Experimental study on the possibility of detecting internal decay in standing *Picea abies* by blind impact response analysis

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Summary

This paper considers detection of internal decay in standing trees of species *Picea abies* (L.) Karst. The novel approach is based on two-dimensional spatiotemporal modal analysis of a cross-section which is excited by the hand-made impact of a hammer. An array of accelerometers is distributed around the cross-section, and the resulting impact response is analysed. The temporal frequency for a special spatial mode-shape is used for comparisons on a tree-to-tree basis. The mechanical properties of wood are inherently variable as they are for most materials of biological origin. This leads to a scatter of the analysed parameters that hinders detection of decay based on the temporal frequencies alone. Using regression analysis, we show that by incorporating the additional information on a surface wave propagation velocity, the scatter of sound trees is significantly reduced. The performance of a detector rule which incorporates the frequency and the surface wave propagation velocity is investigated and found to be better than performance reported for visual tree examination. The analyses are based on the impact responses from 94 standing trees, with 66 sound and 28 in various stages of decay. The proposed technique is yet to be considered an experimental tool. Further research, e.g. on how the mechanical properties are influenced by various environmental factors, is needed before the technique can be applied operationally.

Introduction

*Picea abies* (L.) Karst. (Norway spruce) is like many other conifers susceptible to fungi, whose colonization of the root system and trunk leads to rot and decay of the wood. Generally, there are no definite external signs of the decay and the presence of rot is noticed first upon felling the tree or, more dramatically, when it is wind-thrown. Even trained and highly skilled foresters fail to identify infected trees from visual examination (Vollbrecht and Agestam, 1995). The difficulty lies in that the external indicators of rot and decay may be due to other causes, and also that trunks of decayed trees may appear to be sound since the sapwood is more resistant to decay than is the heartwood. For instance, resin exudation is sometimes observed on severely...
decayed trees (Vollbrecht and Agestam, 1995), but can as well be a symptom of dead spots of inner bark, and cracks, caused by frost late in the growth season, or of drought (Cherubini et al., 1997; Jönsson et al., 2001). On many occasions, the fungus enters the host tree through the root system and then progresses upward through the trunk, leaving a column of rot covering a substantial part of the heartwood's cross-section. In the process, the fungus converts constituents of the cell walls into nutritious carbohydrates and, at the same time, alters the mechanical and aesthetic qualities of the wood (Wagener and Davidson, 1954; Toole, 1971; Kirk and Highley, 1973; Wilcox, 1978; Pratt, 1979).

A number of methods have been proposed as alternatives to visual tree assessment (visual tree assessment here refers to its literal meaning and should not be confused with the VTA method). One of the most widely practised methods is to visually study core samples taken from the trunk using an increment borer (Stenlid and Wästerlund, 1986). The major drawbacks of this method are unreliability due to the risk of missing possibly decayed areas when taking the sample (Stenlid and Wästerlund, 1986), and increased susceptibility of the tree to attacks by fungal spores due to the wound caused by the increment borer. Besides visual inspection of the core sample, analyses such as bending and rupture tests have been proposed (Mattheck et al., 1995). Other methods that, although not based on core samples, cause similar injuries are based on either mechanical resistance (Barrett et al., 1987; Bethge et al., 1996) or measurements of the wood’s electrical resistance (Shigo and Berry, 1975; Shortle and Smith, 1987) in which needle-like probes are punched or drilled into the trunk. Furthermore, immunological probes for detection of certain species of decay fungi in wood samples have been proposed (Clausen, 1997). All of these methods are destructive, although not to an extent that acutely threatens the existence of the tree. Completely non-destructive methods based on, for example, gamma-rays and computer tomography, have been proposed (Habermehl, 1982a, b), but the complexity of the measurements and the expensive equipment represent major obstacles for widespread application.

