Ultrasonic scanning of logs

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Abstract. This paper gives an overview of research on the non-destructive testing of wood by ultrasonics. The main topic of the paper is how ultrasonics may be used to characterize defects in logs and how to develop a way to scan logs in sawmill production. By combining ultrasonics with artificial intelligence, defects can be characterized by a scheme of wavepattern recognition and a procedure of total information reasoning. The newly developed method seems to improve scanning efficiency. The result of defect characterization of a cross-section is found to agree with the result obtained by X-ray tomography.

Keywords. Log scanning, ultrasonics, artificial intelligence, defect characterization.

1. Introduction

1.1. Why log scanning?

Wood is a very important raw material that has many uses. Wood can be used as a solid or as a reconstituted material that emerges from dividing the wood into smaller pieces and rejoining them by gluing and lignin melting. In contrast to the production of many other construction materials, solid wood materials develop as logs that are divided into smaller material pieces, i.e. planks and boards. The inner quality of a log is the main factor that determines the qualities and quantities of the different wood pieces that a log can be divided into. Hence, it is important to be able to judge the inner quality of a log for the optimal cutting pattern. Optimal cutting, based on an inner quality evaluation of Nordic softwoods, can theoretically increase the economic yield of lumber products by 10% or more [1]. To determine the quality and cutting pattern of the log, it is necessary to register types, location, orientation, size and condition of defects.

Several methods are in principle available for scanning of internal defects [2,3]. Internal scanning can be done by X-rays, gamma-rays, infrared rays, microwaves, nuclear magnetic resonance (NMR) and ultrasound. All the methods have advantages and disadvantages.

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One of the main problems when scanning for internal defects is that production speed is high, and the volumes are very large. A modern sawmill may process several thousand cubic meters in an 8-hour shift. Because many of the important defects are fairly small and rather sharply configurated, the resolution of the recognition system must be relatively high and, thus, the amount of data correspondingly large.

1.2. The most important defects of logs

The growth of a tree differs from the growth of other organic matter in that trees add layer to layer outside and on top of itself. A mature tree is made up of a large number of conical layers more or less concentric around the pith. This explains why wood is highly anisotropic and has distinctly different properties, lengthwise, radially and tangentially. The cells are mainly formed in the growth direction of the tree, and as they are newly formed, make up a set of tubes from the roots to the top of the tree. In the radial direction, other cells are formed that act as a connection system between the growth layer just under the bark and the wood inside. A cell or a set of cells will remain in the space in which it was formed for the life of the tree. A branch dying and falling off will leave its beginning in the form of a dead knot in the same place it was formed.

Knots and the fiber deviations surrounding the knots are the most serious defects. Attacks of fungi and insects are also important. In some species, it is important to know where other defects are, for example, resin pockets.

In many species, branch formation follows a somewhat regular pattern, which can be used to predict, to some degree, at what intervals the knots are to be found in a log.

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1.3. *Ultrasonics as a nondestructive testing method for wood*

The concept of ultrasound refers to vibrations of a material medium similar to sound waves but at a higher frequency than can be detected by an average human ear, i.e. vibrations with frequency over 18 kHz [4]. The application of ultrasound in wood technology has mainly involved nondestructive testing (NDT) of wood.

The ultrasonic practice detects and studies the acoustic responses of wood materials to externally applied excitement. The external excitement can be forced generation of stresses in the wood material, or application of ultrasonic waves to the material. The responses usually lie in the frequency range from 50 kHz to 1 MHz.

NDT of wood by ultrasonics was developed from ultrasonic techniques applied to materials like metals and plastics. The earliest applications of ultrasonics to NDT of wood were probably related to detecting decay in telegraph poles [5] and other defects in trees and wood [6,7] and measuring elastic anisotropy of wood [8]. Since then research in these fields has continued.

Research includes studies of ultrasonics for investigating the physical and the mechanical properties of wood and wood-based materials. The physical properties of wood include the acoustic velocity [9–13], the acoustic attenuation coefficient [14], and the modulus of elasticity (MOE) [8,13,15–22]. The physical properties of wood composites include the acoustic velocity and the elasticity [23]. The mechanical properties of wood include compression crushing strength of logs and poles [24], crushing strength of lumber [11,25–27], shear strength [28] and local compression stiffness of knotty lumber [29]. As an application in industry, the technique of measuring the MOE to predict crushing strength is used in timber grading [30].

Research has also included the use of ultrasonics for detecting wood defects. The defects include decay in solid wood, poles and trees [6,14,24,31–40], cross grain in lumber and trees [12,41], cracks in solid wood and in wood based materials [12,42,43], knots in veneer, lumber and logs [10,12,29,33,42,44–49], and holes in solid wood [6,14,33,40,42,50].

1.4. *Commonly used ultrasonic techniques for NDT of wood*

Ultrasonic techniques for wood NDT are classified into two groups, the conventional ultrasonics and the relatively new acousto-ultrasonics [51]. Conventional ultrasonics inspects only ultrasonic velocities. The types of defects detected are very limited. Acousto-ultrasonics has been developed on the basis of conventional ultrasonics. Acousto-ultrasonics measures the energy dissipation. The most commonly used parameters are stress wave factor (SWF), signal level or root mean square (RMS), peak amplitude, frequency contents and velocity. By this method, subtle defects can be recognized.

For investigating physical and mechanical properties, the elastic constant is the most important factor. This is because it has a good correlation with acoustic velocity. Other properties, for instance MOE, are studied by their correlations with the elastic constant. The influence of anisotropy of wood on the acoustic velocity is investigated either by direct testing in diverse directions or by first measuring velocities in the three principal directions. The rest is then computed on the basis of the measurements and a mechanical model of elasticity. The commonly used sensing techniques have been through-transmission and mode conversion.

Concerning defect detection, most of the research methods compare acoustic velocities measured in defect-free wood with wood with defects, and uncover statistical relationships between the acoustic velocities and the number or sizes of the different defects. The commonly used sensing technique has been through-transmission. The pulse-echoing method has proved impractical for defect detection [14].

Most of the specimens studied were of regular shapes — cubic blocks, sawn wood with two parallel flat surfaces, and turned-round poles or logs. In the first two cases, the parameter of analysis, velocity, was replaced by the transit time needed for sound to travel through the specimen dimension. When detecting defects in poles and logs, through-transmission is usually taken along a diameter; and again, the transit time is the analytical means. Some researchers [39,48] have tried to reconstruct sections of poles by ultrasonic computer tomography using derived velocities from measured data of transit time. For development of log-defect detection techniques, use of the attenuation property has been tried [44,46,48]. Amplitude (or attenuation) seems to be a less reliable means of detecting defects of wood since the anisotropy of wood makes amplitude comparisons very complex and because the variations of surface quality and geometry tend to influence the amplitude level.

For NDT of wood by means of ultrasonics, the choice of frequency is important. Factors to be considered are level of the receiver signal and detection resolution. For log or pole specimens, the commonly used frequencies are 50 kHz to 200 kHz and for other cases, 250 to 500 kHz are recommended for transversal through-transmission tests.

Research has shown that wood, as an anisotropical material, has a radial acoustic velocity of about 1 km/s, a longitudinal velocity of about 3 to 5 times the radial, and a tangential velocity in the range of the radial down to about one-half of the radial [10,51]. Attenuation in the three principal directions of wood has the following order: the longitudinal attenuation is smaller than the radial, and the radial is smaller than the tangential [10].

