Wood Science and Technology 34 (2000) 221–236 © Springer-Verlag 2000

Detection of decay in logs through measuring the dampening of bending vibrations by means of a room acoustical technique

D. Ouis

Abstract In this paper a technique is presented to possibly predict the presence of decay in logs. This technique is used in room acoustics to evaluate the Reverberation Time of rooms, a quantity that describes the rate of decay of the sound level, and which is inversely proportional to the amount of absorption in the room. However, as sound is caused by the vibration of air particles, the use of the notion of Reverberation Time may then be extended to any vibrating system. The investigation of the potential application of this technique to logs was first inspired from woodsmen's operation of sounding trees, an operation consisting in judging by ear the response of a tree when struck on its trunk with a hammer. In this respect, the function of main concern is the vibrational response of the log, the impulse response, which, for instance, may be recorded by an accelerometer. In general, the impulse response of a system, be it mechanical, electrical or acoustical, is a sort of signature of the system from which several quantities of interest may be processed (in acoustics, some of these quantities are purposely chosen as quantitative descriptors of subjective impressions). In this study, a log is considered as a mechanical system with its proper vibration characteristics. Hence, the presence of decay in its material, which in general increases the damping properties of wood, is in analogy with a more furnished room expected to be translated by a shorter Reverberation Time as compared to a sound log. The results of this study reveal this fact, and this may open new possibilities for the process of strength grading of wood elements in sawmills.

Introduction

Wood is an important material which has been and is still being used for several ends. Nowadays, the use of wood is mostly confined to the manufacturing of building elements, but it is not limited to only this sector. Other areas where wood is a main provider, either as a raw material or as a semi-finished product, are the furniture or the paper industries to name just a few. However, like any other material, wood may have some defects generally classified under two main categories. The first category includes all internal malformations like knots, splits and cross grain due to the natural and normal growth of the tree, whereas the other category is concerned with those defects resulting from the external attack of the material by natural degrading agents, mostly degrading its strength. The protection of trees from the attack of decay fungi is not yet under full control, and

---

Received 10 October 1998

D. Ouis (✉)
Lund Institute of Technology, Engineering Acoustics,
PO.B. 118, S-22100 Lund, Sweden

in the southern parts of Sweden, in some places, this problem is taking on alarming proportions for forest owners. However, a visual assessment often fails to detect incipient decay in a tree, either still standing or once fallen down. In this case the logs cut from the stem of the tree have to undergo a further strength grading operation in the sawmill before the final sorting of the lumber.

Decay mainly weakens the strength of wood, the quality of prime concern for this naturally renewable material. For many decades, scientists were involved in developing techniques for assessing the strength of wood, either in standing trees, logs, or functional wood elements. Several of the most relevant of these techniques may be found shortly and concisely described in Schad et al. (1996), where their performances are also compared for applications on logs. Among these methods one can name those using stress pulse propagation across the log (Breeze and Nilberg 1971; Schad et al. 1996). Other techniques rather use ultrasonic energy propagation either simply through measuring the ultrasonic propagation speed for in-situ log grading (Sandoz 1998), or for more complex industrial applications evaluating the attenuation of acousticals for internal scanning of logs and defect classification (Han and Birkeland 1992). One can also cite other techniques also inspired from medical applications like the Computer Tomography (CT) imaging for scanning the internal morphology of logs. In the sawmill, these techniques permit establishing a more efficient conversion of raw forest products into lumber and veneer, see for instance Hailey and Morris (1988) for an abundant literature review. These techniques use either X-rays (Funt and Bryant 1987; Gilboy et al. 1982; McMillin 1982; Parrish 1961; Schmoldt et al. 1996; Taylor et al. 1984) or Nuclear Magnetic Resonance, NMR, (Hall et al. 1985; Wang and Chang 1986; Wang et al. 1989). In his pilot study, Skatter also investigated the feasibility of using TV holography for imaging the vibration behaviour of wood logs (Skatter 1996). These techniques, though relatively highly accurate, often necessitate some special training for their adequate use, as well as often being quite costly.

In the present work, a relatively simple technique is presented which permits judging the overall strength quality of a log with regard to its possible hosting of decay. This technique is used in room acoustics to evaluate the amount of damping in a room through measuring its Reverberation Time, RT. This parameter is used for assessing the rate of sound attenuation in a room and is defined as the time taken by the sound level in the room to reach a level 60 dB lower than that when a sound source in the room has been switched off. For not too extreme situations, the RT of a room with a single type of absorbing material is found to be inversely proportional to the total absorbing surface area times the absorption coefficient of the material. For several absorbing materials covering the boundaries of the room, the corresponding absorbing area would be the sum of the absorbing areas of each material. In the past, the evaluation of the RT for rooms was a very time-consuming operation necessitating the use of expensive and heavy equipment. Nowadays, using the PC and the development of specified software, the measurement of this parameter has become the matter of just a few seconds.

In the case of a room, the sound field at some position is due to the build-up of the successive reflections of the signal from the sound source at the various boundaries of the room. As sound results from the propagation of disturbances of air particles, one can make some similarity between a room and any vibrating mechanical system that is vibrating, due to some mechanical excitation. As a consequence the Reverberation Time may be used in any mechanically vibrating system. There is, however, a fundamental difference between the propagation of sound waves in a room and the propagation of waves in a log. In the former case the waves are only of the longitudinal type, caused by air particles vibrating in the direction of wave propagation. On the other hand, for the case of the log, the waves may be of several different types including the longitudinal, bending, torsional and extensional modes, depending on the way the log is set into vibration. So in this respect, it is important to specify the details of the experimental procedure, because different modes of vibration may have different RT's. In the case of a rotten log, decay is known to increase the damping properties of wood, and this may in turn be assessed through the shorter reverberation time as compared to that of a defect free log.