A large class of methods that cause only negligible damage and therefore are accepted as non-destructive is based on the propagation of stress waves (acoustical waves), mainly within the audible frequency range (Matheck and Bethge, 1993). The use of ultrasounds is under investigation (Sandoz et al., 2000; Socco et al., 2000). The destructiveness is limited to attachment of vibration transducers or sensors to the trunk, e.g. using short needles or screws. These methods are based on the fact that the propagation velocity of stress waves decreases when the mechanical properties of the wood are altered by decay (cf. Wilcox, 1978; Graff, 1991). In many methods, the estimated propagation velocity is compared with a species-specific value for sound trees: a velocity below a selected threshold is interpreted as due to decay or other internal defects. A severe drawback with this approach is that mechanical parameters which have a strong impact on the various wave propagation velocities may differ among members of the same species. For instance, the modulus of elasticity may differ more within a species than the average value differs from one species to another; the coefficient of variation (the ratio of the standard deviation to the mean) for mechanical parameters of wood from individuals of the same species is often as large as 20 per cent (Schniewind, 1989). The mechanical properties of an individual tree depend on many factors, e.g. whether it is suppressed by, or dominates, neighbouring trees (Brüchert et al., 2000). As a consequence, sound trees may exhibit stress wave propagation velocities that deviate considerably from the species-specific average value. In tomographic approaches, this issue is avoided since relative propagation velocities within the trunk are examined. Essentially, tomographic approaches correspond to multiple stress wave propagation velocity measurements along different stretches through the trunk (Divos, 2000; Rust, 2000); performed in an organized manner, the presence and location of decay may be unveiled and visualized as a coarse image. Such systems are already in commercial use (PICUS®, Argus Electronic GMBH, Rostock, Germany; ARBOTOM®, RinnTech, Heidelberg, Germany).

In recent years, methods accounting for the dynamic impact response of the trunk have been proposed (e.g. Axmon, 2000; Lawday and Hodges, 2000; Axmon et al., 2002). In these methods the frequency content of the measured
signals is analysed. In Axmon and Hansson (1999) and Axmon et al. (2002), we reported on an estimation method and modal frequencies sorted for different radial displacement modes (i.e. spatial mode-shapes) of a cross-section for trunks of standing Picea abies. Differences were found between the modal frequencies of sound and decayed trees; decayed trees tended to yield lower frequencies. It was also found that the two groups partially overlapped, and that the scatter with respect to the modal frequencies of sound trees with matching physical dimensions was substantial. This implied that the method suffered from individual variations of the mechanical properties. Moreover, it was observed that, in addition to stress waves travelling through the cross-section, surface waves were travelling bidirectionally from the point of excitation and along the circumference. The propagation velocity of the surface wave depends primarily on the outer parts of the trunk, i.e. the sapwood, whereas the modal frequencies depend on the global properties of the trunk, i.e. both heartwood and sapwood. Hence, under the assumption that the individual variations in mechanical properties are somewhat similar for sapwood and heartwood, it may be possible to reduce the scatter of the frequencies for sound trees with matching physical dimensions, by accounting for the surface wave propagation velocity, hence using it as a proxy for the mechanical properties. Provided that the sapwood is intact, it may even be possible to reduce the influence of individual variations for decayed trees such that the effect due to the altered heartwood on the measured frequencies is unveiled. Robust algorithms for estimation of the propagation velocity of the surface wave have been presented in Axmon and Hansson (2000) and Axmon (2000).

In this paper, we examine the hypothesis that the surface wave propagation velocity can be used as a proxy for the mechanical properties and hence, together with the circumference, serves as an explanatory variable for the modal frequencies of sound trees. Furthermore, we demonstrate how this relationship can be used to detect decay; given the circumference and an estimate of the surface wave propagation velocity, it is possible to determine a tree’s expected modal frequency under the presumption that it is sound. Should the measured (estimated) frequency deviate significantly from this value, the tree is likely to be afflicted by internal defects or decay. At present, the proposed technique uses about the same number of sensors that tomographic stress wave methods do, and hence requires almost a similar effort when a tree is examined. It is, however, based on global properties of the trunk and, with increasing knowledge on waveforms and other characteristics of the signals, in the future the number of sensors may be reduced to two or three and the examination of a single tree would only take a couple of minutes.