The above techniques are mainly employed in lab-scale tests or in field inspections where operation efficiency is of minor concern. In the process of testing, therefore, transducers are usually pressed or bonded to the surfaces of specimens.

For quality inspections, grading and sorting logs, lumber, or other wood products, operation efficiency is very critical and a smooth continuous operation is desired. A severe problem with continuous operation is how to effectively couple the wave generated by the transmitter to the surface of the test object so that sufficient energy is injected into the object. Water is the simplest choice.

The Forest Products Lab in Madison, Wisconsin, USA, proposed and developed a continuous scanning system for quality evaluation of lumber and planks [12].

The planks were continuously fed between the ultrasound receivers and transmitters in a water basin, and the transit time across the plank thickness was measured. The laboratory tests clearly demonstrated that the method could be used for grading planks.

Ultrasound computer tomography (CT) developed for medical purposes is an alternative that has been tried for continuous wood scanning. So far, the trials have not been successful because the high degree of anisotropy of wood as well as the high attenuation of the ultrasound passing through the wood causes blurring of the pictures [48].

When compared with its alternatives, ultrasonics has the advantage of good sensitivity to many types of defects and the capability for both geometric measurement and defect detection. An ultrasonic system for wood scanning is relatively cheap to install, easy to operate, can be readily automated, and is safe.

Ultrasonics has some disadvantages that limit its use for some purposes. The most serious one may be that it needs a couplant for continuous operation. In addition, the high attenuation of high frequency across the wood grain makes small details in large wooden objects very difficult to detect.

However, it can still be used for log scanning. Since the acoustic properties (acoustic impedance, for example) of wood in the radial direction are close to those of water, and logs in sawmills have a high moisture content, water can be used as a couplant. The resolution problem is not always serious, especially when logs are expected to have relatively good quality. Furthermore, new signal processing techniques, when combined with artificial intelligence, have shown promises of obtaining good resolution and identification of defects. After considering the promises and the advantages of ultrasonics, we started our research on an industry-oriented log scanning system by ultrasound.

With the relatively cheap, easy-to-operate, and safe ultrasound NDT technique, developing an ultrasonic log scanning system is felt to be within reach without surpassing the lowest level of acceptable requirements on scanning effectiveness and resolution.

2. Log scanning through a combination of ultrasonics and artificial intelligence

2.1. General considerations

2.1.1. *Artificial intelligence*

The main problems in developing an ultrasonic log scanning system are being able to observe and characterize the defects and being able to operate the production line sufficiently fast. The first problem refers to the possible resolution and is caused by the difficulty of ultrasound to penetrate wood. The second problem of getting sufficiently fast operation is caused by the speed requirements of on-line production. The more efficiently decisions are made, the faster the system will operate.

The AI functions that may be helpful for making efficient decisions in ultrasonic log scanning are:

(a) learning, i.e. the ability of the system to accumulate experience and to organize this knowledge so that it can be a basis for improved and faster reasoning;
(b) knowledge-based reasoning, based on the use of available expertise, earlier experiences, and commonly accepted rules;
(c) the ability to handle imprecision, incompleteness and randomness of information;
(d) the ability to adapt to new situations through task shifting and strategy modification.

2.1.2. *Ultrasonic method*

Considering the tasks of log scanning, tomographic methods seem proper, since they are based on reconstructed cross-sectional pictures of logs. A close study of the available tomographic techniques shows that they have the following disadvantages in relation to sawmill production:

(a) A substantial number of scans have to be taken, and a correspondingly large number of equations must be solved for the reconstruction of a cross-sectional picture (or a tomogram) of a test object.
(b) To characterize a defect based on a tomograph picture, further analysis and calculations are usually needed to determine the existence, type, dimensions and orientation of the defects. This phase is both complicated and time-consuming and includes the use of picture processing techniques.

Both disadvantages explain why computer tomography still remains in research environments and has not yet been used in the wood industries.

Our version of log scanning by ultrasound employs three sensing techniques in combination with AI functions:

(a) The *pulse-echo method* is employed to scan the geometry of the log, as shown in Fig. 1. Two transducers placed one on each of the two opposite sides of a log are aligned vertically to the log surface. Each transducer

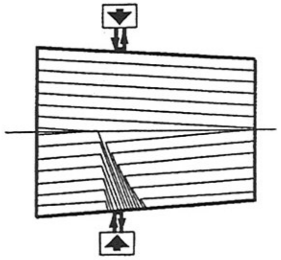

Fig. 1. Pulse-echo method for external geometry scanning.

measures a position of a point on the log surface. The distance between the two opposing points is taken as a measure of the log diameter.

(b) The *through-transmission method* is used as the principal method for detecting internal log defects (Fig. 2). The wave is supposed to travel radially (along a diameter) or through the log center. Earlier research [10] and our experience from preliminary tests found that waves travel fastest and with less attenuation across the log if it takes the radial pass. This is an advantage for detecting log defects, as will be explained later.

(c) The *grain-sound-tracing method* is used to trace the knots that extend to the log surface, i.e. the so-called outgoing knots (Fig. 3). Earlier research has shown that an ultrasonic wave sent from a log end tends to follow the fiber and be lead out to the log surface by the grain of the outgoing knots [49].

Based on the considerations mentioned in the previous sections, an intelligent log scanning system was designed as shown in Fig. 4.

Because of the limits of a paper like this, the following sections will mainly discuss techniques related to the through-transmission method. The other techniques will, without any problem, generate reliable information, such as the geometric data of the log and location of outgoing knots.

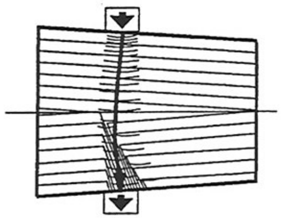

Fig. 2. Radial through-transmission for defect detection.

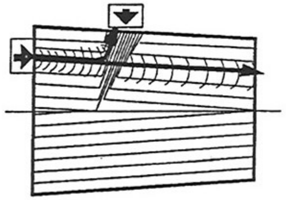

Fig. 3. Grain-sound tracing for knot detection.

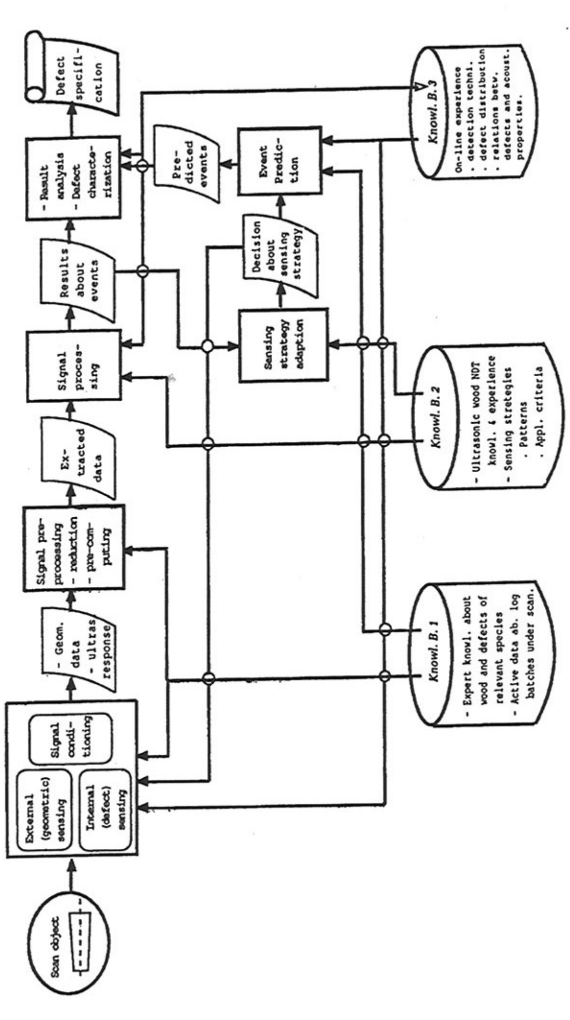

Fig. 4. Block diagram of an intelligent ultrasonic log-scanning system — information flow chart.

