ACOUSTIC EMISSIONS RELATED TO THE DEHYDRATION STRESS BEHAVIOR OF GREEN NORWAY SPRUCE WOOD

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Keywords: AE feature extraction, vulnerability to cavitation, wood shrinkage

Abstract

Waveform features of acoustic emission (AE) signals emitted from cavitation events in water-conducting elements of dehydrating wood bear a lot of information about both wood structure and the behavior under dehydration stress. We present two applications of AE feature extraction on wood; first, the prognosis of the survival prospects of trees under drought stress by constructing vulnerability curves and second, monitoring of the shrinkage behavior during lumber drying. AE testing was performed with resonant 150 kHz transducers on Norway spruce wood with different structural characteristics. Radial wood shrinkage was calculated from changes in the contact pressure between the AE transducer and the wood specimen. The reference method to assess the vulnerability to cavitation was the hydraulic method, where vulnerability curves were constructed by plotting the percent loss of conductivity vs. an overpressure of compressed air. Vulnerability curves were also constructed by relating the cumulated amount of AE energy to the applied overpressure. Samples with smaller conduit diameters showed lower mean AE energies and were less sensitive to cavitation and thus to drought stress. Two shrinkage processes can be observed during wood dehydration; the initial process, induced by tensile stresses, and the final shrinkage process, which started when most of the tracheids reach relative water contents below the fiber saturation point. Wood less sensitive to cavitation showed lower shrinkage and mean AE energy /min but higher total AE activity than wood with higher sensitivity to cavitation. The negative relationship between maximum AE energy and total AE activity and the positive relationship between maximum AE energy and radial lumen diameters reveals that more elastic energy is stored in bigger conduits when under tension. AE testing in combination with feature extraction offers an interesting alternative to the labor-intensive conventional methods to assess the vulnerability to cavitation and can be used to monitor the shrinkage behavior and crack development during lumber drying.

Introduction

Waveform features of AE signals from dehydrating wood bear a lot of information about both wood structure and the behavior of wood under dehydration stress. We present two applications of AE feature extraction on wood; first, a method to assess the vulnerability to cavitation of trunk wood and second, the monitoring of the wood structure-dependent shrinkage behavior during lumber drying processes.
Norway spruce wood consists to 90% of small water-conducting elements with a diameter of about 10-40 µm and a length of 1-4 mm (tracheids, Fig. 1). One annual ring, which consists of earlywood and latewood tracheids, is formed every year. Water in tracheids exists in three states, (1) as “free” liquid water, (2) as water vapor and within the tracheids, and (3) as chemically “bound” water in the cell wall matrix [1]. Water transport from the roots to the crown is achieved under tension, requiring high mechanical strength of the cell walls in order to avoid implosion, and hydraulic safety against the breakage of the water column in the conducting elements (cavitation). Cavitation is induced when the water tension increases above a certain threshold. Once cavitated, the conduit does not conduct water any longer and the hydraulic conductivity of the plant is reduced, leading to impairment of water supply of the transpiring needles [2]. Hydraulic safety depends on wood structure and can be assessed by the construction of vulnerability curves. A vulnerability curve is a plot of the percent loss in hydraulic conductivity (PLC) vs. the pressure potential in the solution of the tracheids. The most widely used drought-stress parameter is the pressure potential that causes 50% PLC. The common approach to quantify 50% PLC is to relate actual hydraulic conductivity to the hydraulic conductivity at full saturation (hydraulic method). The hydraulic method is very time consuming and demands practical experience. A more direct way to detect cavitation events is to record AE in the high-frequency range of 50 kHz to 1 MHz [3]. AE with the strongest frequencies in the range of 100-300 kHz are supposed to be induced by rapid tension release in the tracheid lumen as liquid water at negative pressure is replaced by water vapor very near vacuum pressure.

![Fig. 1 (a) Macerated Norway spruce tracheids of the last latewood cell row (below) and the adjacent first earlywood cell rows formed in the following growing season and (b) tracheids of the earlywood formed later in the growing season. “R” marks a ray cell, which achieve the radial transport in wood. The reference bar represents 200 µm.](image)

