginning of the next pulse on the one hand, and to not introduce spurious echoes on the other hand. The reflected pressure is sensed by the transducer. The received signal passes through the same cable as the transmission signal and enters the connector T/R of generator from which the broadcast signal has been sent. Through a delay system integrated in the pulse generator, the signal is displayed on the digital scope. The latter is being connected to a computer by the IEEE through a capture card for the treatment of the signal reflected by fish. The recording of the temperature at the center of the sample fish during thawing is ensured by an electronic thermometer connected to the computer.

The principle of the technique control is to study the signals reflected by fish initially frozen at a temperature of –20°C. The specific techniques of signal processing are implemented to deduce information characterising the state of fish and its thawing process by examining the evolution of the position echoes reflected by the sample and the viscoelastic parameters of the fish during its thawing.

Preparation of fish sample: Frozen fish

All given the extreme diversity of fish types (different qualities and constitutions), the efficiency of experiments, and the generalization of the results, require manipulation of several types. The experiments were performed on two types: the red drum and salmon. Fresh fish, is cut into fillet form of 15 mm thick, and is identified according to its type and number of cycles of freezing/thawing and then stored in a freezer at –20°C. After being frozen, the sample to be analysed is enclosed in a plexiglas vessel with parallel walls at the ambient temperature 30°C, and whose wall thickness is 20 mm. This thickness is chosen in order to allow the separation of the reflected echoes.

Treatment response

As previously mentioned, the reflection control technique was used to monitor the acoustic response during the thawing process with monitoring the evolution of temperature at the center of the sample. The data acquired by the computer were processed and presented in lines graph that shows:

- evolution of the temperature in the center of the sample
- acoustic response and evolution of the echoes position
- evolution of the amplitude and spectrum of the echoes
- the evolution of the phase velocity of the wave.

Analysis of this lines graph shows the evolution rate and the optimum time of thawing for each fish type studied, and according to the number of cycles of thawing.

RESULTS AND DISCUSSION

Ultrasound response

The implemented method allows to track the evolution signals reflected by the target constituted by the fish during its thawing. This is to draw an ultrasonic echo graph showing the evolution of the position and spectrum of reflected echoes, to deduce the evolution rate and the time just needed for thawing. These values will be compared to values provided by the thermal approach of the problem which consists of monitoring the temperature at the center of the fish. The sample is excited perpendicularly to its plane by a transducer of frequency 0.5 MHz. The incident signal path is shown in Figure 2.

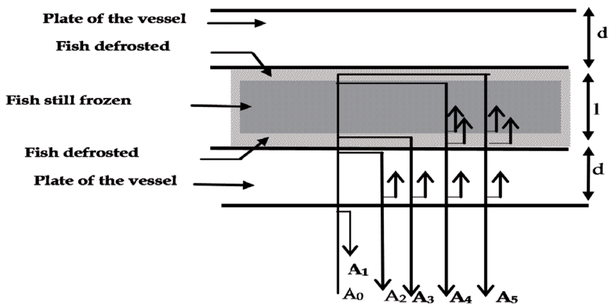

Fig. 2. Schematic path of propagation echoes in the sample

The reflected signal includes two parts. The first part is composed of three echoes:

- A_1, echo related to the specular reflection of the incident beam at the interface between water and the first face plate of the vessel walls.
- The second echo A_2 corresponding to the reflection on the interface between the second face plate and fish.
- The third echo A_3 corresponding to the reflection on the interface between the thawed and the still-frozen fish part.

The second part is composed of two echoes, having all crossed the fish in back and forth:

- The echo A_4 corresponds to the reflection at the interface between the defrosted and the still frozen fish.
- A_5 corresponds to the reflection at the interface between fish and the second plate of plexiglas.