Materials and methods

Trees in the database

A total of 94 trees (Picea abies) was subjected to the experiment during the summers of 1998 and 1999. The trees were selected in three geographically separated, managed forest stands in central Scania, the southernmost part of Sweden. The stands had a similar history in that they had been established on former arable land, had been thinned regularly, and the trees within each stand or sectors of a stand were evenly aged. However, the age of the stands differ; the study contains trees of age spanning 23–58 years, with breast height circumference ranging from 0.26 to 1.15 m. The number of trees at a particular age is given in Table 1.

The trees in the study were chosen from groups that were to be commercially harvested, except for the 11 youngest trees (see stand B; Table 1) which were selected from a group of trees that had to be felled when changing the stretch of a road. Many of the trees had injuries: in forest stand A, the main cause was winter-time grazing
by fallow deer and red deer, and in stands B and C it was a combination of grazing game and the use of heavy machinery in the forest management. In the region, the incidence of butt- and heart-rot in spruce is most often due to the fungus *Heterobasidion annosum* (Fr.) Bref.

**Measurement equipment**

Impact responses of cross-sections of trunks at breast height (~1.2 m above ground) were collected using a uniform linear array consisting of 12 accelerometers (PCB Piezotronics M353B03) positioned along the circumference. Each accelerometer had a sensitivity of 10 mVg⁻¹ with 1 g = 9.804 ms⁻², a frequency range of 0.7–11 000 Hz at 10 per cent tolerance, and a weight of 10 g. An aluminium plate with a needle was used to attach each of the accelerometers firmly to the sapwood. The outputs of the accelerometers were sampled by a PC equipped with an I/O board (National Instruments PCI-MIO-16E-1 enhanced multifunction I/O board) at a rate of 100 kHz per sensor. The data collection was monitored using software developed in National Instruments’ LabView environment. To generate an exciting force, the impacts by hand-force of a standard hammer with a weight of ~0.2 kg were used. To avoid damage to the bark and attenuation of the exciting force, the impacts were applied onto a screw positioned between two of the accelerometers in the array. The screw penetrated the trunk to a depth of about 15–20 mm, such that it was firmly attached to the sapwood. The exciting force was not measured, and hence the method is referred to as blind; the output of the system is known, but the input that caused the output is unknown. The distribution of sensors and the screw around a cross-section is shown in Figure 1a, along with sketches of waveforms that will be discussed below.

**Measurement procedure**

Before collecting the impact responses, each tree was given a unique identifier for the database. The

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**Figure 1.** Initial wave propagation: (a) distribution of sensors and a screw around the cross-section and initial propagation of a stress wave (PW) and a surface wave (SW); (b) initial propagation paths. Time-of-arrival for (c) stress waves propagating through the cross-section at a velocity corresponding to covering a distance of one diameter in $T_D$ seconds, and (d) surface waves propagating along the circumference at a velocity corresponding to covering a distance of one circumference in $T_C$ seconds.
circumference and two perpendicularly taken measurements of the trunk’s radius at breast height were registered. Observations of abnormalities of the tree, e.g. resin exudation, dead branches and injuries, were added to the database. When positioning the array of sensors, we avoided as far as possible putting accelerometers on knots or injuries. A total of 20 responses was recorded from each tree, to allow a study on possible variations due to the hand-made hammer blows, and to rule out outliers, e.g. where the hammer touches the bark after hitting the screw.

Post-measurement assessment procedure

To obtain the true status of each tree, which is required for evaluation of the method, the trees were felled. The status of each tree was determined visually from the fell cut at ~0.2 m above ground level. Since wounds at the surface of the trunk increase the risk of rot not necessarily developed at the butt, two subclasses of sound trees were used (see Table 2). The decayed trees were arranged into three subclasses, each describing how developed the decay was.