Materials and methods

The measurement technique

The technique referred to in this study is based on a widespread concept used in acoustics for studying the response of vibrating systems. The method consists of submitting the system to a short excitation, a pulse, and then to assess the system's response to the pulse. This response, called Impulse Response, is normally used to predict the response of systems that are intended to be used under shock vibration conditions, but in its widest application area it is also used as the signature of the system under test (Fig. 1). In relation to that, one can for instance name the classical practice of music connoisseurs and orchestra conductors who judge the sound quality of a newly inaugurated concert hall by listening to its response to a single strong hand clapping. In room acoustics, the past counterpart of this operation was to record with the help of a microphone the pressure response of the room to a pistol shot. Afterwards, the signal may be analysed either on the screen of an oscilloscope or with the help of a spectrum analyser. From the impulse response, several objective quantities may be processed, and in room acoustics these quantities are often connected to some subjective human impressions. The application of some of these concepts may be extended to a system built-up from a solid material, but here the impulse response would rather be concerned with the vibration. Hence, the impulse response may be obtained through sending a stress pulse, often from a hammer blow, through the system and then to record the response of the system by means of a vibration sensor, most often an accelerometer of the piezoelectric type.

In acoustics, the damping capacity of a room may be estimated through evaluating the rate at which sound dies down in it. For the same volume, a more

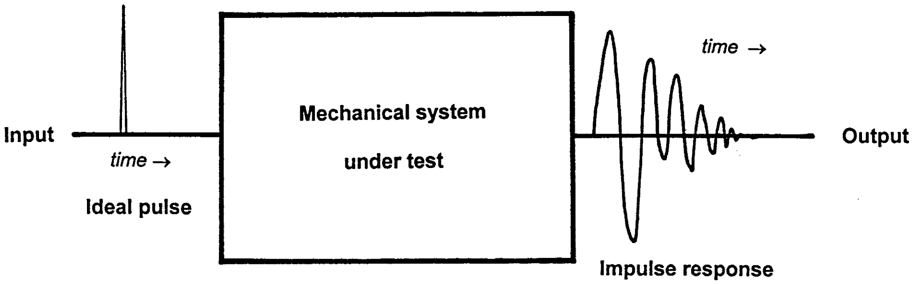

Fig. 1. Determination of the Impulse Response of a system under ideal operating conditions

furnished room absorbs more sound energy than a less furnished one. This daily observation led to the introduction of the concept of Reverberation Time, short RT. The RT is defined as the time T_{60} in seconds for the sound level in a room to decay by 60 dB from the level when the sound source has been shut off (Cremer et al. 1978; Kuttruff 1991). In the measurement of the RT, the sound field within the room has to reach the steady state, i.e. equilibrium condition, before turning off the sound source (Fig. 2).

For a room with a volume V in m^3, containing a total absorbing area A in m^2, a simple equation permits to predict quite accurately the value of the reverberation time T_{60}:

$$T_{60} \cong 0.16 \frac{V}{A} \text{s} \tag{1}$$

For an absorbing material with a surface area S, the absorbing area A is given by the product of S and the *absorption coefficient* of the material, this latter taking a value somewhere between 0 and 1. All materials have in general an absorption coefficient that is dependent on the frequency, and this in turn leads to the frequency dependence of the reverberation time. From Equation (1) one can directly draw the conclusion that a room with a larger amount of absorbing material has a higher capacity of damping sound in it, and hence a shorter RT.

Fortunately, nowadays it is possible to avoid the cumbersome and time-consuming operation of averaging RT values calculated from curves like those in Figure 2, with the possible errors that are likely to be committed. As a matter of fact, it has been made possible to measure the RT more simply and more

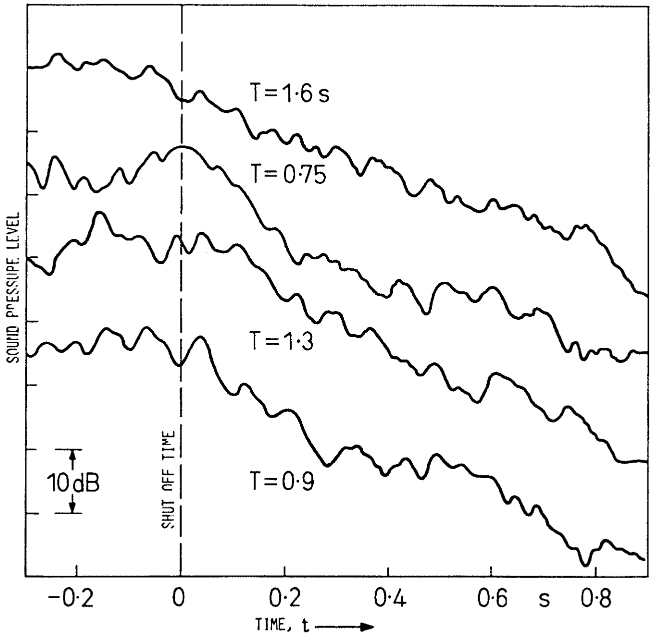

Fig. 2. Different curves for the sound level decay in a room obtained after identical initial conditions. After (Schroeder 1965)

accurately from the impulse response after Schroeder proposed his elegant "Method of Integrated Impulse Response" (Schroeder 1965). In the classical technique, the operator has to rely on his intuition to evaluate as correctly as possible the value of the RT from some curve fitting on the decay curves, which even for apparently the same conditions of measurements may look very different. This is due to the fact that at the time of switching off the sound source, the phase of the signal may have any value taken randomly, and it is impossible to exert control over it. The new technique on the other hand permits to make a more accurate evaluation of the RT without paying any attention to the behaviour of the decay curves, and it has the other major advantage of making this evaluation from one single measurement. This is possible because the impulse response is a time-domain quantity and its measurement may be obtained with a confident degree of repeatability. The impulse response is first squared, and then it is integrated backwards to yield the energy decay curve from which the RT can easily be calculated as illustrated in Figure 3. For the same source and receiver positions, this so-obtained *Schroeder plot* is in fact equivalent to the average of an infinite number of decay curves obtained from random noise excitation.