2.2. Signal acquisition

When bursts of sinusoids are employed as a transmitter signal, the waveform captured at the receiver is usually made up of several pulse responses in the form of peaks observed in the envelope of the waveform. Information of the log interior located in the wavepath is given by the location, the levels and the number of these peaks. As the defects are rather small relative to the log cross-sectional area, the information-bearing peaks are located around a position on the time axis where a peak from a defect-free path should occur. Therefore, there is always a predictable range in the time domain in which the information of log interiors reside. This information-intensive range is called an effective wave window. The waveform observed in an effective window is known as effective waveform. The limits of a window are derived from the geometric and acoustic properties of largest defects within a diameter which are predicted on the basis of rules-of-thumb. A new wave window is computed for each new scan position.

By using the effective wave windows, effects of three noise sources are reduced:

(i) wave leakage through the coupling water;
(ii) energy that is scattered and follows irrelevant paths in the log;
(iii) induction of an electrical field in the environment.

These three types of noise are found outside effective windows if the windows are correctly defined. If a knot occurring in the wavepath is a radially outgoing knot extending from the center to the surface of the log, the wave will travel along the wood fibre of the longitudinal direction of the knot. The transit time across the log diameter will reach its lowest value because the speed of sound is higher along wood fibers than across them. If the knot is intersecting the transmission direction and has the largest possible diameter, the transit time will reach its highest value. This is because the sound travels around the knot taking a non-radial path, which means a longer transmission path and lower transmission speed. Accordingly, a lower and an upper limit of the wave window are given.

2.3. Wave patterns as a means to recognize defects

2.3.1. General considerations

Because wood structure is complex, it is difficult to find patterns relating waveforms to each type of detect. To establish a connection between waveforms and a group of defects is much simpler. Such a connection is known as a wave pattern. To identify a defect in a recognized group, further reasoning is required.

To interpret the wave patterns, a method called "wave path analysis" is used. If only sound wood occurs in the path of a wave, a significant peak is obtained in the effective waveform received. In the case of a tilting knot (taking the oval shape in a log cross-section or cut from its chest by the cross-section) occurring with its longest axis intersecting the wavepath, the wave that results tends to take two paths around the knot as described earlier. These paths will cause two overlapping peaks and appear to be one in the effective waveform. A peak caused by a tilting knot occurs at a delayed position on the time axis compared with that of a peak

caused by sound wood. This is because the wave travels a longer distance and travels slower in the non-radial segment around the knot. In this way, we have a link between a tilting knot and the property of a peak. In this case the link is a relative delay. Similarly, we can analyze the peak levels caused by other defects as compared to a peak caused by sound wood.

To achieve more definite links, we use both the relative delay (or lead) and relative peak level. However, the disadvantage with these two properties is that they vary with the log diameter. To have a better reference for each property, we substitute the two properties with the acoustic velocity and the acoustic attenuation coefficient, respectively, which are rather constant.

The construction of wavepatterns is based on the following:

(1) Signals are acquired by through-transmission by having the transducers diametrically opposite each other.
(2) Transducers are placed close to the log surface. The attenuation caused by water is negligible.
(3) Noise and errors resulting from water disturbance, eccentric positioning of transducers, log shape assymmetry and log roughness are small enough to be insignificant. The most important factors of errors to be considered are orthogonal anisotropy of the wood structure and slight variations of the radial acoustic properties of sound wood.

2.3.2. Pattern description

Based on the principles described in the previous section, an analysis of wave paths for different defect types was conducted. By means of the velocity and the attenuation coefficient derived from the paths caused by different types of wood interior, different wave patterns were depicted.

For a better description of the features of a path, descriptive values or classes of the velocity and the attenuation coefficient are introduced. A velocity with a given value may be low, normal or high. A normal velocity is loosely defined as one that is in the order of the velocities of defect-free paths. A high velocity is defined as one that is in a higher order than that of the normal velocity, and a low velocity as one in a lower order. In terms of the time-domain spectrum, the normal velocity corresponds to the normal location of the peaks from defect-free paths, the high velocity corresponds to a time lead relative to the normal location, while

Table 1
Codes of velocity and attenuation classes

Classes	Codes
Low velocity (lead)	$m(k)=0$
Normal velocity (normal location)	$m(k)=1$
High velocity (delay)	$m(k)=2$
Normal attenuation (normal peak level)	$n(k)=2$
High attenuation (low peak level)	$n(k)=1$
Extra high attenuation (extra low peak level)	$n(k)=0$

the low velocity corresponds to a time delay relative to the normal location. Both the high-velocity property and the low-velocity property are regarded as symptoms of defects.

Attenuation with a given value of attenuation coefficient can be normal, high or extra high. Attenuation is defined as normal if the value of the attenuation coefficient is in the order of or lower than the order of the attenuation of the defect-free paths. Attenuation is defined as high if the value of the coefficient is in a higher order than that of the defect-free paths. Attenuation is defined as extra-high if no peaks are detected or the peak level is in the order of the background noise. In terms of the time domain, normal attenuation corresponds to the normal peak level, high attenuation corresponds to a low peak level, and the extra high attenuation, to an extra-low peak level.

For convenience, the descriptive values or classes of acoustic velocity and attenuation are coded with numbers, as shown in Table 1. In order to construct the pattern of an interior type, features of each peak it leads to are depicted by codes of the two descriptive values corresponding to the peak. We call the code pair an attribute-class array.

If one defect is included in a wave path and there is only one peak in each effective waveform significantly indicating the wave path properties, the wave patterns for each type of wood interior are given as in Table 2. The patterns are called single-peak patterns because they are derived from the single-peak assumption. One can see from this table that several types of interiors may have a common pattern. The interiors that possess a common wave pattern form an interior group. Each interior group has a unique wave pattern.

There may be several peaks in an effective waveform that together represent the properties of the wave path. Three dimensions are needed to describe a waveform: the number of peaks in a waveform, the attenuation class and the velocity class for each peak. As each velocity class corresponds to a peak-location range, peaks may be categorized into three distinguished location ranges. For each range, only one peak is assumed to be representative. Each waveform has at most three peaks presenting the composition of the three velocity classes.

