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ORIGINAL PAPER

Evaluation of the quality of standing trees using an Arbotom acoustic stress tomograph

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Abstract

The assessment of wood quality in forestry operations is crucial for both forestry enterprises and the wood processing sector. Acoustic equipment utilizing excited stress acoustic waves has emerged as a valuable tool for evaluating the internal structure of standing trees. By measuring the propagation speed of these waves within the trunk, it becomes possible to assess the properties of wood before harvesting, aiding in management, planning, and maximizing resource value. The Arbotom acoustic stress tomograph represents one such device designed for evaluating standing trees' qualitative properties. In a study evaluating its efficacy, 136 trees in a specific forest stand were examined over a period spanning October 2021 to March 2024. The acquired data underwent analysis, with 17 trees selected for qualitative evaluation using both image analysis in ImageJ software and the STN EN 1309-3 standard. The study revealed that, on average, the tomographer tended to overestimate the extent of damage by qualitative features by approximately 14.9% compared to digital image assessment and 9.9% compared to assessment according to the standard. The method could still serve as a component within a broader framework of precision forestry. Combining the acoustic tomography method with other precision forestry techniques could potentially yield more satisfactory results, paving the way for the development of automated systems for assessing tree quality in forest stands. This integration could enhance the efficiency and accuracy of wood quality assessment, benefiting both forestry management and downstream processing operations.

Key words: acoustic tomograph; image analysis; qualitative features of wood; wood quality; raw-wood assortments

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1. Introduction

Effective qualitative evaluation and sale of raw wood assortments are essential for the economically viable operation of forestry enterprises. The increasing demands of the processing and energy industry for the quantity and quality of delivered wood, in cooperation with the requirements for nature protection and the limitation of the volume of intentional fellings, are increasingly putting pressure on the efficient management of harvesting and transport processes. This management includes not only the accurate qualitative assessment of harvested wood but also of standing wood in forest stands. Typically, raw wood is classified into appropriate technical conditions based on the permissible range of observed features, aligning with the quality classes of raw wood assortments. (Gejdoš et al. 2019; Taube et al. 2020; Grigorev et al. 2021). The economic evaluation of wood in commercial forests is of utmost importance for forest owners and forestry companies. It serves as the foundation for long-term planning in forest management, influencing decisions regarding harvesting, replanting, and overall resource allocation. (Kankare et al. 2014; Korhonen et al. 2016).

Wood classification into quality classes relies on a combination of quantitative and qualitative features. While positive features like wood type and color shade are considered, they alone are insufficient for determining the wood's purpose of use. Therefore, a system of negative qualitative features, often arising during tree growth or due to abiotic or biotic factors, is employed for classification purposes (Gejdoš et al. 2021, 2023a).

However, current legislation primarily focuses on assessing quality features post-harvest, limiting exact

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determinations to cut or harvested trunks or log cut-outs. Yet, there's a need for at least approximate knowledge of wood quality distribution within standing forest stands for effective managerial planning of sales, trade, and harvesting schedules. In forestry operations, methods predominantly used for these purposes often rely on subjective evaluation by assessors. Many available methods suitable for forestry operations are either destructive, semi-destructive, or impractical for use in exposed forest terrain (Wang 2021).

Non-destructive methods are those that do not damage the wood. The quality of the given wood is subsequently determined using measured values or properties characteristic of a particular method. These methods can be divided into: Electric (for example, Vitamat, Dielektrik); Ultrasonic (for example, Arbosonic, Pundit, Sylvatest); Acoustic 2D and 3D tomographs (for example, Fakkop 2D, Arbotom 2D and 3D, Arbosonic 3D); X-ray (mobile or stationary CT computed tomography, X-ray and neutron radiography) (Reinprecht & Hrivnák 2012).

Dynamic progress is also recorded by methods based on terrestrial laser scanning and the subsequent creation of algorithms for the qualitative classification of tree trunks standing in the forest stand from the obtained point clouds (Van Leeuwen et al. 2011).

Devices working based on an excited stress acoustic wave evaluate the internal structure of standing trees based on the principle of its propagation speed inside the trunk. Research has confirmed that acoustic wave propagation in healthy wood is faster than in wood containing an internal defect (Wang & Alison 2008; Johnstone et al. 2010; Rabe et al. 2012). Therefore, researchers report that any defects in standing trees can be detected by this basic principle and test method (Deflorio et al. 2008; Li et al. 2012). Acoustic methods are among the oldest methods of evaluating wood properties. The acoustic velocity spreads through the material in the form of transient elastic waves generated by the sudden release of energy. The source is an acoustic impulse, such as a hammer blow or an excited acoustic signal (sound). Therefore, scanning the speed of acoustic waves in wood is most often used for assessment (Ondrejka et al. 2021). The obtained results of the speed of the acoustic wave are usually modified by different algorithms depending on the conditions, the type of wood, etc. (Fang et al. 2011; Lin et al. 2011a). Limits for practical use in operation are also represented by the relatively high purchase price of such devices. For example, the price of an acoustic tomograph starts at around 7,000 euros and can reach up to 25,000 euros, depending on the configuration and number of analytical sensors.