The other advantage acquired from measurements of the impulse responses using the aforementioned technique is that the values of the RT at different frequency bands may be calculated from the same original impulse response after, however, filtering it. On the other hand, measurements using the continuous excitation procedure necessitate the application of the required filter beforehand.

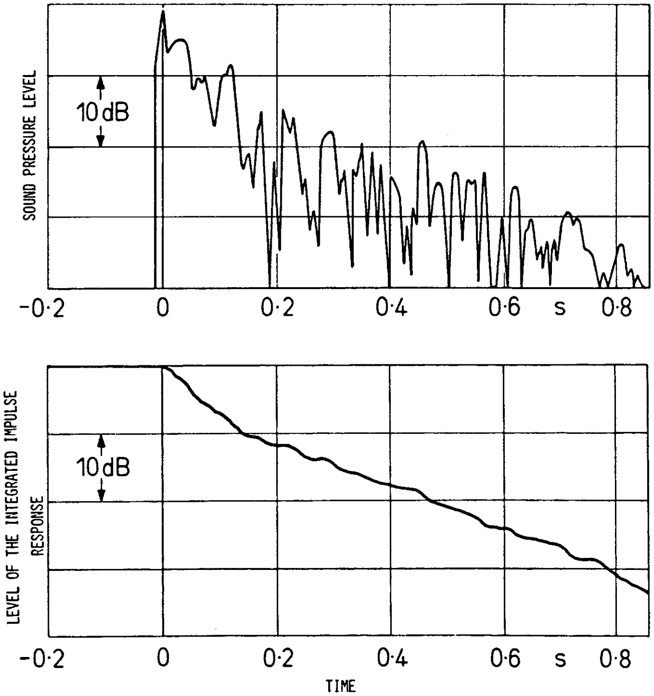

Fig. 3. Upper: Level decay for excitation of a room by a 1/3 octave band random noise. Lower: Integrated Impulse Response. After (Schroeder 1965)

Theoretical background: simple vibrating system and generalisation to a complex system

The case of a system whose motion can be described by a single co-ordinate variable is taken here as a simple example. In mechanics, the number of independent motion variables necessary to describe the behaviour of a system is called the number of *degrees of freedom*, DOF, of the system. The simplest vibrating mechanical system is a system with a *single-degree-of-freedom* (SDOF) which in general may be represented by a combination of a mass m, a spring with a *stiffness constant* K and a damper (dashpot) with a *damping constant* R. This system is called a single-degree-of-freedom because it consists of a single mass which moves along one axis only and which in Figure 4-left is taken as x in the vertical direction.

The motion of the mass can thus be described by a single differential equation; which in the case of free motion reads as:

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + R\frac{\mathrm{d}x}{\mathrm{d}t} + Kx = 0 \qquad (2)$$

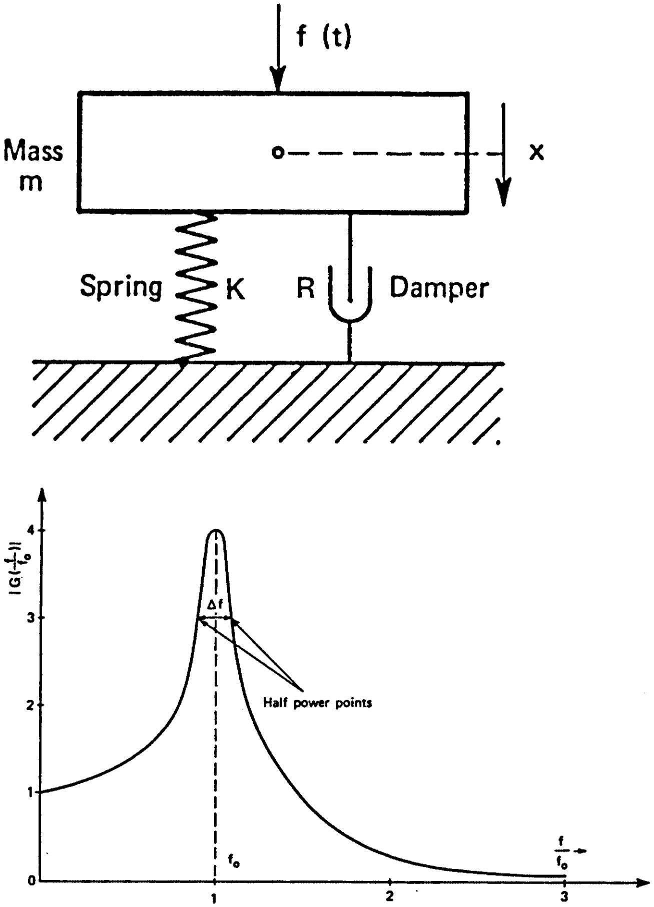

Fig. 4. Example of a single-degree-of-freedom (SDOF) system in vibration. Upper: system. Lower: typical frequency response

Applying an external force $f(t)$ to the system changes the right hand side of equation (2) which becomes:

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + R\frac{\mathrm{d}x}{\mathrm{d}t} + Kx = f(t) \tag{3}$$