During periods of drought stress, decreases in the stem diameter of living trees can be observed [4]. This tensile strain is a consequence of adhesive forces between the water molecules and the inner conduit walls when “free” water in the tracheids comes under tension [5]. It has been hypothesized by many authors that the elastic behavior induced by water tension is strongly related to the elastic properties of the swelling tissues [5, 6] and thus to wood structure. When the moisture content of the tracheids drops below the fiber saturation point (FSP), that is when lumina contain no “free” water but cell walls are fully saturated with liquid, further dehydration leads to cell wall shrinkage processes. Checking during lumber drying occurs because wood is an anisotropic material concerning cell-wall shrinkage (radial:tangential = 1:2) and the FSP is reached far earlier in the shell than in the core of a specimen. Some authors suggest, however, that internal checks can even be induced by water tension because checking occurs long before most of the cells reach the FSP [e.g., 7]. AE testing is an established method for optimizing lumber drying conditions, where the analysis of the amplitude or energy distribution of AE signals
has been successfully used to pinpoint checking [8, 9]. Combined shrinkage- and AE tests are, however, scarce in AE literature on wood [10] and on live stems such investigation are performed at moisture contents well above the FSP [4]. Lumber shrinkage assessment starts either at moisture contents around the FSP or at “green” moisture content [11], defined as the moisture content at the time of harvesting [1]. “Green” moisture content will not correspond to the moisture content at 100% saturation when trees suffered at the time of harvesting from drought stress or when water was lost by evaporation during harvesting, transport or storage. In the present study we relate AE of dehydrating Norway spruce (Picea abies (L.) Karst.) sapwood with different structural characteristics to radial wood shrinkage processes from the totally saturated state till the end of all shrinkage processes.

**Hydraulic Method to Assess the Vulnerability to Cavitation**

Vulnerability curves were obtained on fully saturated juvenile (age = 1-2 years) and mature (age = 17-19) Norway spruce (Picea abies [L. Karst.]) wood beams (0.6 cm tangential, 0.6 cm radial, 10.0 cm longitudinal). After determination of the conductivity at full saturation, a positive pressure was applied to the lateral sides of the samples, while the transverse ends protruded from a double-ended pressure chamber (PMS Instruments Co., Corvallis, OR), to induce cavitation. After pressure treatment samples were weighed and hydraulic conductivity was measured again. The continuous pressure treatment leads to a decrease in hydraulic conductivity. Initially, the pressure chamber was pressurized to 0.5 MPa, and the pressure was subsequently increased after each conductivity measurement in steps of 0.5 MPa till more than 95% loss of conductivity was reached. The whole measuring procedure is described in [12]. Dry weight of the wood beams was obtained by drying wood samples at 103°C to constant weight in order to calculate the relative water loss (RWL). The pressure application was related to RWL by cubic functions [12].

**AE Testing Procedure and Data Analysis**

AE testing was performed with the µDiSP™ Digital AE system from Physical Acoustics Corporation (PAC, Princeton Jct, USA). Preamplifiers (40 dB) were used in connection with R15 resonant transducers (50 to 200 kHz). AE signals were recorded with a detection threshold of 30 dB (0 dB = 1 µV input). Extraction of AE energy (pVs) was carried out with AEWin® software (PAC). AE energy (also referred to as “PAC-Energy”) is defined as the area of the rectified voltage signal over the duration of the AE signal.

AE transducers were positioned on the tangential face of the wood beams using an acrylic resin clamp. The whole measuring procedure, where coupling pressure during the dehydration process was recorded with a DMS load cell (Type 8416-5500, range 0 - 500 N; amplification with an inline amplifier for DMS, Type 9235; Burster, Gernsbach, Germany) and water loss was measured with a balance, is described in [12]. Percent radial shrinkage (given in negative values) was calculated for 10 min time steps by relating the total radial shrinkage (digital gauge, accuracy 1 µm) to the total coupling pressure decrease. Percent radial shrinkage was referred to the nearest 5% RWL step.

AE data filtering was done with Vallen VisualAE™ software (Vallen Systeme GMBH, Munich, Germany). Mean AE energy values were calculated for 1 minute and 10 minute time steps. Relative cumulated AE energy data were obtained by relating the stepwise cumulated mean AE energy values/10 minutes to the sum of all mean AE energy values/10 minutes. AE data were
Fig. 2. (a) Percent loss of hydraulic conductivity (PLC), (b) cumulated AE signals and (c) cumulated AE energy/10 min plotted against positive pressure. Open symbols represent mature wood (n = 12), closed circles juvenile wood (n = 6).

referred to the nearest 5% RWL and thereafter to 0.5 MPa steps in order to construct vulnerability curves. Values are given as mean values ± standard error. Differences between mean values were tested for significance by Student’s t-test. Associations between two variables were examined using linear or quadratic regression analysis.