Table 2
Wood interiors and their corresponding peak-attribute arrays

Wood interiors	Class arrays
Sound wood	(1, 2)
Horizontal (radial) knot	(2, 2)
Tilting (oval-shaped) knot	(0, 1)
Hole (non-radial)	(0, 1)
Decay	(0, 1)
Ring shake	(1, 1)
Resin pocket	(1, 1)
Bark inclusion	(1, 1)

In order to clearly but simply code the wave patterns, 3-digit 3-nary codes were designed. The low velocity ($m=0$), the normal velocity ($m=1$) and the high velocity ($m=2$) are expressed by a non-zero attenuation-class code respectively on the first digit (the 3^0-digit), the second digit (the 3^1-digit) and the third digit (the 3^3-digit). The three attenuation classes ($n=0$, 1 and 2) are expressed by the three numbers (0, 1 and 2) on each digit. For instance, the pattern of sound wood may be coded as 020. From the code, one can see that the sound wood pattern contains one peak (only one non-zero digit) with $m=1$ (the 3^1-digit is non-zero) and $n=2$ (the number on the second digit is 2). The pattern of a horizontal knot, as an example, may be coded as 200. From the code, one can read that the pattern includes one peak (only one non-zero digit) with $m=2$ (the 3^2-digit is non-zero) and $n=2$ (the number on the non-zero digit is 2).

The connections between wood interior types and waveforms depicted by such codes may be derived by "wave path analysis". The results are shown in Fig. 5. The wave patterns so constructed are called multiple-peak wave patterns.

We apply fuzzy set theory [52] to mathematically redefine the imprecisely defined classes of velocity and attenuation. A fuzzy set is a set of distinct objects which imprecisely define a property, for instance, "normal velocity" in our pattern description. Each object is associated with a degree for the property corresponding to the set. Grades of membership take on values in the range (0, 1), inclusive.

The reason for using fuzzy set theory is that properties of wood interiors, even defect-free wood, vary from part to part and from piece to piece. The similarity of the same type of wood interiors exists in a loose sense or on some scale of the concerned properties. It is more proper to define a characteristic property of a wood interior with a "set of values" than with a single value.

Wave patterns are regarded as fuzzy subsets of the pattern universe PTN (pattern). Each pattern is defined on some designated velocity class(es) and some designated attenuation class(es), and each of the classes is defined by a series of values together with their membership values for that class. Each pattern is finally defined by a 2-D matrix of values of the two attributes together with membership functions derived from the membership functions of the two attributes. However, when defining wave patterns, it is essential to find the membership functions of the two attributes in their different classes. The membership functions can be found through learning from opened cross-sections of log samples or from cross-sectional pictures obtained by X-ray tomography. The theoretical forms, bell shape or S-shape, of the different membership functions are shown in Fig. 6.

2.3.3. *Recognition of wave patterns*

2.3.3.1. Peak detection. Peak detection is the most essential procedure of pattern recognition. Generally, a wave path corresponds to a significant peak in the effective wave, but not conversely. Noise may cause extra peaks in an effective waveform. The peaks caused by background noise, however, may be reduced by proper instrumentation and installation. The task of peak detection is to find the most significant peaks by a significance test. Such a test involves the following aspects:

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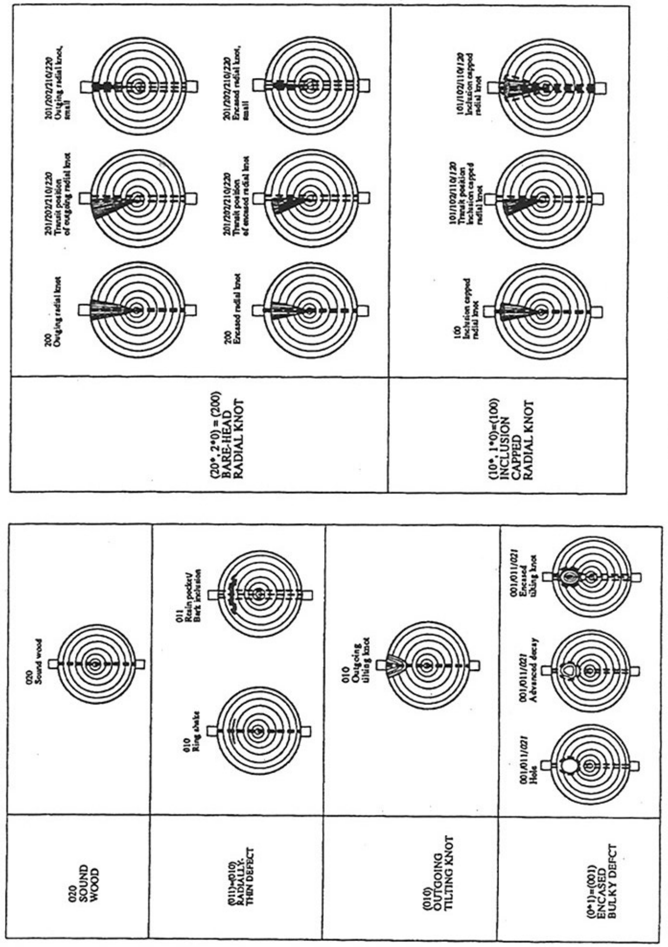


Fig. 5. Standard multiple-peak wave patterns. (The oblique pattern codes indicate possible pattern interpretations in the case of transit positions of the defects. The interior may be translated either as a defect or as defect-free, depending on the confirmation of the conjugate wave pattern.)

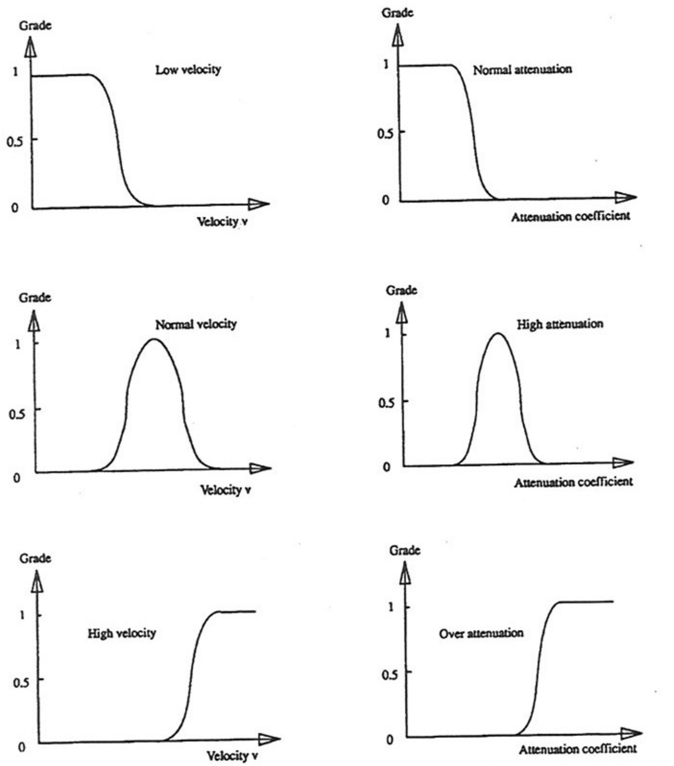


Fig. 6. Theoretical curves of membership functions for different classes of the acoustic velocity and the acoustic attenuation in wood.

(a) Identification of a crest (a crest is a waveform segment with the largest amplitude level within a local area).