A method using the superposition principle is to determine the Fourier transform $F(f)$ of $f(t)$ and to study the response of the system to each frequency component separately. The frequency response function $G(f)$ of the system is defined as the Fourier transform of its impulse response function $g(t)$. Hence, the Fourier transform X of x may be expressed as:

$$X(f) = G(f) \cdot F(f) \tag{4}$$

where f is the frequency of the oscillation. Returning to equation (3), one can determine the frequency response $G(f)$ of the system through replacing the general excitation function $f(t)$ by an arbitrary harmonic one, e.g., if one sets $f(t)F_0e^{j2\pi ft}$. Thus the resulting frequency response would be:

$$G\left(\frac{f}{f_0}\right) = \frac{1/K}{1-\left(\frac{f}{f_0}\right)^2 + j\frac{1}{Q}\frac{f}{f_0}} \tag{5}$$

where:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \qquad \text{and} \qquad Q = \frac{1}{R}\sqrt{Km} \tag{6}$$

f_0 is the *resonance frequency* of the system and Q, its *quality factor*, a measure of the system's damping capacity. The larger the damping, the lower the value of Q, and the wider the curve at resonance. In practice, an approximate measure of Q is obtained by measuring the width Δf of the response curve at the so-called *half power points* (Fig. 4-down) which is approximately given by:

$$Q \cong \frac{\Delta f}{f_0} \tag{7}$$

The solution of Equation (2) which would be satisfied by the particle displacement when the system is left for itself, i.e. in the free vibration regime, may be written in complex form as:

$$x = x_0e^{j\omega_0 t}e^{-\eta\omega_0 t} \qquad \omega_0 = 2\pi f_0; \quad \eta = R/2\sqrt{mK} \tag{8}$$

where x_0 is the initial amplitude. It is customary, however, in mechanical vibration theory, to substitute the quality factor by that of the *loss factor*, designed by η above, and which is an indication on the part E_l of the total reversible vibratory energy E_R that is dissipated during one cycle of the vibration.

$$\eta = \frac{1}{2\pi}\frac{E_l}{E_R} \tag{9}$$

Thus the quantity $\eta\omega_0$ becomes the decay constant of the system, and the curve of the variable x is then a periodic function of time (the first exponential in equation (8)) the amplitude of which decays exponentially with time (amplitude modulation by the second exponential in equation (8)). This latter is the envelope of the displacement curve (Fig. 5). In more precise terms, the displacement equation above is not exact, because usually the presence of damping slightly reduces the vibration frequency of the originally undamped system. However, for small damping, this error is often neglected because it is of the same order of magnitude as that of the loss factor η.

The Reverberation Time T_{60} which is the time within which the energy of the system is reduced to one millionth of its initial value, or equivalently the time taken for a 60 dB decay in the energy or the amplitude level, is then given by (Cremer and Heckl 1988):

$$T_{60} = \frac{\ln 10^6}{\omega_0 \eta} \approx \frac{2.2}{f_0 \eta} \tag{10}$$

In daily life, physical systems are generally far more complex to be treated as simple SDOF's, and strictly speaking, all mechanical systems are continuous. Therefore, one would rather speak of multiple-degree-of-freedom, MDOF, systems. Whenever possible, the analysis of such systems is often facilitated if one can describe the extended system as the build-up of many simple ones. The motion analysis of the MDOF system can thus be satisfactorily described only after taking a number large enough of the constituent simple elements. It is therefore usual to draw the analogy between a complex system like a beam, a plate or a room to that of a combination of an infinite number of resonators, each resonating at its own resonance frequency and decaying with its own damping characteristic. This analogy becomes even more evident at relatively low frequencies, where most systems to which we are familiar have their strongest response. When the discretisation of a complex system into simple ones is possible, one talks of a lumped parameter system.

Example of a beam in flexural vibration

A uniform and homogeneous beam may be considered as an example of a complex vibrating system, and is therefore relevant to our study. A simplified version of the equation describing the motion of the particles of the beam is:

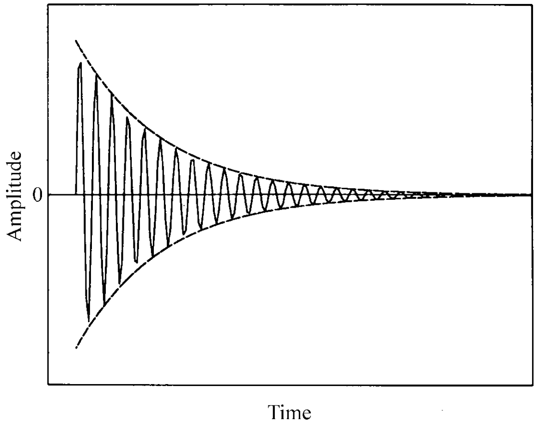

Fig. 5. Typical response of a damped vibrating SDOF system

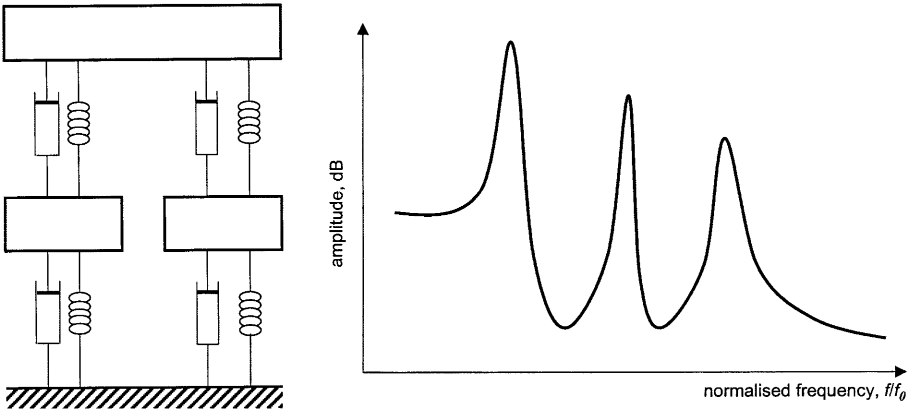

Fig. 6. Example of a three-degree-of-freedom system. Left: mechanical system. Right: typical frequency response

$$EI\frac{\partial^4 u}{\partial x^4} + \rho\frac{\partial^2 u}{\partial t^2} = 0 \tag{11}$$

where E is the MOE of the material constituting the beam, and ρ its mass per unit length. I is the momentum of inertia of the beam, a quantity depending on the geometry of its cross section. The solution to equation (11) requires also the knowledge of the boundary conditions, i.e. the manner in which the beam is supported.