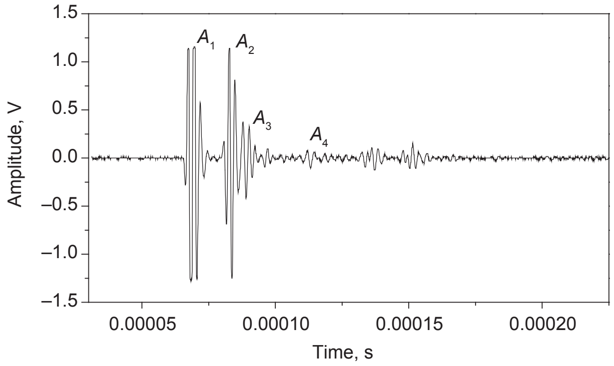

Fig. 3. At the beginning of the thawing, there is an overlapping of echoes A_2 and A_3

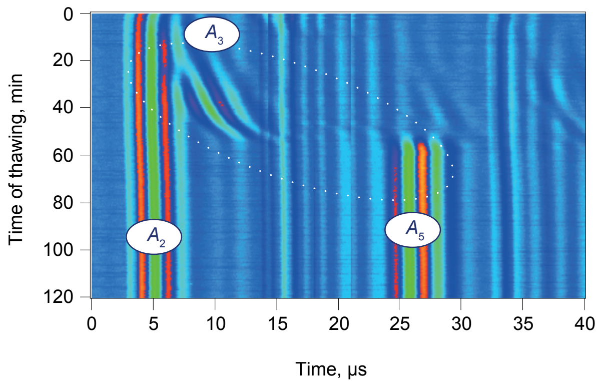

Fig. 5. Evolution of the echoes position of the signal reflected by the red drum during its first thawing

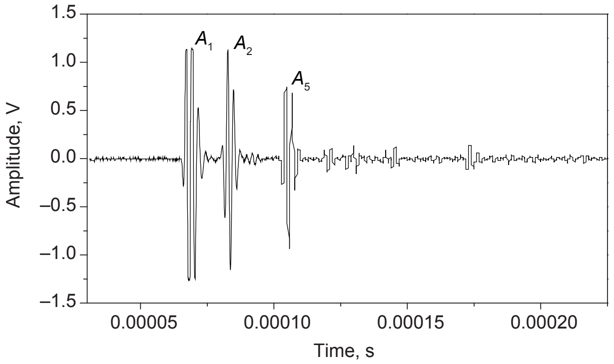

Fig. 4. At the end of the thawing, there is a disappearance of A_3 and appearance of A_5

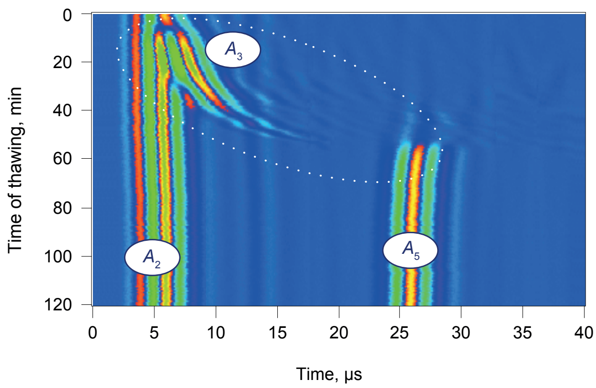

Fig. 6. Evolution of the echoes position of the signal reflected by red drum during its second thawing

Figures 3 and 4 present a typical waveform of the ultrasonic signal reflected by a sample of the red drum 15 mm thick at the beginning and at the end of thawing.

The superposition of these reflected signals allows to follow the evolution of the position of the bottom echoes (A_3 and A_5), this allows to control the cycle of thawing. Figures 5 and 6 present, in the form of echo graphs, the evolution of the signal reflected by the red drum during its first and second thawing. The position of the interface plexiglas/fish echo A_2 does not evolve except at the beginning; this is due to thermal shock received by the plate of plexiglas at the moment of contact with the frozen fish.

At the beginning, there is an overlapping of echoes A_2 and A_3. The beginning of the first and second thawing is marked by evolution of the position of the echo A_3; this is after 10 minutes (5 min for the second thawing). The bottom echo A_5 appears after 50 minutes (40 min for the second thawing) which marks the end of the thawing. A_5 echo stabilizes at 80 minute (about 70 min for the second thawing); the evolution rates of the first and the second thawing are quite different.