(b) A crest between two troughs (a trough is a waveform segment with the lowest amplitude level in a local area).

(c) If conditions (a) and (b) are true, the crest is taken as a peak. A peak is said to be significant if its significance level is one of the highest among all the peaks detected in an effective waveform. The level of significance of a peak is measured by a parameter, peak significance level (PSL).

Since the pulse injected into the test object is a burst of sinusoids, a response signal (peak) acquired at the receiver should also be a train of cyclic waves. However, the received signal is usually not a train of sine waves because of the effect of the transducers. The edges of the signal train are rounded out. The train envelope tends to be bell-shaped instead of being rectangular (Fig. 7). The top of the "bell" is the amplitude point. As a measure of peak level, the root mean square (RMS) measured over a range around the amplitude point is better than the single reading directly from the point itself, and helps eliminate the noise effect. If the number of cycles in a transmitter burst is NC, then NC or less cycles around the amplitude point (depending on the level of the background noise and resolution required) should be used for calculating the RMS.

RMS is calculated over an effective wave, and the largest RMS value, A, in a local area with NC cycles is taken as a crest or a peak. The lowest RMSs, A_1 and A_2, on both sides of the peak are taken as troughs. We use fuzzy set theory to define the fuzzy concept "significant peak". For each peak, the peak significance level is defined as:

$$\mathrm{PSL}=\sqrt{(A-A_1)(A-A_2)}/A.$$

PSL is a measure of the reliability that a peak stands for a useful signal presenting properties of the wood interior rather than the background noise.

2.3.3.2. Computing peak attributes. The two attributes of a peak are velocity and attenuation coefficient and can be calculated by the following formulas:

$$v=D/t,$$

$$\alpha=\frac{8.686}{D}\left(\ln\frac{A_w(S)}{A(D)}+\ln\frac{2\,\rho_w v_w}{\rho_w v_w+\rho\, v}+\alpha_w S\right),$$

where D is the log diameter; t is the transit time through diameter D; α is the acoustic pressure attenuation coefficient of wood measured from a peak of the waveform taken at log diameter D; $A(D)$ is the pressure amplitude measured from a peak of the waveform taken at diameter D; S is the distance between the receiver and the transmitter arranged for measuring the output amplitude of the transmitter; this output will later be used for log scanning; ρ is the specific gravity of wood under scanning; v is the acoustic velocity of wood measured from the diameter D

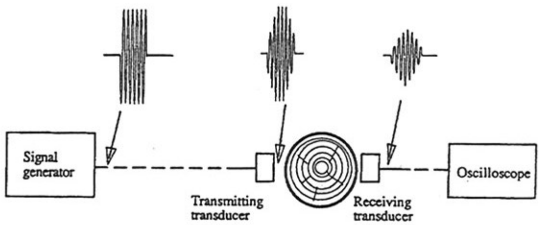


Fig. 7. Changes of shape of the pulse envelope observed at the outputs of different instruments.

of the log under scanning; $A_w(S)$ is the pressure amplitude measured at the receiver while the transmission is through water only; ρ_w is the specific gravity of water; v_w is the acoustic velocity in water; and α_w is the acoustic pressure attenuation coefficient of water at a given frequency.

The second term in the expression of the attenuation coefficient α may be omitted because the acoustic impedances of water and wood are very close.

2.3.3.3. Pattern recognition. The procedure of pattern recognition based on the fuzzy set theory by Zadeh [52] and the multiple-peak wave patterns is formulated as follows:

(a) Find the attribute array of the unknown waveform in question.
(b) Find the grade of membership of the attributes in each of their possible classes by using the learned membership functions of the classes. Take the class giving the highest grade of membership as the final class of the attribute and take this grade as the final one of the attribute. The velocity class arrived at is used to indicate the location range of the peak.
(c) Group the final classes of the two attributes of the peak to form its attribute-class pair.
(d) Find the grade of membership of the attribute-class pair by taking the smaller of the grades of the pair's components.
(e) Repeat steps (a) and (d) for all the significant peaks in the effective waveform.
(f) Convert the results from step (e) into three-peak patterns against the form of the three-peak standard patterns. In doing this, the peak possessing the highest grade of membership is chosen to represent the location range.
(g) Match patterns given by step (f) against the standard patterns, on the basis of rules given in the knowledge base containing experience about ultrasonic techniques.

Considering the possible combinations of the three dimensions that define a pattern, the result from step (f) may have 27 possibilities. If it is not one of the standard patterns, step (g) is taken.

To recognize an unknown waveform against the single-peak wave patterns, only one of the most significant peaks is to be used in making the final recognition decision. There may be two ways to do this: the most-significant-peak method and the highest-membership-peak method.

If y is a receiver waveform, $P'(y)$ is a wave pattern derived from step (f), and PTN_s is the set of standard wave patterns, the best matched standard multiple-peak pattern for waveform y, $\mathrm{RR}(y)$, is decided by the following rule:

```
    **if** $P'(y)$ not $\in \mathrm{PTN}_s$
    **then if** $P'(y)=222$ **or** 111 **or** 000
    **then** recognition by single-peak patterns
    **otherwise** $\mathrm{RR}(y)=P'(y)-111$,
```

where $P'(y)-111=110$, for instance, when $P'(y)=221$.

This rule retains the most important defective features indicated by the velocity components of the pattern and discards the effect of the water–wood interfaces on the attenuation measurement.

By the highest-membership-peak method, several highly significant peaks are used. Steps (a)–(e) are to be taken. The result of recognition will be the pattern given by the peak that possesses the highest grade of membership. A Max-operation is taken among the grades of membership of the peaks as derived from step (e).

By the most-significant-peak method, only the most significant peak is involved in the categorization of peak attributes. The result will be the pattern given by the peak with the highest PSL.

With the result of pattern recognition, the type of wood interior(s) may be identified from Table 2 or Fig. 5.

2.3.4. Defect characterization

As mentioned before, a waveform pattern tends to correspond to a group of defects. Therefore, a further step of reasoning is needed for figuring out the real identity. Because of the guesswork involved in the recognition process, the wave pattern recognized usually is not fully reliable. Information from other sources is used to further confirm or modify the recognition results. All these activities are included in a total information reasonsing process.

Total information reasoning means that the inference operation is not only based on ultrasonic waveforms but also on other sources useful for reaching a clearer picture of log interiors. The following is a rather complete list of the sources of information and knowledge used:

(a) wave patterns of waveforms from radial through-transmission;
(b) other properties of the waveforms, such as signal level, frequency contents;
(c) synthesized results of the wave patterns and other properties of the conjugate waveforms;
(d) results from grain sound tracing;
(e) recent defect history for a log and for a batch of logs out of available scanning results, and knowledge of defect distribution and forms;
(f) relationship between different types of defects;
(g) rules for grading forest logs and rules for grading sawn timber;
(h) tree silvicultural conditions and the expected relationship between log geometry and defects;
(i) tree silvicultural conditions and their influences on log interior;
(j) influence of log management on log quality.