Sensor array signal processing

The measured signals were subjected to two analyses: (1) modal analysis and (2) surface wave propagation velocity estimation, whose results are the basis for the work presented in this paper. In the modal analysis, temporal and spatial frequencies were estimated. While the former are measured in hertz (Hz), the latter are associated with different shapes that the cross-section of the trunk attains when it vibrates. For the modes examined in the analysis, each temporal frequency is associated to a spatial mode-shape. When using impact excitation, one has little or no control over which modes will be excited, and furthermore, several modes are excited simultaneously, hence the measured responses contain the combined vibrations of many modes. However, the spatial mode-shape can be used as an identifier, such that corresponding modes can be compared on a tree-to-tree basis although the temporal frequencies differ. The algorithm used for the modal analysis and the results are described in Axmon et al. (2002). Since it was found that the mode for which the cross-section attains an oval shape was found in recordings from all but one tree, i.e. 93 out of 94, our attention is on that mode.

The surface waves, which travel from the point of excitation along the circumference in both directions, generate a pattern in the measured signals that is clearly separable from the pattern created by the stress waves. In an isotropic, homogeneous and linearly elastic medium, a stress wave travels along the straight line from the point of excitation to the respective sensor, whereas a surface wave follows the contour of the boundary, i.e. the circumference, see

Table 2: Classification based on visual inspection of the fell cut at ground level for the 94 subjects of Picea abies in the database

<table>
<thead>
<tr>
<th>Class</th>
<th>Subclass</th>
<th>Description</th>
<th>Stems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound</td>
<td>I</td>
<td>Subjects with a fell cut without signs of decay and without comments on injuries, resin exudation and other remarkable signs.</td>
<td>43*</td>
</tr>
<tr>
<td>Sound</td>
<td>II</td>
<td>Subjects with a fell cut without signs of decay, but with comments on one or more of the issues above.</td>
<td>23</td>
</tr>
<tr>
<td>Decay</td>
<td>I†</td>
<td>Subjects in incipient decay, noticed by light-shaded discoloration of the still hard wood.</td>
<td>7</td>
</tr>
<tr>
<td>Decay</td>
<td>II‡</td>
<td>Subjects in advanced decay, noticed by dark-shaded discoloration of the still hard wood, and by minor changes of the wood texture.</td>
<td>7</td>
</tr>
<tr>
<td>Decay</td>
<td>III‡</td>
<td>Subjects in the final stage of decay, noticed by soft and brownish wood.</td>
<td>14</td>
</tr>
</tbody>
</table>

* Only 42 trees are used in the subsequent analysis due to one tree lacking a frequency estimate.
† The mechanical properties of the wood are somewhat affected (Habermehl, 1982b).
‡ The mechanical properties of the wood are impaired (Habermehl, 1982b).
Figure 1a and b. The arrival times to the respective sensors are for stress waves, governed by the law of cosine, which for uniformly distributed sensors yields a profile which is half a period of a sinusoid (Figure 1c). The surface waves, traveling along the circumference with constant velocity, generate a linear time-of-arrival for each direction (see Figure 1d). These clearly distinguishable kinds of time-of-arrival profiles are found in all 93 recordings used in the present work, and one representative example for a sound tree with a circumference of 0.81 m is given in Figure 2. The acceleration for the initial 2.5 ms of the sensor outputs is shown in Figure 2a. There is obviously an agreement between the time-of-arrivals of the different wavefronts visible in Figure 2a and the slopes in Figure 1c and d, even though wood is not isotropic, but constitutes a structured anisotropy (Bodig and Jayne, 1982; Côté, 1989). However, the anisotropy in the radial–tangential plane of the trunk (the cross-section) is much smaller than in, for example, the radial–longitudinal plane. The half period of a sinusoid assumption for the initial stress wave is supported by the zoomed plot in Figure 2b showing the initial 0.7 ms. The algorithm used for estimating the surface wave propagation velocity is detailed in Axmon and Hansson (2000), and further developed in Axmon (2000) where results for the trees in the database are reported.