Control of the phase velocity

The principle of the control method is to plot the reflected frequency spectrum by calculating the Fast Fourier Transform of the reflected signal portion located in the measurement window between echo A_2 and A_5. The longitudinal phase velocity c_L is expressed according to Shannon et al. [2004] by:

$$c_L = \frac{2l\omega}{|\varphi_{A_5} - \varphi_{A_2}|} \tag{1}$$

Where $\omega = 2\pi f$ is the pulsation of the wave and l is the thickness of the sample.

$$\varphi_{A_2} = Arc\tan\left[\frac{I_2(\omega)}{R_2(\omega)}\right] \quad \varphi_{A_5} = Arc\tan\left[\frac{I_5(\omega)}{R_5(\omega)}\right]$$

Here, R_2, R_5 are the real and I_2, I_5 are the imaginary parts of the echoes A_2 and A_5. Figure 7 presents the frequency spectrum of the isolated bottom echo A_5 reflected by the red drum at the end of its first thawing.

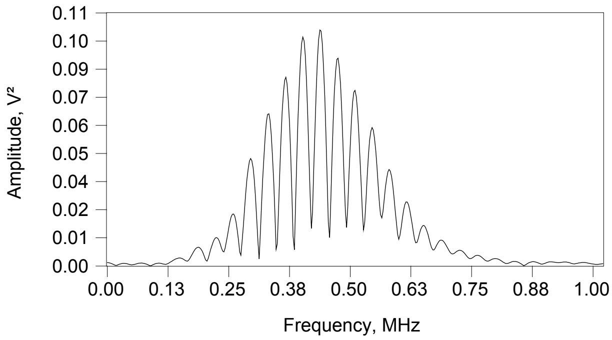

Fig. 7. Typical frequency spectrum reflected by red drum during its first thawing

This spectrum presents the minimums values that are regularly spaced; these troughs are due to excitation of longitudinal vibration in the sample. The frequencies f_L where these minimums are correspond to an integer number of half-wavelength of the longitudinal wave in the sample. We infer:

$$f_L = p\frac{c_L}{2l} \tag{2}$$

Where p is the order of appearance of a trough, c_L is the phase velocity, and l is the thickness of the sample. Hence the phase velocity is:

$$c_L = 2l\Delta f_L \tag{3}$$

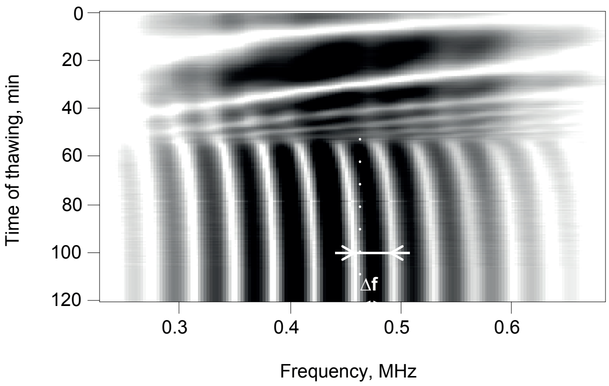

Fig. 8. Evolution of the signal spectrum reflected by red drum during the first thawing

The superposition of the reflected signals spectra during thawing allows to monitor the position of its minima, hence we can follow the evolution of the phase velocity of the wave in fish. Figure 8 shows an echo graph of the evolution of the signal spectrum reflected by a sample of red drum, 15 mm thick, excited by a transducer with a center frequency of 500 KHz during its first thawing.

Thermal behaviour

The ultrasonic control of thawing process is done simultaneously with monitoring the temporal and spatial evolution of temperature in fish; the objective is to approve a relationship between the acoustic behaviour of fish and its thermal state. The sample of fish fillet that is a large and is 80 mm long and 15 mm thick, initially frozen at a temperature $T = 20°C$ assumed to be uniform, is enclosed in a rectangular vessel. The set is immersed in a tank containing the water at a constant ambient temperature $T_a = 30°C$.

The recording of the temperature of the sample studied is assured by a digital thermometer connected to the computer. Figure 9 shows the evolution of the temperature at the center of a sample of red drum during its first thawing.

This evolution stabilizes for a while around 0°C. This is due to a decrease in the thermal conductivity of the fish when the parts of ice become transformed to water; furthermore the thermal conductivity l depends on the temperature [Archer et al. 2008, Hobani 2005, Tamene 2009].