Anatomical investigations

Tangential double wall thickness of adjacent tracheids and lumen diameters were measured by means of a Leica DM4000M microscope interfaced with a digital camera and Leica image analysis software (Leica Microsystems Wetzlar GmbH, Germany). Tracheid dimensions of the first formed cell rows (earlywood) were measured on microtomed transverse cut faces of juvenile and mature Norway spruce wood (Fig. 5). Mean values of anatomical parameters were derived from 40 single measurements per standard beam, respectively.
Fig. 3. (a) Changes of the mean AE energy/10 min and (b) radial shrinkage against relative water loss (RWL). (c) and (d): same AE energy and radial shrinkage against time. Open circles represent mature wood, closed circles juvenile wood (n = 12, respectively).

Results and Discussion

Assessment of vulnerability to cavitation

Juvenile wood had a lower vulnerability to cavitation than mature wood: For juvenile wood from the tree top much more pressure was necessary to result in 50% loss of conductivity (PLC) than for mature wood from the tree base (3.20 ± 0.16%, 2.26 ± 0.04 MPa, respectively, P < 0.001, Fig. 2a). The cumulated number of AE signals was not a good predictive for the PLC, because 50% cumulated AE signals were reached at much higher pressures (Fig. 2b). 50% of the cumulated AE energy was induced at 3.73 ± 0.11 MPa in juvenile and at 2.31 ± 0.05 MPa in mature wood (P < 0.001, Fig. 2c). We assume that the cumulated AE energy is a more reliable measure for PLC than the AE number per se, because the hydraulic conductivity is proportional to the 4th power of the radius of a capillary (Hagen-Poiseuille equation) and tracheid diameters are variable within a wood specimen. High mean AE energies detected at moderate water losses or pressures resemble cavitation events of more vulnerable large diameter tracheids [12].

Relationship between shrinkage processes and AE

The AE and radial shrinkage data are given in Fig. 3. Two different radial shrinkage processes were observed (Fig. 3d). First is a shrinkage period at moderate water losses, which was termed “tension shrinkage”, and second is the cell-wall shrinkage period. Prior to cavitation, dehydration stress generates tensile strains inside the most vulnerable tracheids and in tracheids near the specimen surface. Tension shrinkage started therefore right from the beginning of dehydration, before any AE signals were detected (Figs. 3a-b) and ceased in mature wood at
Fig. 4. Maximum mean AE energy/min related to the number of AE signals by a quadratic regression model. Open symbols represent mature wood, closed circles juvenile wood beams (6 mm x 6 mm x 100 mm).

53.99 ± 1.91% RWL and in juvenile wood at 58.94 ± 2.48% RWL. Maximum tension shrinkage was more than three times higher in mature than in juvenile wood (–1.44 ± 0.11%, –0.42 ± 0.01%, respectively, P < 0.001). Maximum AE energies were detected at moderate water losses, when already more than 50% of the tension shrinkage had taken place (Figs. 3a-b). Tension shrinkage ceased when mean AE energies reached constantly lower values, and was even reversible to some extent (Figs. 3c-d). Recovery from shrinkage induced by cavitation seems to occur also in live stems [4], where it can either occur as a result of cavitation, or because of a decrease in crown transpiration. In debarked sapwood specimens, shrinkage can only be reversed by a local tension stress release after cavitation, when water is pulled out of the conduit into the surrounding wood. Recovery from tension shrinkage due to cavitation occurred at higher relative water losses than one would expect, being probably masked by continuous shrinkage in wood parts, which still contained “free” water. Shrinkage and regeneration from shrinkage should therefore occur at different locations at the same time in the numerous tracheids within a standard size wood specimen, which might be the reason why there is almost no time lag between periods of stem diameter decrease and increases in cumulated AE [4].

During late dehydration stages, the reversibility of tension shrinkage was additionally overlaid by cell-wall shrinkage [10]. The fiber saturation point (FSP) refers to the moisture content of a conduit and not to a whole piece of wood and it should be therefore not the same throughout a whole wood specimen [1]. During late dehydration stages, when the drier shell of the specimen had already reached moisture contents below the FSP, cell wall contraction could therefore additionally mask recovery from tension. The partial reversibility of tension shrinkage indicates however that the first shrinkage process at moderate water losses in standard size wood specimens was not entirely induced by cell wall shrinkage of the shell at water contents below the fiber saturation point but by tensile stresses due to water tension.

The final shrinkage process started after the shrinkage recovery peak, at about 80% RWL, corresponding to moisture contents given for the FSP of spruce species 35 – 37% [13]. Mature
wood showed higher total shrinkage than juvenile wood (−3.86 ± 0.13%, −2.31 ± 0.23%, respectively, P < 0.001, Fig. 3d). AE ceased when only 50% of shrinkage had taken place, giving strong evidence that no crack formation occurred at moisture contents below the FSP [7].