The approximate expression for the eigenfrequencies of the free-free, f–f, vibrating circular beam with radius a and length l is given by (Cremer and Heckl 1988):

$$f_{f\text{-}f} = \frac{\pi}{8}\sqrt{\frac{B}{m}}\frac{(2n-1)^2}{l^2}; \quad n\text{: } \mathit{number\ of\ nodes} \text{ and } I = \frac{\pi a^4}{2} \tag{12}$$

m being the mass per unit length of the rod. For the f-f1 mode Equation (11) becomes:

$$f_{f\text{-}f1} = \frac{9\pi a}{8l^2}\sqrt{\frac{E}{2\rho}} \tag{13}$$

Materials: logs of spruce

The present study is a preliminary investigation, and is more of a comparative character. The aim is to compare the values of the RT for two logs of Norway spruce (*Picea Abies*), one subject to decay attack and the other one defect free. The two specimens chosen for this study were taken from the same forest stand with nearly similar physical characteristics (size, shape and weight). The investigation of the potential use of the presented acoustical technique is done in view of a possible future implementation in wood technology.

Effect of decay on the strength properties of wood

The ability of wood to resist loads is characterised by its strength and this property depends on several factors which include the type of load (tension, compression, shear), direction of load application, and the wood species. Ambient conditions of temperature and moisture are also important, as well as past histories of load and temperature (Schniewind 1989). The strength of a material is usually characterised by the value of its Modulus of Elasticity, MOE, and its Modulus of Rupture, MOR. For small amplitude vibrations, the MOE determines the propagation speed of longitudinal waves in the material. Under the assumptions of elastic behaviour, the MOE is defined as the slope of the stress-strain curve below the linear proportionality limit. The MOR, on the other hand, is a measure of the ultimate stress before rupture in a sample of material and is thus a parameter of mechanical failure.

Strength loss in wood due to decay is often expressed as a percentage value of the comparable value for sound or undecayed wood proposed for use in laboratory evaluation of decay severity (Toole 1971). The loss in strength of decayed wood often occurs before significant loss in weight (Pratt 1979). The general relationship between strength and the effect of decay first shows an initial rapid loss of strength in the early stages followed by a gradual decrease in the rate at higher weight losses (Kim et al. 1994). The consequences of the early stages of decay on strength loss of wood have been reported as an average loss in toughness of around 50% for only 1% weight loss (Wilcox 1978).

Effect of decay on the damping properties of wood

The damping capacity of a material under vibration is determined by its ability to decrease the amplitude of vibrations when left to itself. Wood, as all solid materials has some damping properties. These damping properties are also affected by decay because decay changes the physical structure of the material. Generally speaking, decay increases damping (Dunlop 1983), and brown rot has a more noticeable effect than white rot, particularly on coniferous wood species (Bariska et al. 1983). Damping depends also on the direction along which it is determined. In the transverse direction, radially to the tree stem, damping may be as high as three times than it is in the longitudinal direction, i.e. along the grain. This fact makes sometimes some preferences on measurements (Dunlop 1981; Fukada 1950), but it is to be noticed that research in this area is rather limited.

Results

The two specimens of spruce logs used in the present investigation were assumed to behave as homogeneous cylindrical beams in vibration. The logs were set on knife edge supports fulfilling the free-free boundary conditions of the first bending mode. The log under test was then subject to a light hammer blow at its midst, and the response was recorded by the means of a piezoelectric accelerometer, Fig. 7.

The measured quantity of interest was the acceleration, although quantities like the velocity or the displacement would show a similar behaviour. These latter can easily be processed from the acceleration through simple integration with respect to time (for harmonic motion, this would correspond to successive divisions by $j\omega$, j being the imaginary unit and ω the angular frequency). Typical results of such experiments are shown in Fig. 8 in the time domain. Figure 9 illustrates the result in the frequency domain, where a simple digital Fourier transform, DFT, was applied to the signals of Figure 8.

Although the excitation of the logs is only intended for the bending vibration modes, one cannot exclude the possibility of setting into motion other modes of vibrations of for instance the extensional or the torsional type. This depends

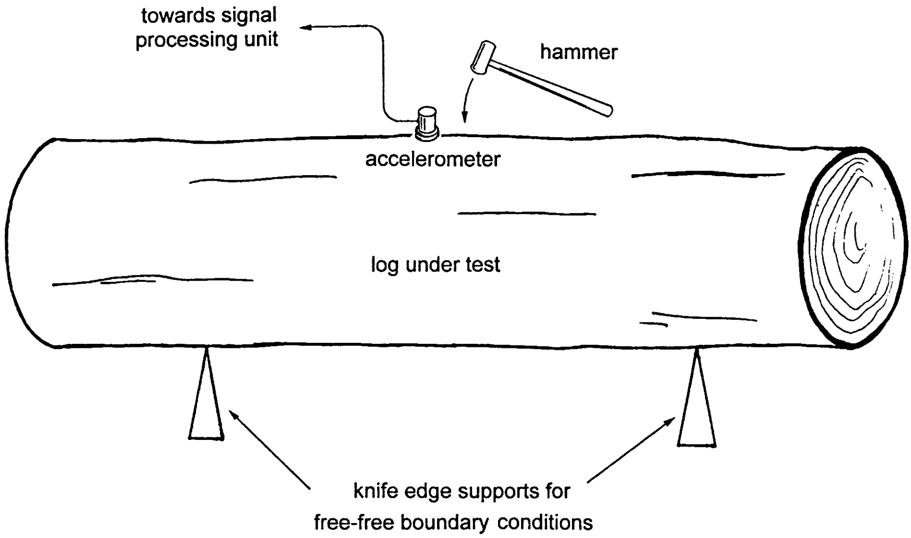

Fig. 7. Experimental set-up for measuring the impulse response of a log in bending vibration

critically on the way of striking the test specimens. Moreover, even if the boundary conditions are carefully made to satisfy those of the first bending free-free mode, other bending modes of higher order or of other boundary conditions might also show their peaks in the frequency response curves. However, one expects the peak of the sought first bending mode with free ends to be the most prominent one in the frequency response. This is denoted by f_{b1} in the frequency curves.