Signal processing results

The sensor array signal processing results are summarized in Figure 3, where the frequency of the ovaling mode in Figure 3a, and the propagation velocity in Figure 3b, are plotted versus the circumference of each tree. The results are taken from Axmon et al. (2002) and Axmon (2000), respectively. The markers are coded according to the status of each tree (cf. Table 2). Evidently, there is a considerable scatter for sound trees with similar dimensions. This scatter may to some extent depend on individual variations of the mechanical properties.

Regression analysis and hypothesis testing

For trees in subclass Sound I, a nearly reciprocal relationship between the frequency of the ovaling mode and the circumference is observed; see Figure 3a. Hence, the circumference \( C \) is obviously an explanatory variable in the sense that it explains the general functional dependency between measured frequency and dimension of the cross-section. The hypothesis is that the surface wave propagation velocity \( \upsilon \), too, is an explanatory variable, such that the scatter in Figure 3b explains some of the scatter in Figure 3a. The hypothesis is based on the theory of isotropic, homogeneous, linearly elastic cylinders, for which the functional relationship...
between frequency $F$ of the ovaling mode, circumference $C$ and shear wave propagation velocity $\upsilon_s$ is

$$F = xC^{-1}\upsilon_s$$  \hspace{0.1cm} (1)

where $x$ is a dimensionless factor which is dependent upon the Poisson ratio, and for the case of hollow cylinders, on the relative thickness of the walls (Axmon, 2000). The propagation velocity of the shear wave is dependent upon the modulus of shear $G$ and the mass density $\rho$ through $\upsilon_s = \sqrt{G/\rho}$. A similar relationship can be established for the stress wave. Shear and stress waves are the only kinds that can propagate within this simplified medium. However, at the boundaries, Rayleigh surface waves which are neither pure stress waves, nor pure shear waves, propagate (Graff, 1991). Although the precise characteristics of the surface wave observed in trees is unknown, the wave is most certainly dependent on the mechanical properties of the outer parts of the trunk: modulus of shear, mass density and Poisson’s ratio. For the simplified medium, the latter has been found to have a smaller impact than the former two on equation (1) (Axmon, 2000).

To test the hypothesis, the following two regression models are examined:

$$F_1(C; \theta_1) = \frac{\theta_1}{C},$$  \hspace{0.1cm} (2)

$$F_2(C, \upsilon_s; \theta_1) = \frac{\theta_1 \upsilon_s}{C}$$  \hspace{0.1cm} (3)

where in equation (2) it is assumed that the frequency is independent of the surface wave propagation velocity, and in equation (3), that the frequency depends on the propagation velocity in a manner similar to the idealized case in equation (1). It is assumed that $C$ and $\upsilon$ are independent. Although it is understood that both $C$ and $\upsilon$ are estimates, it will be ignored in the analysis; all other estimates are marked by a circumflex. The regression analysis of the models $F_1$ and $F_2$ is performed under a least-squares error criterion using the data for the trees in Sound I. In the selection between competing models, bias and standard deviation of the regression residuals are studied, where the standard deviations are adjusted for the degrees of freedom in each model (Rawlings, 1988).

To verify the assumption that the propagation velocity may be considered independent of the circumference, the following competing regression functions are examined:
of the ovaling mode are determined, upon which the residual

$$e = \hat{F} - F_p(C, \hat{\upsilon}; \hat{\theta}_1, \hat{\theta}_2, \hat{\theta}_3)$$

(7)

is formed. The residual corresponds to the difference between the measured frequency and the predicted frequency for a presumed sound tree. A sound tree is expected to yield a small residual, whereas a decayed tree is expected to yield a large negative residual since decay reduces the propagation velocity of the waves within the trunk. However, other abnormalities (e.g. effects of drought) may lead to large positive residuals, since the mechanical properties of wood are dependent on, for example, moisture content (Bodig and Jayne, 1982; Booker et al., 1996). Furthermore, in a severely decayed tree, the mechanical properties of the outer wood of the trunk may have been significantly altered. In that case, it may lead to a lower propagation velocity of the surface wave. This would then result in a small residual, since a low measured frequency then is explained by a low surface wave propagation velocity used in the prediction by $F_p$. To avoid such situations, a threshold on the surface wave propagation velocity is used. Hence, the following detection rule may be defined, where $\epsilon_{TH}$ and $\upsilon_{TH}$ are thresholds acting on the residual and the propagation velocity, respectively:

\[
|\epsilon| \leq \epsilon_{TH} \text{ and } \hat{\upsilon} > \upsilon_{TH}
\]

(8)

are fulfilled.