Juvenile wood beams emitted significantly more AE (numbers in 10^6 counts) than mature wood beams (1.70 ± 0.11, 0.62 ± 0.03, P < 0.001) and maximum AE energy/min was lower in juvenile than in mature wood beams (1.17 ± 0.12 pVs, 4.21 ± 0.32 pVs, P < 0.001). The maximum AE energy/min was strongly related to the total number of AEs (Fig. 4), total shrinkage (r = −0.80, P < 0.001) and maximum tension shrinkage (r = −0.88, P < 0.001). The total number of AE signals was higher in samples with lower total shrinkage (r = 0.80, P < 0.001) and tension shrinkage (r = 0.83, P < 0.001). The higher total number of AE signals and lower mean AE energies measured in juvenile than in mature wood indicate that lower vulnerability to cavitation was associated with a higher number of tracheids/volume with smaller lumen diameters [12]. Anatomical investigations showed that juvenile wood had significantly thinner double cell walls (3.34 ± 0.06 μm, 4.41 ± 0.11 μm, P < 0.001) and radial lumen dimensions (21.35 ± 0.60 μm, 39.68 ± 1.57 μm, P < 0.001) than mature wood (Fig. 5). The maximum AE energy/min increased therefore linearly with the radial lumen diameters (Fig. 6).

Norway spruce trees mainly vary cell size to optimize water transport and mechanical stability whereas modification of the cell wall organization plays a minor role [14]. Mature wood, which was more vulnerable to cavitation showed higher tension shrinkage and total shrinkage (Fig. 3d). Mature wood was thus more prone to deformation due to the same tension than
juvenile wood, indicating that the latter seems to be designed to resist implosion under high tension. High hydraulic vulnerability seems to be related to high AE energy signals, but what is the reason for this relationship? Hydraulically less vulnerable juvenile wood showed much lower radial lumen diameters than mature wood. Wall thickness increases as well with tree ring age, however to a much lower extent than the lumen diameters. The reinforcement against collapse from bending due to tension forces increases when the thickness of the double cell wall increases relatively to its span [15]. Juvenile wood showed thus a higher wall/lumen ratio than mature wood, which results in lower susceptibility to elastic deformation due to the same tension stress. Therefore, more elastic energy is stored in bigger tracheids when under the same tension. This energy is suddenly released when the water column breaks and liquid water at negative pressure is replaced by water vapor very near vacuum pressure and later by air. Conduits, which show higher deformation under tensile stress, will therefore release AE signals with higher energy when the cell wall relaxes due to cavitation. AE signals from more hydraulically vulnerable mature wood are therefore characterized by higher mean AE energies than those from less hydraulically vulnerable juvenile wood (Fig. 6).

Fig. 6. Radial lumen diameter related to maximum mean AE energy/min by a linear regression model. Open symbols represent mature wood, closed circles juvenile wood beams (6 mm x 6 mm x 100 mm).

**Conclusion**

Analysis of the spectrum features of AE signals during wood dehydration offered an interesting alternative to the hydraulic method for assessing the hydraulic vulnerability of spruce trunkwood. Vulnerability curves were constructed by relating the relative cumulated amount of AE energy during dehydration of standard beams under defined conditions to the xylem tension. Xylem tension of the dehydrating specimens was calculated with a parallel sample set, where air overpressures were related to the relative moisture loss by cubic functions. The xylem tension corresponding to 50% of the cumulated AE energy can be a useful parameter to quantify hydraulic vulnerability. The major advantage of the AE method presented is that it is readily automated and easier in handling compared to the labor-intensive hydraulic method.
Combined AE and shrinkage testing gave strong evidence that the relationship between changes in xylem tension and tensile strains measured at the surface of a tree trunk are strongly dependent on wood structure. Diurnal stem-diameter changes caused by tensile strain are used to pinpoint periods of drought stress in trees. Our results underline that the relationship between water potential and tensile strain is not constant, but requires time-consuming calibrations for each single tree if different trees should be compared [15]. Another source of error, which might underestimate actual drought stress, is that tension shrinkage is not only reversible due to an increase in water potential and refilling of cavitated water conducting elements in the night, but also due to tension release by cavitation. Combined AE and shrinkage testing could be also a useful tool to monitor the shrinkage behavior leading to crack development during industrial lumber drying.

Acknowledgements

This study was financed by the Austrian Science Fund FWF (Project T304-B16).

References