The main interesting observation from these results is perhaps the relatively more extended time response of the sound log as compared to that of the decayed one, as shown in Fig. 8. A better account of this phenomenon is given in terms of the Reverberation Time as described above and as calculated from the curves of Figure 10. These values along with other quantities of interest are summarised in Table 1.

The RT is usually calculated from an extrapolation of the portion of the decay curve in the interval [−5 dB, −35 dB]. However, the value so determined often does not lead to a quantity which is strongly correlated to our subjective judgement of the reverberation phenomenon. In fact, even if the calculated reverberation time as expressed by Equation (10) is the same for all positions in a room, it is an almost generally known fact that the feeling of reverberation is different for different positions in the same room. This has led to the introduction of more refined versions of this room acoustical descriptor, most of which take into consideration only the early part of the decay process. Moreover, it was experimentally shown that the *Early Decay Time*, EDT, which is processed from the portion of the energy decay curve in the interval [0 dB, −10 dB] is subjectively more meaningful than the classical 60 dB Reverberation Time (Cremer et al. 1978, p. 416).

It may consequently be observed from Fig. 10 that the energy decay curves are not straight lines as required in the range [−5 dB, −35 dB] for the calculation of the Reverberation Time, and this is due to the different damping characteristics of

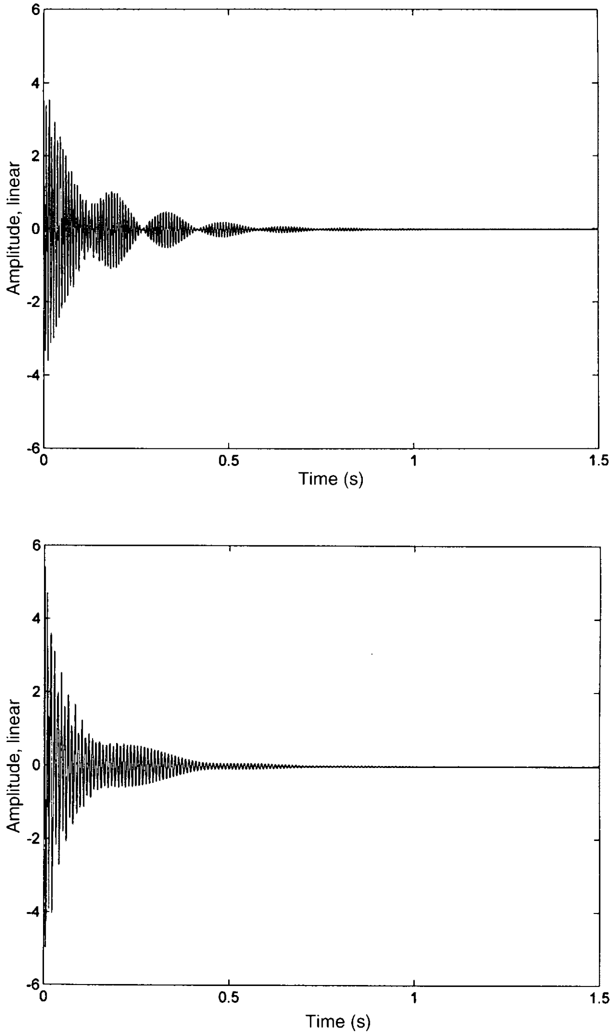

Fig. 8. Impulse responses of two spruce logs under bending vibrations and supported to satisfy the boundary conditions of the first free-free mode. Up: sound log, Low: decayed log

the various modes included in the decay process of the acoustical energy. If on the other hand the impulse response is filtered so that only one single mode of vibration is represented, then the energy decay curve would be ideally a straight line. The decay curves are in the general case "tortuous", and the way of determining the value of T_{60} becomes then often questionable. On the other hand, the portion of the curves in the level range [0 dB, −10 dB] is better behaved because the duration of this decay range is short enough to include nearly all the strongest modes of vibration. It follows then, and with reference to Fig. 10, that one can more clearly see the steeper slope of the curve of the rotten log leading thus to a shorter reverberation time as compared to the defect free log. Another observation made in this study is the clear appearance of an amplitude modulation of the impulse response of the sound log (Fig. 8-up). This behaviour results from a mode splitting at the frequency of the major bending mode (the frequency peak at f_{b1} is actually made of two small peaks). The resulting "beating" phenomenon is obviously seen in the time response curves of Fig. 8 and which is translated by the