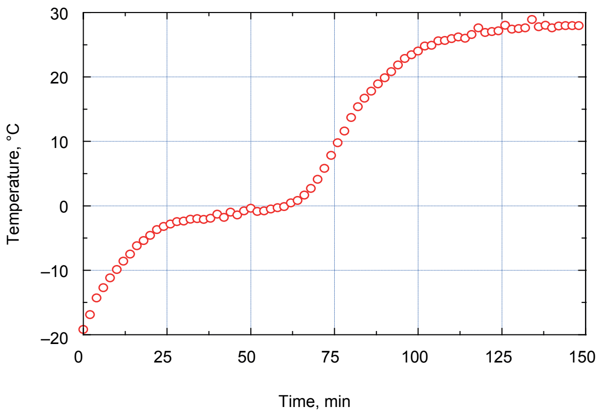

Fig. 9. Evolution of the temperature of the red drum during its first thawing

Case of salmon in the first thawing

The superposition of the signals reflected by a sample of salmon allows to control its thawing. Figure 10 presents the evolution of ultrasonic signal reflected by salmon during its first thawing.

Echo A_3, one of the interesting echoes, appears after 10 minutes. Its position evolves gradually during the thawing; as we can intuitively imagine, the thawing occurs from the outside to the center of the sample. This echo A_3 disappears at 40 minutes. This marks the end of thawing. This echo is related to the bottom of the sample, its position and its magnitude change before stabilizing at 80 minutes. The evolution of the position of this echo reflects the variation of the phase velocity of the wave in fish; this is due certainly to the thawing process of fish. The bottom echo is stabilized when the temperature of the fish is near the ambient temperature.

The measure of the amplitude of echo A_2, echo reflected in the interface plate/fish, and that of the bottom echo A_5, evaluates the attenuation and therefore the acoustic impedance of the sample of fish during thawing. The attenuation is expressed by:

$$\alpha(\omega) = -\frac{1}{2L}\ln\left[\frac{A_5(\omega)}{A_2(\omega)}\xi_{ref}\right] \tag{4}$$

With

$$\xi_{ref} = \frac{(Z_{pg} + Z_{fish})^2}{4Z_{pg}Z_{fish}}$$

Z_{pg}: acoustic impedance of plexiglas. Z_{fish}: acoustic impedance of fish. Figure 11 shows the evolution of the peak-to-peak voltage of the bottom echo A_5 and the temperature at the center of the salmon during its first thawing.

This evolution is characterised by three distinct regimes: During the first minutes, the amplitude of the echo is very low; giving strong acoustic impedance, this is at low temperatures. Between 30 minutes and 60 minutes, there is an abrupt increase in the amplitude of the signal with a stagnant form of temperature around 0°C: This is the moment of transformation of the ice to water beyond 60 minutes there is a gradual decrease in amplitude of the echo and a rise of temperature of

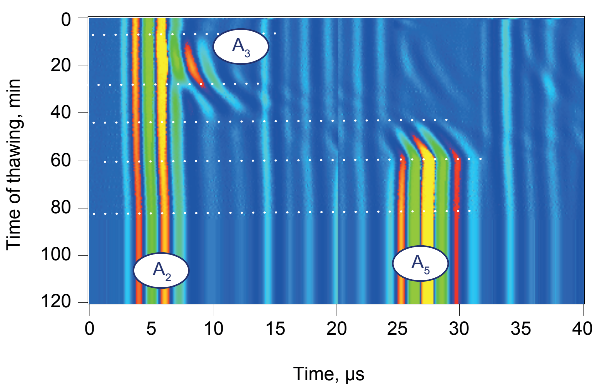

Fig. 10. Evolution of the signal reflected by salmon during the first thawing

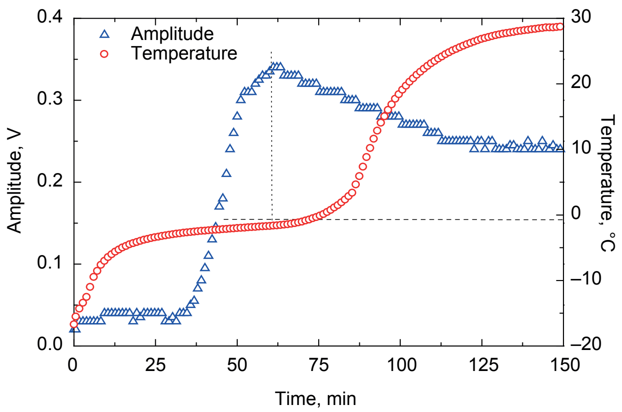

Fig. 11. Temperature and peak-to-peak voltage of the signal reflected by salmon during first thawing

the sample before reaching the steady state when the temperature is near to 30°C. This proves that there is a correlation between the acoustic behaviour and thermal state of the fish during its thawing.