The advancement of acoustic equipment for assessing standing trees has revolutionized the evaluation of wood properties before harvesting. This advancement significantly aids in the management and planning of harvesting and wood processing operations, allowing for the maximization of resource value. In recent decades, acoustic technologies have established themselves as reliable tools for evaluating materials in the woodworking industry. Acoustic devices have become widely accepted for quality control and product classification in the woodworking industry. Moreover, they are utilized in breeding research, particularly for assessing young trees. Most acoustic devices designed for evaluating tree properties are tailored for radial measurements, which are taken perpendicular to the trunk's axis. A certain limitation for the deployment of devices operating on this principle is the current legislation, standards, and technical conditions, which define the exact method of evaluating quality features based on their surface area.

Our study evaluates the potential and limitations of using the Arbotom acoustic stress tomograph in forestry operations, focusing on selected trees during experimental measurements. This research aims to explore the efficacy of Arbotom tomography in assessing wood properties in real forestry praxis conditions. By doing so, it contributes to the ongoing efforts to enhance the efficiency and accuracy of wood quality evaluation processes in forestry operations.

2. Material and methods

The field measurements were conducted using an ARBOTOM® acoustic tomograph equipped with a total of 24 sensors and integrated Arbotom 2.11 Standard software, as depicted in Figure 1. The study analyzed

Fig. 1. Measuring equipment with acoustic tomograph ARBOTOM.

a total of 136 trees located in stand number 911 of Locality Stráže (Zvolen) over the period spanning October 2021 to March 2024. Among these trees, 87 were oak (constituting 64% of the sample), 45 were linden (33%), 3 were pine (2.2%), and 1 piece of fir wood (0.8%). Subsequently, 17 trees were selected from the analyzed sample for further examination. These consisted of 13 linden trees and 4 oak trees. They were subject to photographic verification along with manual measurements to validate the data obtained from the acoustic tomography.

The average number of sensors deployed on the trunk during the analysis was 7, with 6 sensors being the most common (mode). The average thickness of the analyzed trunks was 47.7 cm (mode: 35.6 cm). The average mounting height of the sensors on the analyzed trunks was 73.7 cm (mode: 75 cm).

The tomograph in the integrated software evaluates higher propagation speeds of the excited acoustic wave and displays them in a green-yellow color spectrum (healthy, denser wood) and lower speeds in a red-violet color spectrum (disturbed, thinner wood). The digital output from the tomographic software was further analyzed using ImageJ software. Image analysis served to accurately determine the proportions of potentially damaged parts inside the trunk (Fig. 2). The cross-sectional area of the trunk, which was rendered in the violet color spectrum by the tomograph software, was considered to be wood damaged by a quality feature. The principle of the analysis consists in entering the reference dimension (diameter of the cross-section) in centimeters. Subsequently, the area of the cross-section and the analyzed area of the respective color spectrum are defined. The software then calculates the area of the cross-section and the area of the potential quality feature in the cross-section (Fig. 2).

As part of the analysis, a portion of the examined trees underwent planned harvesting intervention. The qualitative features of these harvested trees were evaluated through manual measurement according to the STN EN 1309-3 standard. Additionally, digital images of the harvested trees were created and subjected to image analysis using ImageJ software, as depicted in Fig. 3. Given the specific context of the planned harvesting intervention in stand number 911, 17 trees were harvested, with 13 being linden wood and 4 oak wood. The methods of image analysis from the acoustic tomograph output