A hierarchy representing the problem of total information reasoning is given in Fig. 8. This hierarchy takes a form of an OR/AND tree. In such a tree, the root is formed by the descriptions of the log interiors and the leaves are information sources, i.e. the different sensing arrangements and knowledge bases. The connections between the three tasks and the information sources are OR- and AND-branches, which are formed by different intermediate states of information. An

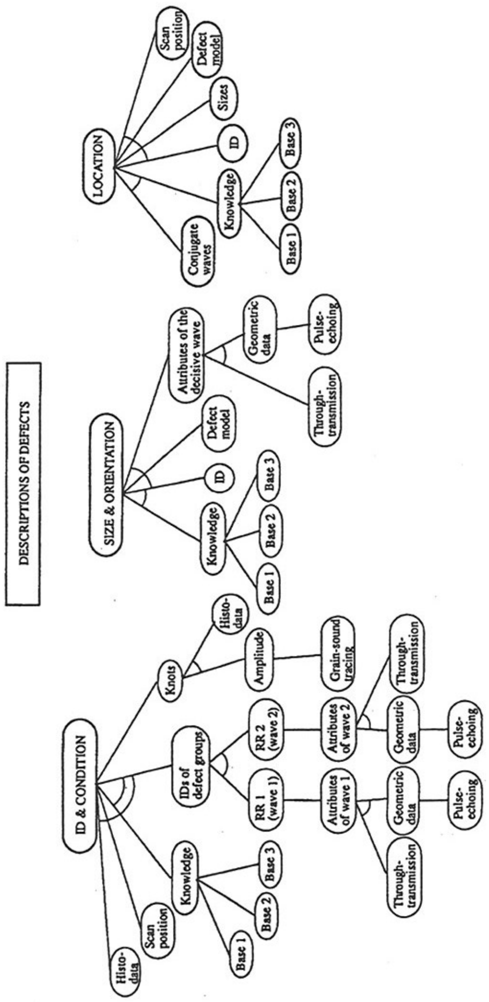


Fig. 8. A hierarchy representing the problem of total information reasoning.

OR-branch leads to an independent solution path. An AND-branch shows a dependent-solution path, or incomplete solution path. In order to reach a rather complete solution, all the component AND-branches must join force. Otherwise, an incomplete solution is arrived at. Some AND-branches may be components in different groups of dependent solution paths. The different groups are alternatives to each other. Some AND-branch group may be a sub-group of another one. This relation means that the sub-group may occasionally lead to a complete solution. If not, the larger group should be used. The larger group gives a complete solution by employing additional AND-branches.

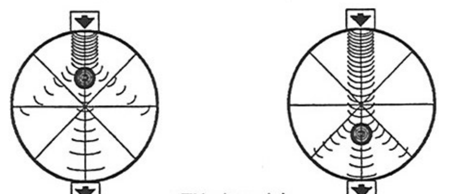
We have discovered two rules that may be helpful. The first rule states that as long as one of a pair of conjugate waveforms indicates a defect, then a defect is said to be in this position (diameter). This rule is given to avoid missing a defect. The second rule states that if a defect has been detected and the RMS of the effective wave from one transmission direction is higher than that from the other, then the defect is judged to occur on the receiver side with respect to the first transmission direction. This rule enables one to tell the approximate location of a defect in the scan diameter (Fig. 9). The closer a defect is to the receiver, the less wave energy is scattered away from the receiver and the higher energy intensity will be received by the receiver. This is reflected in the RMS.

After the defect identity has been recognized, the size of the defect is computed based on the geometric model of the defect and the difference between the measured velocity and the velocity taken from a defect-free path.

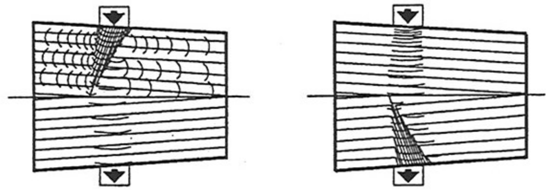
3. Simulation and results

The principles of the designed log scanning system was tested as shown in Fig. 10. A log segment 0.6 m in length and 20 cm in diameter was used as a test object. During the scanning process, the log was deeply immersed in a water basin. The log was rotated, and the transducers moved axially back and forth over the log surface. The ultrasound used in the pulse echo method for external geometry scanning had a frequency of 700 kHz, and that used in the radial through–transmission and the grain sound tracing methods for internal defect scanning had a frequency of 125 kHz. Data acquisition and signal processing were realized by using the software pack ASYSTANT.

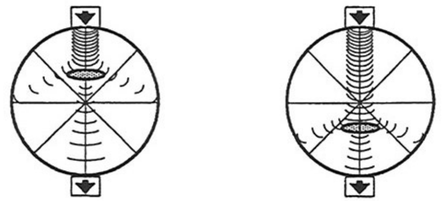
For the purpose of learning about membership functions, the log was first scanned in a commercial X-ray computer tomograph, and internal defects were registered by human judgement. The same positions were then scanned in the ultrasonic device. By linking the identities of wood interiors with peaks detected in effective waveforms from the corresponding positions, membership functions were obtained (Fig. 11). By applying the membership functions to recognition of waveform patterns and by performing total information reasoning, wood interiors of a log section were recognized (Tables 3 and 4). The results show that the new defect recognition technique identifies wood interiors at error rates 2/24 to 6/24 with respect to the results from X-ray tomography.



a. Tilting knot or hole



b. Horizontal knot



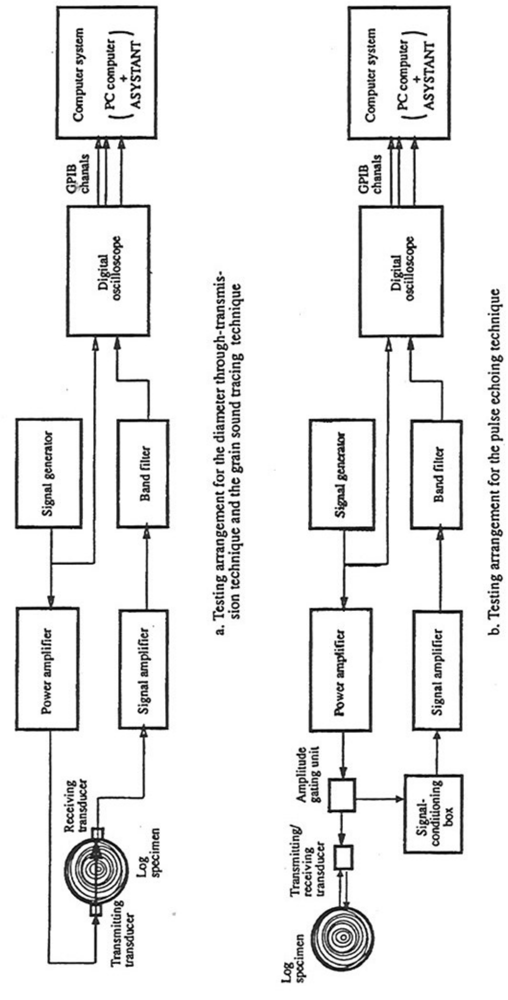
c. Radially thin defect

Fig. 9. The amplitude-RMS level of the effective wave differs in the two conjugate opposite transmission directions.

4. Conclusions

Tables 3 and 4 show that the new defect recognition technique has presented a description of defects in a log section rather agreeable to that presented by analysis of the X-ray tomogram.