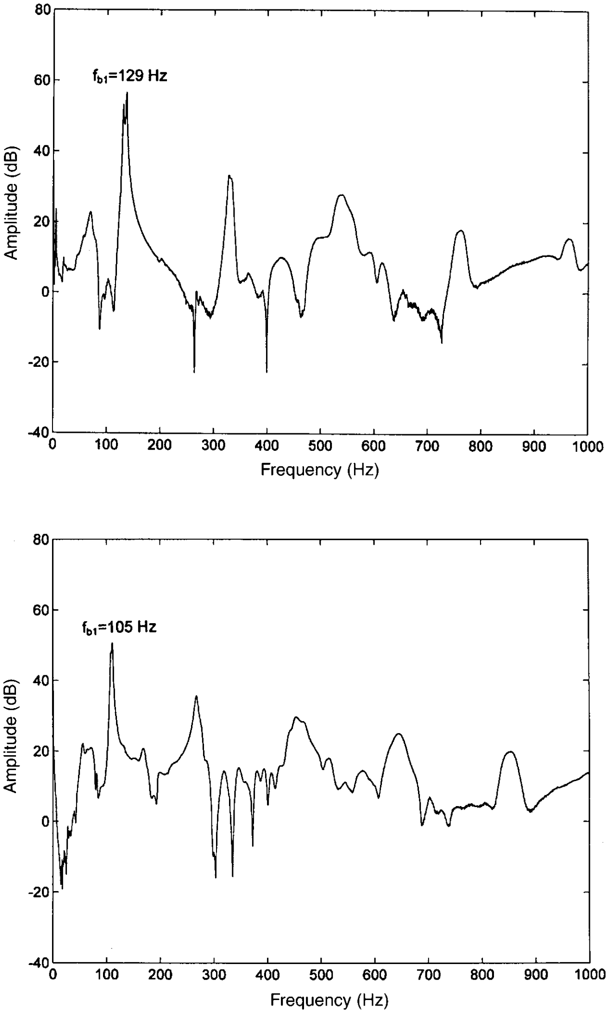

Fig. 9. Same as Fig. 8 but in the frequency domain

undulated energy decay curves. Hence, drawing the analogy of the vibration modes to that of energy reservoirs, the vibratory energy during the course of its decay seems to flow alternately from one reservoir to the other.

Discussion and conclusions

In this study, the potential use of an acoustical technique has been investigated with the aim to detect the presence of decay in logs. The study was mostly of a comparative character and was conducted on two specimens with comparable geometrical and physical characteristics. The acoustical measurement technique permits to evaluate the Reverberation Time, RT, which from a room acoustical point of view is a quantity used to quantify the amount of sound absorption in a room. Generalised to any vibrating mechanical system, the concept of the Reverberation Time may be used to account for the ability of the system to dissipate energy. The implementation of the technique in question to wood based systems

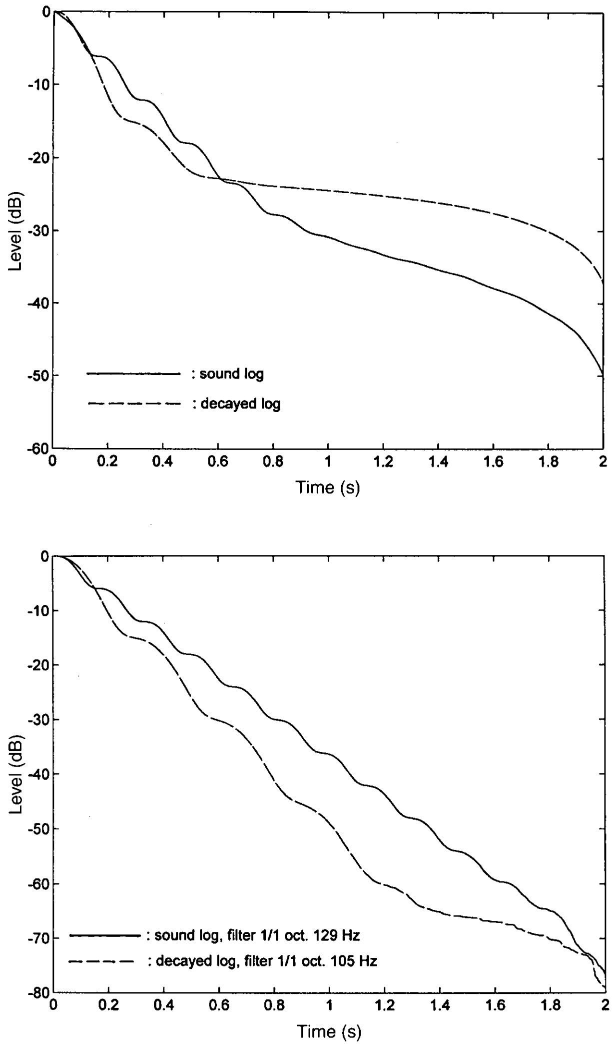

Fig. 10. Comparison of the energy decay curves for a sound and for a decayed log. Up: unfiltered. Low: filtered with a 1 octave bandwidth filter centred at the frequency of the first bending mode

was inspired from the important observation that decay increases the damping properties of wood.

To the best of the author's knowledge, this is the first contribution to implementing the concept of the Reverberation Time to studies on simple wood

Table 1. Summary of comparative values of interest processed from the impulse responses of two logs of spruce in bending vibration

	Sound log	Decayed log
T_{60}, s	2.43	6.39
EDT, s	1.52	1.10
f_{b1}, Hz	129	105
T_{60} (f_{b1}, 1 oct.), s	1.62	1.22
EDT (f_{b1}, 1 oct.), s	1.61	1.16

elements. In related studies, the usual way to determine the damping in vibrating systems is often based on measuring the half power bandwidth of the frequency response curve at resonance. One of the advantages of measuring the RT by the technique exposed in this work is that from a single measurement of the impulse response, the RT may be calculated for any frequency and at any frequency bandwidth through an adequate filtering of the impulse response. The advent of powerful computers together with especially designed hard- and software make of the *Method of Integrated Impulse Response* an attractive way for calculating the RT. The time required for completing the measurement of a single impulse response is the matter of some seconds.

The technique was used on logs under flexural vibration, but this does not prevent its use to other modes of vibration. The experimental results were found favourable in that it was found as expected that for a decayed log the RT is shorter for a decayed log than for a sound one. This is a straightforward consequence of the fact that decay increases the damping properties of wood. However among the various variants of the RT, it is found that the EDT, which is more related to the subjective judgement of the reverberation feeling in a room is a better descriptor of the reverberation process in logs. This is equally valid for either the unfiltered or the filtered impulse responses. The damping properties of wood seem to be less affected by decay than the MOE; the relative change of the RT, and consequently that of the loss factor, is about 25%, whereas the corresponding change in the value of the MOE is of 37% (from eqn (13), $\Delta E/E$ corresponds to $2 \cdot \Delta f/f$). The EDT shows a somehow more pronounced variation, 28% from Table 1.