To evaluate the performance of the detector rule for a set of thresholds $\epsilon_{TH}$ and $\upsilon_{TH}$, the fraction of correct detections within each major class Sound and Decay are studied. Since it is observed in Figure 3b that none of the sound trees exhibit a propagation velocity below 310 m s$^{-1}$, the threshold on the velocity is chosen to $\upsilon_{TH} = 310$ m s$^{-1}$. The threshold on the prediction residual $\epsilon_{TH}$ is examined for increasing values beginning at $\epsilon_{TH} = 1$ Hz. The parameters $\theta_i, i = 1, 2, 3$ are estimated using the trees in the subclass Sound I.

Results

The results for the regression analysis of the competing models $F_1$ and $F_2$ are shown in Table 3.
Both models result in biased regression residuals, but the adjusted standard deviations differ significantly. When including the propagation velocity, $F_2$, the standard deviation is reduced to 55 percent of the one obtained for $F_1$ which only uses the circumference as explanatory variable. This means that much of the scatter in the measured frequency is explained by the scatter of the propagation velocity, and hence, the propagation velocity is an explanatory variable that should not be neglected. The results from the regression analysis of $\nu_1$ and $\nu_2$ are shown in Table 3. The bias is negligible for both models, but the adjusted standard deviation of the regression residuals is somewhat lower for $\nu_1$ than for $\nu_2$. Thus $\nu_1$ is selected, i.e. the propagation velocity of the surface wave is considered independent of the circumference of the trunk at breast height, yielding an average value of $\bar{\nu} = 353.2$ ms$^{-1}$ for the sound trees in Sound 1. Conclusively, the hypothesis that the propagation velocity is independent on the circumference is justified.

The coefficients for the frequency predictive function $F_2$ which is used in the detector rule are shown in Table 3. They were determined for the average velocity of $\bar{\nu} = 353.2$ ms$^{-1}$ which was obtained from $\nu_1$. By inclusion of the two first-degree monic polynomials, the bias is significantly reduced, and the adjusted standard deviation somewhat reduced, compared with the $F_2$ model. A scatter plot of residuals from equation (7) versus propagation velocity is shown in Figure 4. It is found that many of the decayed trees separate from the group of sound trees either by a low propagation velocity or by a large positive or negative residual. The standard deviation for the subclass Sound I was 40.1 Hz, and for the major class Sound (i.e. Sound I plus Sound II) is 46.9 Hz. Most of the decayed trees yield residuals that fall outside the plus one to minus one standard deviation of the major class Sound. The performance of the detector rule is shown in Figure 5 for $\nu_{TH} = 310$ ms$^{-1}$ and $1 \leq \varepsilon_{TH} \leq 120$ Hz. The curves describing the success of the classification intersect at $\varepsilon_{TH} = 53$ Hz, where 74 percent of the sound and the decayed trees, respectively, are correctly classified. For $\varepsilon_{TH} < 53$ Hz, an increasing number of decayed trees are correctly detected as decayed at the expense of an increasing number of sound trees falsely detected as decayed, and for $\varepsilon_{TH} > 53$ Hz vice versa.

**Discussion**

The hypothesis that the scatter of the measured frequency of the ovaling mode is explained by a
scatter of the surface wave propagation velocity is supported by the results from the regression analysis. Validation using an independent data set, i.e. a data set that was not included in the estimation of the parameters of the regression function, is not only considered good practice, but is important especially when the regression function is used for a predictive rather than a descriptive purpose (Rawlings, 1988). Such validation has not been performed, and the reason is that there are too few trees in Sound I to split the data set into one for regression analysis and one

Figure 4. Scatter plot of residuals $\epsilon$ versus surface wave propagation velocity $\upsilon$ for the 93 trees included in the study. The horizontal lines indicate plus one and minus one standard deviation (46.9 Hz) for the residuals in the major class Sound. For a legend on the remarks, see Figure 3.