The newly developed method intends to improve scanning efficiency by taking rather neat approaches through signal sensing, acquisition and processing. By radial sensing of the log and actively framing of the waveforms, tasks of signal acquisition and processing are reduced to a very low level. By direct presentation



a. Testing arrangement for the diameter through-transmission technique and the grain sound tracing technique

b. Testing arrangement for the pulse echoing technique

Fig. 10. Testing arrangements for log-scanning.

Table 3
Defect characterization of a log cross-section by the approach of fuzzy sets in comparison with the results obtained by X-ray tomography —Example 1

Row	Angle (°)	v(1) (km/s)	Att(1) (db/cm)	v(2) (km/s)	Att(2) (db/cm)	v(3) (km/s)	Att(3) (db/cm)	Grade/ code(1)	Grade/ code(2)	Grade/ code(3)	Wave RMS	X-ray result
1	0	1.11	1.79	0.74	2.38			0.78/020	0.80/001		61.7	knot at 0°
2	15	0.93	1.76					0.73/020			61.1	defect free
3	30	0.83	1.68					0.87/020			61.9	defect free
4	45	0.88	1.78					0.81/020			61.3	knot at 225°
5	60	1.01	1.83					0.78/020			62.6	defect free
6	75	1.47	1.70	0.83	1.79			0.86/200	0.80/020		61.2	knot at 75°
7	90	0.82	1.95					0.67/020			61.1	knot at 90°
8	105	1.49	2.10	0.93	2.05	0.74	2.08	0.59/200	0.62/020	0.60/002	60.9	defect free
9	120	0.92	1.59					0.94/020			65.3	defect free
10	135	0.92	1.72					0.90/020			62.9	knot at 135°
11	150	1.47	2.27	0.96	2.15	0.74	1.94	0.75/100	0.56/020	0.68/002	60.9	knot at 150°
12	165	0.77	1.98					0.57/020			60.8	defect free
13	180	1.27	1.89	0.78	1.89			0.70/020	0.57/020		61.1	knot at 0°
14	195	1.06	2.15	0.84	2.00			0.56/020	0.65/020		61.9	defect free
15	210	1.06	1.94					0.68/020			60.8	defect free
16	225	1.14	2.28	0.78	2.10			0.65/010	0.59/020		61.0	knot at 225°
17	240	1.54	1.92					0.69/020			60.5	defect free
18	255	1.47	1.66					0.85/020			61.9	knot at 75°
19	270	0.87	1.79					0.67/020			62.6	knot at 90°
20	285	0.99	1.62					0.99/020			66.0	defect free
21	300	0.91	2.17					0.56/020			61.4	defect free
22	315	1.37	1.81	0.72	1.89			0.58/200	0.70/002		62.9	knot at 135°
23	330	0.93	2.26	0.74	2.16			0.60/010	0.56/002		61.1	knot at 150°
24	345	1.16	1.95	0.74	2.26			0.67/020	0.60/001		61.3	defect free

Table 3 (continued)

Row	Single-peak patterns (highest grade)					Multi-peak patterns			
	Pattern	RR fr. conjug.	Results	ID hit	Locat. hit	Pattern	RR fr. conjug.	Results	ID hit
1	0.80/001*	0.70/001*	encased tilt. knot at 180°	yes	no	0.78/021	0.78/021	encased knot	yes
2	0.73/020	0.73/020	defect free	yes		0.73/020	0.73/020	defect free	no
3	0.87/020	0.87/020	defect free	yes		0.87/020	0.87/020	defect free	yes
4	0.81/020	0.65/010**	outg. knot or crack at 225°	yes	yes	0.81/020	0.59/010	outg. knot/thin defect	yes
5	0.78/020	0.78/020	defect free	yes		0.78/020	0.78/020	defect free	yes
6	0.86/200*	0.85/200*	horiz. knot at 75°	yes	yes	0.80/220	0.80/220	horiz. knot	yes
7	0.67/020	0.67/020	defect free	no		0.67/020	0.67/020	defect free	no
8	0.62/020	0.99/020	defect free	yes		0.59/222	0.99/020	defect free	yes
9	0.94/020	0.94/020	defect free	yes		0.94/020	0.94/020	defect free	yes
10	0.90/020	0.70/021*	encased tilt. knot maybe at 135°	yes	yes	0.90/020	0.58/202	horiz. knot	yes
11	0.75/100*	0.60/100*	horiz. knot at 150°	yes	yes	0.56/122 (011)	0.56/011	tilted knot	yes
12	0.57/020	0.67/020	defect free	yes		0.57/020	0.60/021	tilt. knot	no
13	0.70/020	0.70/001*	encased tilt. knot at 180°	yes	no	0.57/020	0.78/021	encased knot	yes
14	0.65/020	0.73/020	defect free	yes		0.65/020	0.73/020	defect free	no
15	0.68/020	0.87/020	defect free	yes		0.68/020	0.87/020	defect free	yes
16	0.65/010*	0.65/010*	outg. knot or crack at 225°	yes	yes	0.59/010	0.59/010	outg. knot/thin defect	yes
17	0.69/020	0.78/020	defect free	yes		0.69/020	0.78/020	defect free	yes
18	0.85/020	0.85/200*	horiz. knot at 75°	yes	yes	0.85/020	0.80/220	horiz. knot	yes
19	0.67/020	0.67/020	defect free	no		0.67/020	0.64/020	defect free	no
20	0.99/020	0.99/020	defect free	yes		0.99/020	0.99/020	defect free	yes
21	0.56/020	0.94/020	defect free	yes		0.56/020	0.94/020	defect free	yes
22	0.70/001*	0.70/021*	encased tilt. knot maybe at 135°	yes	yes	0.58/202	0.58/202	horiz. knot	yes
23	0.60/010*	0.60/110*	horiz. knot at 150°	yes	yes	0.56/012	0.56/011	tilted knot	yes
24	0.67/020	0.67/020	defect free	yes		0.60/021	0.60/021	tilt. knot	no

Error rates — single-peak patterns: 2 out of 24; multi-peak patterns 6 out of 24.

Table 4
Defect characterization of a log cross-section by the approach of fuzzy sets in comparison with the results obtained by X-ray tomography —Example 2

Row	Angle (°)	v(1) (km/s)	Att(1) (db/cm)	v(2) (km/s)	Att(2) (db/cm)	Grade/ PP(1)	PSL (1)	Grade/ PP(2)	PSL (2)	RMS	X-ray RR
1	0	0.99	1.72			0.90/020	0.63			15.24	free
2	15	1.09	1.72	1.00	1.74	0.82/020	0.47	0.88/020	0.30	20.35	free
3	30	1.25	1.88			0.71/020	0.47			11.27	free
4	45	1.29	1.83	0.89	1.71	0.65/020	0.31	0.88/020	0.61	19.18	tilted knot at 225°
5	60									16.25	free
6	75	1.37	1.65	0.86	1.84	0.58/200	0.45	0.75/020	0.30	19.69	horiz. knot at 75°
7	90	0.89	1.73			0.89/020	0.17			26.64	free
8	105									10.90	free
9	120	0.98	1.95	0.80	2.10	0.68/020	0.52	0.59/020	0.36	9.19	tilted knot at 300°
10	135	1.16	1.79	0.98	1.79	0.78/020	0.32	0.80/020	0.48	15.78	free
11	150									18.16	free
12	165	0.93	1.46			0.90/020	0.64			30.25	free
13	180	1.24	1.98	0.88	2.13	0.65/020	0.81	0.58/020	0.58	9.60	free
14	195	0.84	1.66			0.86/020	0.44			18.48	free
15	210	1.11	2.06	0.79	2.10	0.61/020	0.39	0.60/020	0.60	9.19	free
16	225	1.21	1.91			0.64/020	0.48			11.75	tilted knot at 225°
17	240	1.21	1.91			0.64/020	0.27			12.40	free
18	255	1.29	1.52			0.65/020	0.90			24.75	horiz. knot at 75°
19	270	0.97	1.48			0.97/020	0.46			28.98	free
20	285	1.20	1.52	0.97	1.55	0.78/020	0.29	0.97/020	0.42	29.85	free
21	300	1.07	1.47			0.86/020	0.35			32.09	tilted knot at 300°
22	315	1.17	1.45			0.78/020	0.72			27.10	free
23	330	1.11	1.75			0.78/020	0.58			18.10	free
24	345									15.74	free