Salmon in the second thawing

The second thawing of salmon (Fig. 12) is characterised by a more important evolution rate than that of the first thawing (Fig. 10).

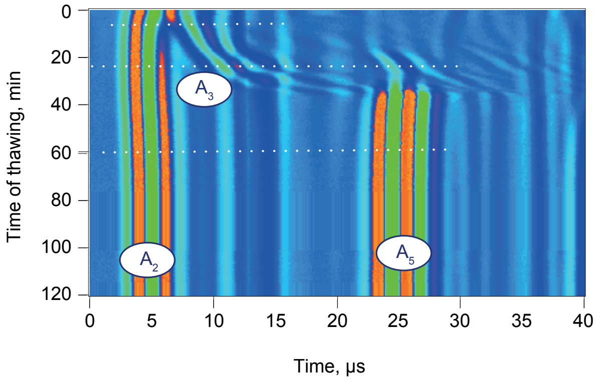

Fig. 12. Evolution of the signal reflected by salmon during his second thawing

The second thawing of salmon already starts at the beginning of the experiment (after 10 min for the first thawing), and already ends at 25 minutes (40 min for the first thawing); the first and second thawings of salmon are completely different. This is due to the loss of fluids (particularly the water, proteins and mineral salts) during the first thawing. The evolution of the peak-to-peak voltage of the bottom echo A_5 is shown in Figure 13.

Compared with the first thawing, we observed a faster evolution rate of the second thawing, and an increase of the amplitude of the reflected signal, therefore a decrease of the attenuation thus that of acoustic impedance; that reflects the changing of the fish composition. This is due to the loss of liquid containing proteins and mineral salts.

The simultaneous monitoring of the temperature of the sample, the peak-to-peak voltage of the bottom echo, and the phase velocity of the wave in the sample gives the waveforms of Figures 14 and 15.

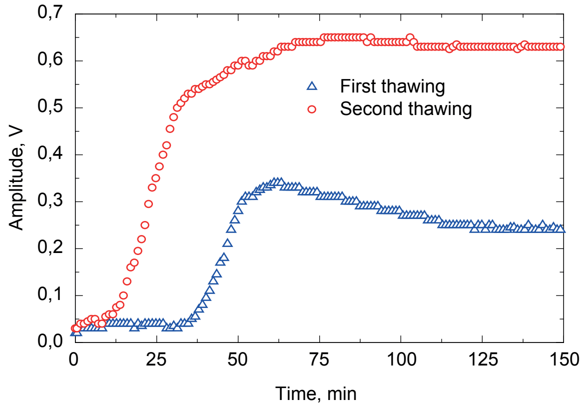

Fig. 13. Evolution of the peak-to-peak voltage of the signal reflected by a sample of salmon

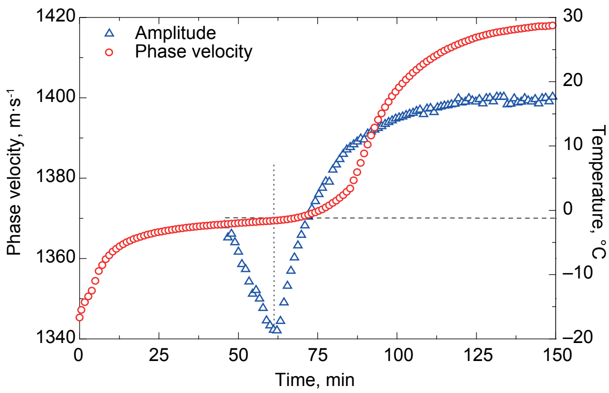

Fig. 14. Temperature and phase velocity of wave reflected by salmon during the first thawing