Figure 5. Performance evaluation of the detector rule for a threshold $\upsilon_{TH} = 310$ m s$^{-1}$. Successful classifications within the major classes Sound and Decay, respectively, versus double-sided residual threshold $\epsilon_{TH}$.
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for validation. All estimates in Sound I are required to ensure a satisfactory excitation in the analysis. Validation using Sound II resulted in larger bias and standard deviation of the residuals, but did not affect the selections of the regression function \( F_2 \) over \( F_1 \) and \( \nu_1 \) over \( \nu_2 \). There is, however, a reason for splitting the major class Sound into the subclasses Sound I and Sound II, cf. Table 2, and therefore validation using Sound II has little credibility. The uncertainty on whether the trees in Sound II suffer from decay at breast height could have been avoided by cutting the trunks at breast height, upon which the status of the tree in the vicinity of where the measurements were performed could have been determined. The reason for not doing so was purely economical: generally the lower part of the trunk is the most valuable one. In the case of follow-ups to this study, we recommend that the trunks are cut at the height where the measurements are performed; there would then be no need for two subclasses of sound trees.

The detector rule is evident from studying a scatter plot of prediction residual \( \epsilon \) versus propagation velocity \( \theta \) for the 93 trees included in the analysis (Figure 4). It is evident that many of the decayed trees fall outside the plus one to minus one standard deviation (± 46.9 Hz) for the major class Sound indicated by the dashed, horizontal lines. Many of the trees in Decay III which exhibit low propagation velocities had hollow trunks filled with moist and spongy leftovers of what once was wood; those trees are in the ultimate stage of decay. Although the measurements are performed at breast height, it is reasonable to assume that a large area of the examined cross-section for trees in Decay III is severely decayed (Wagener and Davidson, 1954; Habermehl, 1982b). It is also expected for Decay II that the decay extends to the examined cross-section, but for trees in Decay I, it is likely that some trees are perfectly sound in the vicinity of the cross-section. The reason for this is the coarse, qualitative separation of the continuum of stages of decay into three subgroups. The least developed decay in Decay I corresponds to a spot of discoloured wood, and since most heart-rotting fungi have a vertical extent of 0.3–0.6 m beyond the lowest visible sign of decay (Wagener and Davidson, 1954), the rot column might not reach to breast height. Similarly, some of the trees in Sound II may be decayed at breast height, although they appear to be sound at the fell cut, since injuries of the trunk may serve as entrances for fungal spores.

Studying the fraction of correct detections within each class for a range of thresholds on the residuals (Figure 5) we see that the curve describing the success in identifying decayed trees intersects with the curve describing the success in identifying sound trees at 74 per cent for a threshold \( \epsilon_{TH} = 53 \) Hz. If there were no overlap, a simultaneous success of 100 per cent would be achievable. Hence, trade-offs have to be made. Although the results may appear to be displeasing, a comparison is made with the study by Vollbrecht and Agestam (1995) where five trained foresters individually assessed 372 trees of Picea abies by visual examination of the standing trees. In the study, it was found that the assessments by individual foresters were only slightly better than random. To be able to compare the results in the study with the performance of the detector, figures for the majority’s decision, i.e. where at least three of the five foresters had the same opinion on whether an individual tree was sound or decayed, were extracted from the reported bar graphs, and converted into appropriate success figures for each class. It was found that ~53 per cent of the sound trees and 67 per cent of the decayed trees were correctly classified. A comparison with the present study shows that the success of the detector rule in detecting decayed trees is 86 per cent, given a success of 53 per cent in detecting sound trees. The success in detecting sound trees is also 86 per cent, given a success of 67 per cent in detecting decayed trees. Should these results be representative for a larger study, it means that there is a prospect of detecting decay more accurately than possible from visual tree assessment.