Table 4 (continued)

Row	Single-peak (highest grade)				Single-peak (highest PSL)			Multi-peak patterns			
	Pattern	RR fr. conjug.	Results	ID hit	Pattern	RR fr. conjug.	ID hit	Pattern	RR fr. conjug.	Results	ID hit
1	0.90/020	0.90/020	free	yes	0.90/020	0.90/020	yes	0.90/020	0.90/020	free	yes
2	0.88/020	0.88/020	free	yes	0.82/020	0.86/020	yes	0.88/020	0.88/020	free	yes
3	0.71/020	0.71/020	free	yes	0.71/020	0.71/020	yes	0.71/020	0.71/020	free	yes
4	0.88/020	0.88/020	free	no	0.88/020	0.88/020	no	0.88/020	0.88/020	free	no
5		0.64/020	free	yes		0.64/020	yes		0.64/020	free	yes
6	0.75/020	0.75/020	free	no	0.75/020	0.75/020	no	0.58/220	0.58/220	horiz. knot at 75°	yes
7	0.89/020	0.89/020	free	yes	0.89/020	0.97/020	yes	0.89/020	0.97/020	free	yes
8		0.97/020	free	yes		0.97/020	yes		0.97/020	free	yes
9	0.68/020	0.68/020	free	no	0.68/020	0.86/020	no	0.68/020	0.86/020	free	no
10	0.80/020	0.80/020	free	yes	0.80/020	0.80/020	yes	0.80/020		free	yes
11		0.78/020	free	yes		0.78/020	yes		0.78/020	free	yes
12	0.90/020	0.90/020	free	yes	0.90/020	0.90/020	yes	0.90/020	0.90/020	free	yes
13	0.65/020	0.90/020	free	yes	0.65/020	0.90/020	yes	0.65/020	0.90/020	free	yes
14		0.88/020	free	yes	0.86/020	0.86/020	yes	0.86/020	0.88/020	free	yes
15	0.61/020	0.71/020	free	yes	0.60/020	0.71/020	yes	0.61/020	0.71/020	free	yes
16	0.64/020	0.88/020	free	no	0.64/020	0.88/020	no	0.64/020	0.88/020	free	no
17	0.64/020	0.64/020	free	yes	0.64/020	0.64/020	yes	0.64/020	0.64/020	free	yes
18	0.65/020	0.75/020	free	no	0.65/020	0.75/020	no	0.65/020	0.58/220	horiz. knot at 75°	yes
19	0.97/020	0.89/020	free	yes	0.97/020	0.97/020	yes	0.97/020	0.97/020	free	yes
20	0.97/020	0.97/020	free	yes	0.97/020	0.97/020	yes	0.97/020	0.97/020	free	yes
21	0.86/020	0.68/020	free	no	0.86/020	0.86/020	no	0.86/020	0.86/020	free	no
22	0.78/020	0.80/020	free	yes	0.78/020	0.80/020	yes	0.78/020	0.80/020	free	yes
23	0.78/020	0.90/020	free	yes	0.78/020	0.78/020	yes	0.78/020	0.78/020	free	yes
24		0.90/020	free	yes	0.90/020	0.90/020	yes	0.90/020	0.90/020	free	yes

Error rates — single-peak (highest grade) patterns: 6 out of 24; single-peak (highest PSL) patterns: 6 out of 24; multi-peak patterns 4 out of 24.

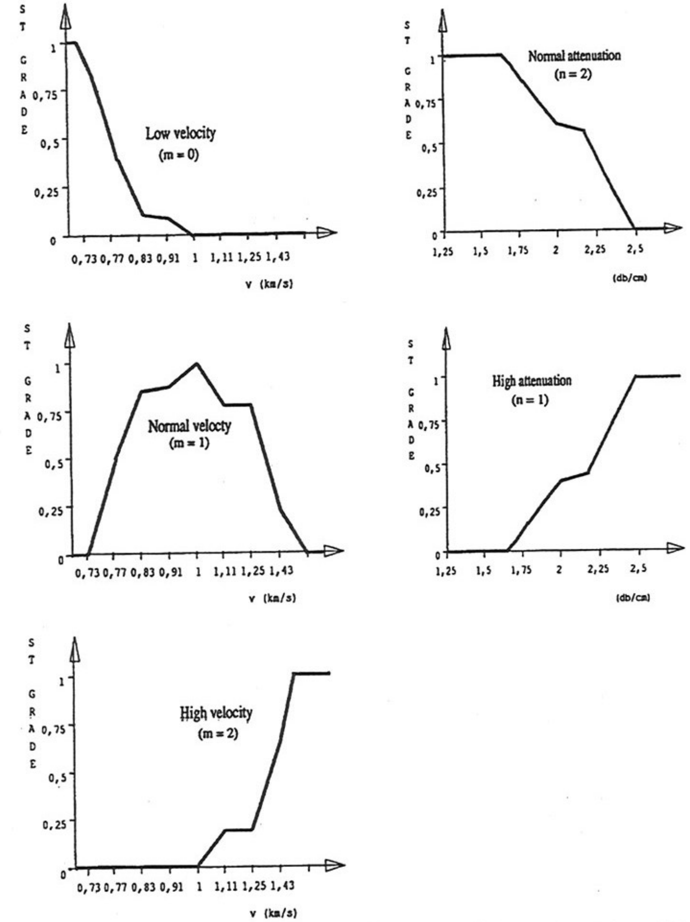


Fig. 11. Standardized membership functions of different classes of the acoustic velocity and the acoustic attenuation in Scots pine obtained by learning.

of defect features, it is not necessary to have a picture processing procedure as is usually required by conventional tomography techniques. During pattern recognition and total information reasoning, only a few simple mathematic operations, such as Min or Max operations on finite numbers of data, are necessary. Therefore, data volume and computing time for presenting defect features are small.

All these have indicated the rather positive aspects of the new method in both the effectiveness and the efficiency of log scanning. However, this method has a shortcoming as compared to, for instance, an X-ray tomograph in that some features, e.g. sizes and location, of defects can only be determined rather roughly.

Although the ultrasonic log scanning technique still needs to be tested on an industrial scale, the positive research results together with such features as low investment costs, fast operation, safety and easy handling for operators encourage further development towards a practical log scanning system for the sawmill of the future.

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