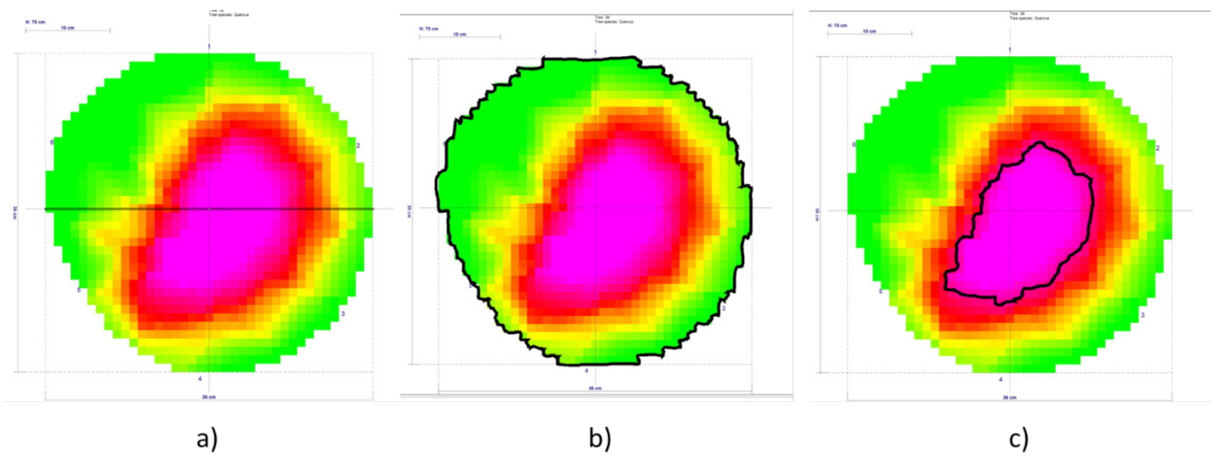

Fig. 2. Assessment of the trunk quality from image developed by tomograph in software ImageJ (a – setting scale according diameter; b – setting the area of cross cut; c – setting the area of damaged wood).

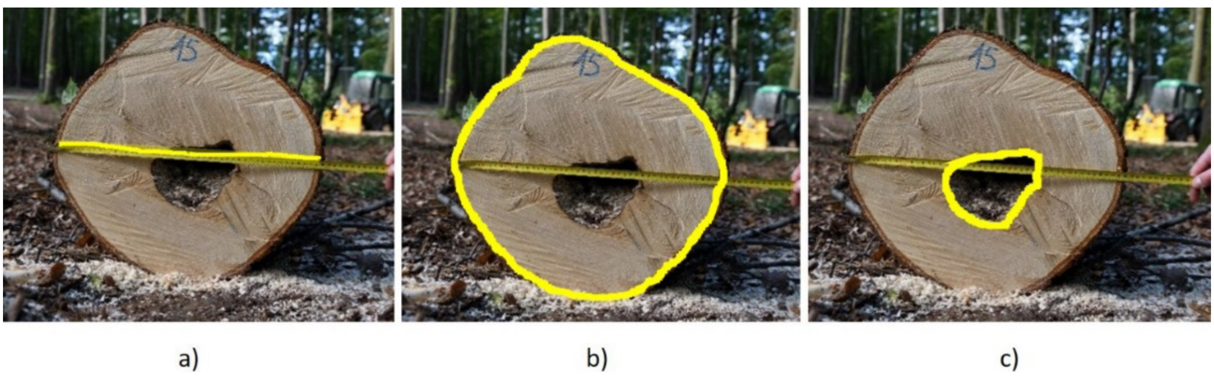

Fig. 3. Assessment of the trunk quality from digital image after harvesting in software ImageJ (a – setting scale according diameter; b – setting the area of cross cut; c – setting the area of damaged wood).

and the photographs after felling were compared with each other. Furthermore, the results obtained from both image analysis methods were compared with the conventional evaluation of qualitative features according to the standard. To conduct statistical evaluations, the software STATISTICA v. 12.0 and MS Excel were utilized. These tools facilitated the comparison and analysis of data obtained from different evaluation methods, allowing for a comprehensive assessment of the effectiveness and reliability of the acoustic tomograph in comparison to conventional manual measurement methods and image analysis techniques.

3. Results

The evaluation process of the outputs obtained from the acoustic tomograph involved image analysis to identify potential damage in standing trees. These results were then compared with the image analysis of felled trees and manual measurements conducted in accordance with relevant legislation governing the measurement and evaluation of qualitative features.

3.1. Image analysis of damage detection through the ARBOTOM tomograph

Figure 4 illustrates the percentages of the cross-sectional area of individual trees identified by the tomograph as potential damage zones. The tomograph software represents areas where the excited acoustic stress wave propagates at a slower speed as red and purple zones. In our analysis, we considered purple zones as indicative of potential damage.

For oak trees, the average size of the red zone in the cross section was 42.6%, while the purple zone (indicating damage) covered 15.8% of the cross-sectional area of the trunks. In the case of Linden wood, the average area of the red zone was 56.2% of the cross-sectional area, with the purple zone accounting for an average of 16.8% of the cross-sectional area. However, the number of analyzed trunks for pine and fir was insufficient for descriptive statistics.