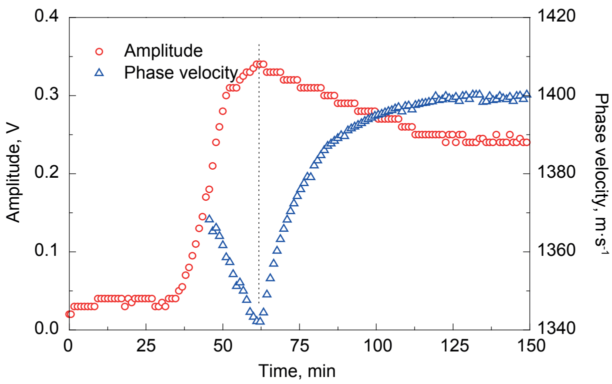

Fig. 15. Velocity and peak-to-peak voltage of signal reflected by salmon during its first thawing

The maximum of magnitude corresponds to a phase velocity of 1342 m·s^{-1} which corresponds to that of fish before freezing (fresh fish): At this point, the thawed fish behaves like fresh fish. The increase in phase velocity from this point is due to the increase of temperature of fish.

The Figure 16 presents the phase velocity of salmon during the first and second thawings.

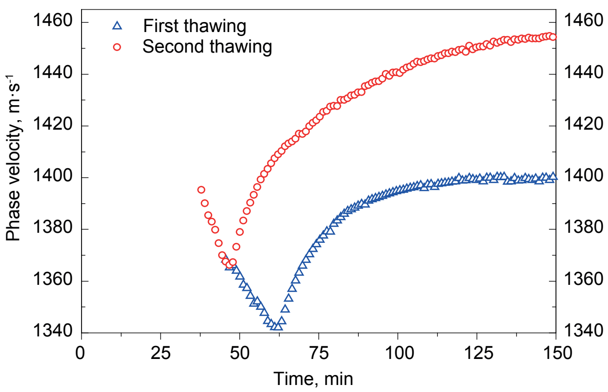

Fig. 16. Phase velocity of the ultrasonic wave in salmon during the first and the second thawing

There is a relative increase in phase velocity during the second thawing; this variation appears to be a good indicator of the deterioration of the fish quality which due to the loss of liquid containing proteins. The following Tables 1 and 2 summarize the phase velocity, amplitude, and time of the first and second thawings.

Table 1. Time of the first and of second thawing

	Start of thawing min (evolution of A_3)	End of thawing min (appear of A_5)
Red drum in the 1st thawing	10	50
Red drum in the 2nd thawing	05	40
Salmon in the 1st thawing	10	40
Salmon in the 2nd thawing	06	25

Table 2. Amplitude of echo and phase velocity

	Amplitude of the echoes A_5 at the end of thawing, V	Phase velocity at the end of thawing m·s^{-1}
Red drum in the 1st thawing	0.33	1 442.3
Red drum in the 2nd thawing	0.58	1 538.5
Salmon in the 1st thawing	0.25	1 401.9
Salmon in the 2nd thawing	0.62	1 554.4

CONCLUSION

The ultrasonic technique for control thawing process of fish is based on the temporal and frequency analysis of the signal reflected by the fish during its thawing. The monitoring evolution of the position, amplitude and frequency spectrum of reflected echoes, allows to follow the evolution rate of thawing and to show the effect of an accidental thawing.

The results of this study show a decrease of time of the second thawing (36%) and an optimal time and evolution rate of thawing specific to each type of fish thus avoiding the risk of microbial growth. The magnitude of the bottom reflected echo is a good indicator to see if fish has suffered an accidental thawing; the increase of this magnitude reflect the adverse effect of freezing/thawing on the quality of the fish texture. The monitoring of the viscoelastic parameters of the sample of fish studied is done simultaneously with tracking of variation of temperature; this shows a correlation between the acoustic behaviour of fish and its thermal state, whence the possibility to substitute the thermal control of thawing by the ultrasonic technique to insure a direct, precise and online control of quality of all fish treated, instead being limited to chemical and microbiological analysis of a single sample of line production. It would be interesting, following this study, to use the ultrasonic technique to analysis of freshness of different types of fish in order to establish a database for each type to check whether fish has suffered an accidental thawing.

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