Regarding the measurement of RT at some frequency bandwidth, there is a further precaution to be taken into consideration. It has been shown from theoretical considerations that errors could be induced in the evaluation of short RT's, and as a rule of thumb the product of the frequency bandwidth and the RT should at least be equal to 16 (Jacobsen 1986). This extra safety measure should be borne in mind whenever measurements are made on too damped systems or in case the resonance frequencies are relatively low, a situation occurring with extended vibrating systems. The present study also supports the observation that the frequency spectrum of the major bending modes of interest is shifted towards lower values in the case of the decayed log.

Decay decreases the value of the MOE and increases the damping of wood. Hence, the RT which is a measure of the damping may be used in combination with the MOE for characterising the strength properties of wood. In the present study, both the RT and η may be acquired from a single measurement of the Impulse Response with the help of a measurement system conceived for room acoustical measurements. This system is quite affordable, easy to run, and its hardware consists of a single circuit board ready to be slotted in a laptop computer, allowing the performance of in-situ test measurements (MLSSA 1999).

References

Bariska M, Ozusk'y A, Bosshard HH (1983) Changes in mechanical properties of wood after decomposition by basidiomycetes. Holz Roh- Werkstoff 41: 241–245

Breeze JE, Nilberg RH (1971) Predicting by sonic measurements the strength of logs and poles having internal decay. Forest Prod J 21: 39–43

Cremer L, Heckl M (1988) Structure borne sound, 2nd ed. Springer-Verlag, Berlin

Cremer L, Müller HA, Schultz TJ (1978) Principles and applications of room acoustics. Applied Science Publishers, London, Volume I

Dunlop JI (1981) Testing of poles by using acoustic pulse method. Wood Sci Tech 15: 301–310

Dunlop JI (1983) Testing of poles by acoustic resonance. Wood Sci Tech 17: 31–38
Filer TH (1972) Gamma radiation detects defects in trees and logs. Phytopat 62: 756–757
Fukada E (1950) The vibrational properties of wood I. J Phys Soc Jap 5: 321–326
Funt BV, Bryan EC (1987) Detection of internal log defects by automatic interpretation of computer tomography images. Forest Prod J 37: 56–62
Gilboy WB, Foster J, Folkard MA (1982) Tomographic gamma-ray scanner for industrial applications. Nucl Instrum Methods 193: 209–214
Hailey JR, Morris PI (1988) Applications of scanning and imaging techniques to assess decay and wood quality in logs and standing trees. Report F0 42-91/142-1988E. Forintek Canada Corp
Hall LD, Rayanayagam V, Stewart WA, Steiner PR (1985) Magnetic resonance imaging of wood. Can J Forestry Res 16: 423–426
Han W, Birkeland R (1992) Ultrasonic scanning of logs. Industr Metrol 2: 253–281
Jacobsen F (1986) A note on acoustic decay measurements. J Sound Vib 115: 163–170
Kim H, Barnes HM, Lyon DE (1994) Effect of decay on the mechanical properties of full-sized lumber. Holzforschung 48: 145–149
Kuttruff H (1991) Room acoustics, 3rd ed. Elsevier Applied Science, London
McMillin CW (1982) Application of automatic image analysis to wood science. Wood Sci 14: 97–105
MLSSA (1999) see for instance the website www.mlssa.com for more information on the MLSSA and other related measurement systems
Parrish WB (1961) Detecting defects in wood by the attenuation of gamma rays. For Sci 7: 136–143
Pratt JE (1979) Loss of strength of wood in various categories of rot. Forestry 52: 31–45
Sandoz JL (1998) Ultrasonic timber grading applied to forest products. Proc WCTE98 Vol II: 818–819
Schad KC, Schmoldt DL, Ross RJ (1996) Nondestructive methods for detecting defects in softwood logs. Research paper FPL-RP-546, USDA Forest Service
Schmoldt DL, Li P, Abbott AL (1996) CT imaging of hardwood logs for lumber production. Proc 5th Industr Eng Res Conf: 387–392
Schniewind AP, Ed. (1989) Concise encyclopedia of wood and wood-based materials. Pergamon Press, Oxford
Schroeder MR (1965) New method of measuring reverberation time. J Acoust Soc Am 37: 409–412
Skatter S (1996) TV Holography as a possible tool for measuring transverse vibration of logs: a pilot study. Wood Fiber Sci 28: 278–285
Taylor FW, Wagner GJr, McMillin CW, Morgan IL, Hopkins FF (1984) Locating knots by industrial tomography – a feasibility study. Forest Prod J 34: 42–46
Toole ER (1971) Reduction in crushing strength and weight associated with decay by rot fungi. Wood Sci 3: 172–178
Wagner FG, Taylor FW, Ladd DS, McMillin CW, Roder FL (1989) Ultrafast scanning of an oak log for internal defects. Forest Prod J 39: 62–64
Wang PC, Chang SJ (1986) Nuclear Magnetic Resonance imaging of wood. Wood Fib Sci 18: 308–314
Wang PC, Chang SJ, Olson JR (1989) Scanning logs with an NMR scanner. Proc 7th Symp Nondestr Test Wood: 209–219
Wilcox WW (1978) Review of literature on the effects of early stages of decay on wood strength. Wood Fib Sci 9: 252–257
Zhu D, Conners RW, Schmoldt DL, Araman (1996) A prototype vision system for analyzing CT imagery of hardwood logs. IEE Proc Syst, Man and Cybernetics – part B, 26: 522–532