Table 1 presents the basic descriptive statistical characteristics of the extent of the red and purple zones in the analyzed strains. In the red zone, 95% of all detected dimensions were within 88.5% of the cross-sectional area of the trunk. In the purple damage zone, this figure was 49.9%. The average extent of the zones from the trunk cross-section was 48.34% for the red zone and 16.94% for the purple zone. The extent of the purple zone was significantly correlated with the occurrence and extent of the red zone detected by the tomograph (correlation coefficient $r_{xy} = 0.743$). The extent of the purple and red zones showed only a low indirect dependence on the number of sensors and the thickness of the analyzed trunks (r_{xy} correlations from –0.152 to –0.291). There was also a low direct dependence of the extent of the damaged zones on the height parameter of the tomograph sensors (r_{xy} = 0.027 and 0.062).

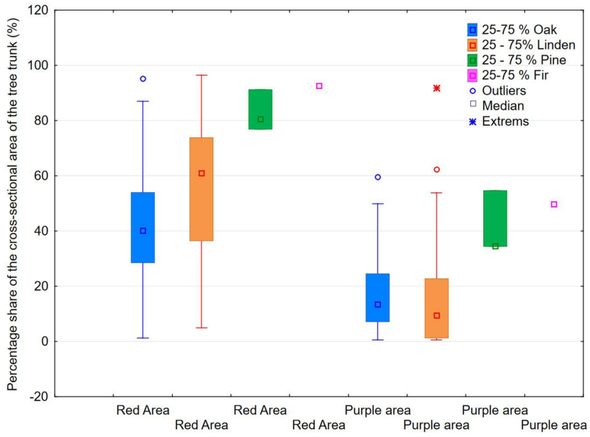

Fig. 4. Percentages of the cross-sectional area of individual zones of potential damage detected by the tomograph for each wood species.

In Figure 5, the number of trunks of individual tree species in classes according to the percentage extent of the purple zone of potential damage from the cross-section of the trunk is subsequently evaluated. It is clear from the

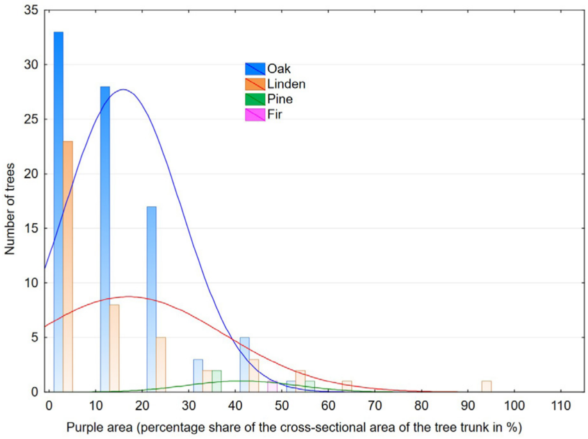

Fig. 5. Histogram of frequencies according to the percentage share of damage (purple zone) from the cross-sectional area of individual wood species identified by the tomograph.

Table 1. Basic descriptive statistics for red and purple areas in analyzed trunks.

	N	Mean	Median	Modus	Quantile 50%	Quantile 90%	Quantile 95%	Std. deviation
Red area	136	48.34	45.250	28.14	45.25	82.50	88.5	23.52
Purple area	136	16.94	13.554	0.70	13.55	40.20	49.9	16.16

results that the highest numbers of trees were with the minimum degree of identified possible wood damage in the cross-section. It concerned the two numerically most represented tree species in the analysis (oak and linden). For both types of trees, the highest number of trees was detected with a damage zone in the interval 0–10%. In total, 33 analyzed oak tree trunks and 23 analyzed linden tree trunks belonged to this category (more than 41% of all analyzed trunks). A higher degree of damage (over 50% of the purple zone from the cross-section area) was identified only in 6 trees (4 Linden trees, and one oak and pine tree each).

3.2. Comparative qualitative analysis of harvested trees

From the trees analyzed with an acoustic tomograph, 17 individuals (13 lindens and 4 oaks) were harvested at the turn of 2023/2024 by the planned harvesting intervention. The results of the image analysis of the outputs from the acoustic tomograph were compared with the results of the image analysis of harvested individuals. In the case of the occurrence of qualitative features that are measured and evaluated based on the surface area of the cross-sectional area of the end of the trunk (e.g., rot, discoloration, etc.), these features were also measured under the procedure established according to STN EN 1309-3. The results of this analysis were also compared. A comparison of the analysis of the occurrence and extent of damage to individual tree trunks that were harvested is presented in Table 2.