One may have objections concerning the predictive function \( F_1 \) used in the detector, and the performance evaluation. The parameters \( \theta_i, i = 1, 2, 3 \), were determined by regression analysis using the presumed perfectly sound trees in Sound I. This means that the parameters are adapted to sound trees from the examined forest stands. Season, climate and other environmental conditions, e.g. soil, terrain and water-table, may influence the mechanical properties of the trunks. Hence, the parameters may be different for other
forest areas, and may even differ for the examined forest stands during the year. Should one use such a detector, one would first have to understand the impact of the influential factors, or to tune the parameters on a subset of sound trees representative for the forest area under the scope. The objection concerning the performance evaluation is that the predictive function was tuned using the trees in Sound I, constituting 65 per cent of the trees in the major class Sound. The standard deviation of the regression residuals for $F_p$ was 40.1 Hz. Thus at the residual threshold $\varepsilon_{TH} = 40.1$ Hz and assuming a normal distribution, 68 per cent of the trees in Sound I, corresponding to 44 per cent of the major class Sound, are successfully identified. As evident from Figure 5, the relative success figure for the class Sound is 56 per cent, meaning that 34 per cent of the trees in Sound II are within this threshold. The success per subclass differs by 10 percentage units, merely corresponding to two trees in Sound II. Thus $F_p$ seems appropriate in predicting the frequency for the trees in Sound II, too. Of course, performance evaluation using independent data would be more reliable but, as discussed above, this has not been an option in the present study.

The main achievement of this paper was to show that the surface waves capture the mechanical properties and thus can be used in reducing the scatter due to individual variations among members of *Picea abies*. It ought to be examined whether stress wave time-of-flight methods (e.g. Mattheck and Bethge, 1993) and combined single-sensor dynamical analyses (e.g. Lawday and Hodges, 2000) would benefit from information on the surface wave propagation velocity. Finally, and obviously, a characterization of the surface waves arising due to impact excitation of the trunks ought to be conducted. Knowledge on the type of surface wave, e.g. whether it resembles a Rayleigh wave, may lead to a better understanding of the mechanics of standing trunks, from which all impact-based methods would benefit.

The measurement technique used for the present work requires about the same effort as tomographic stress waves methods, since an array of sensors has to be distributed around the trunk; it is time consuming and may require as much as 5 min per tree. Therefore, at present the method is more experimental than operational. A stationary PC and a portable power supply were used for the data acquisition; this increased the total time spent on each tree. Today, the performance of budget laptop computers is more than sufficient for managing the data acquisition and the analyses, thus cumbersome equipment is no longer required. However, a large reduction of time consumed at each tree would be achieved if the number of sensors were reduced. At present, the main obstacle is the fashion in which the surface wave propagation velocity is estimated. Signal processing algorithms which are based on information gathered from further analyses on the characteristics of surface waves may probably lead to a minimum requirement of two or three sensors, from which a considerable reduction in time spent per tree follows.

**Conclusions**

It has been established that the propagation velocity of a surface wave arising from impact excitation is correlated to the modal frequency of the ovaling mode for cross-sections of trunks of *Picea abies*. The surface wave captures the mechanical properties of the wood, and thus can be used for reduction of the effects of the natural, individual variations of the mechanical properties among members of *Picea abies*. Furthermore, it has been demonstrated that the joint information on the modal frequency of the ovaling mode and the propagation velocity of the surface wave can be used in the detection of decayed trees. Comparison with other studies (Vollbrecht and Agestam, 1995) shows that the detector performs better than visual tree examination. Although the proposed detector suffers from drawbacks, e.g. that it likely has to be tuned using sound trees from similar forest stands, and the necessary selection of a residual threshold, it shows that there is a prospect of detecting decay using modal frequencies. Research on, and characterization of, the surface wave is recommended, since it is likely that all impact-based non-destructive testing methods for detection of decay in standing trees would benefit from a reduction of the effects of the individual variations of the mechanical properties.
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