Table 2. Assessment of identified trunk damage based on the proportion of damaged area from image analysis and manual measurement.

Nr.	Tree species	Share of identified damage by individual method in %		
		Arbotom	Digital image	STN EN 1309-3
1	Linden	53.9	0	0
2	Linden	1.2	1.53	19
3	Linden	62.4	68.9	63.8
4	Linden	40.2	1.14	4.4
5	Linden	18.2	0	0
6	Linden	28.7	1.09	2.7
7	Linden	9.5	0	0
8	Linden	1.6	1.58	18.33
9	Oak	33.7	0.81	0
10	Linden	0.8	0.26	0
11	Oak	49.9	12.5	34.2
12	Linden	13.8	0	0
13	Linden	17.4	0	0
14	Oak	25.9	50.97	59.6
15	Linden	12.8	8.72	30.6
16	Oak	7.6	0	0
17	Linden	22.7	0	0

When comparing individual methods, relatively large differences are evident. Visualization of the differences in the assessment of areas of damage by qualitative features by individual methods, as a percentage of the cross-sectional area, is shown in Figure 6. On average, the tomograph overestimated the extent of damage by qualitative features compared to the assessment from the digital image by 14.9%. Since the assessment according to STN EN 1309-3 takes into account the area of the circle that describes the given qualitative feature and its subsequent share of the cross-section of the end of the trunk, it can be concluded that this method will almost always overestimate its surface area compared to the real

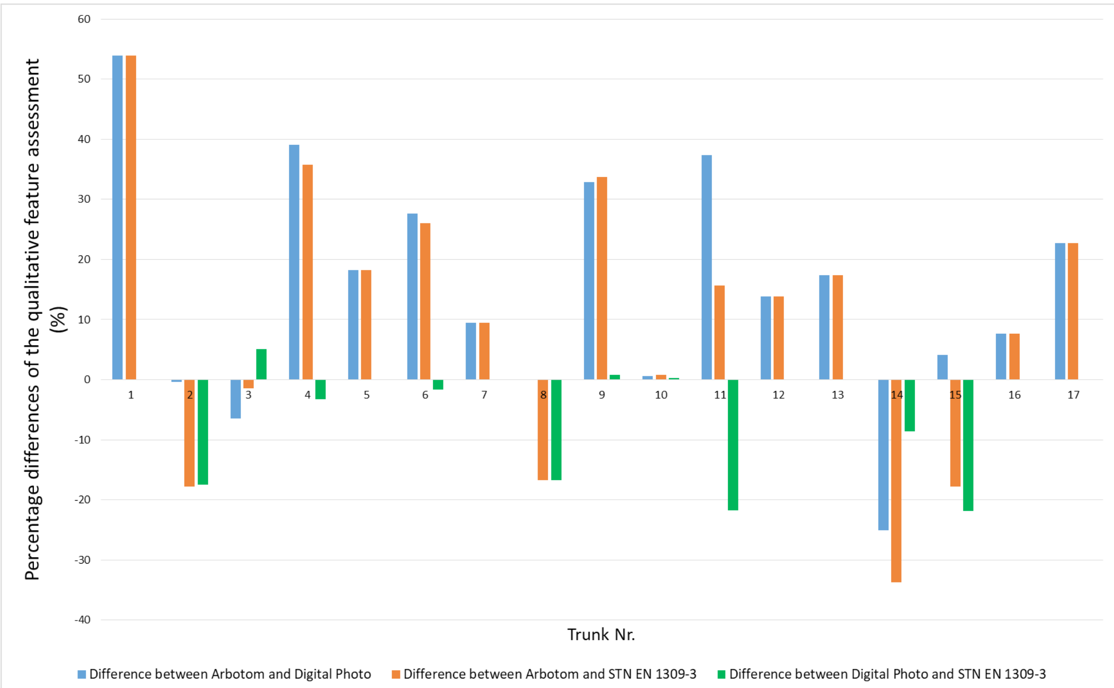

Fig. 6. Comparison of qualitative feature area differences between Arbotom, Digital Photo, and STN EN 1309-3 assessments.

area of the feature. Based on this, the average difference between damage assessment by the tomograph and damage assessment according to this standard is also lower. The average deviation was 9.9%. When comparing the assessment based on image analysis from a photograph and manual measurement according to the standard, the previously mentioned systematic overestimation was on average 5% higher in the assessment according to STN EN 1309-3.

4. Discussion

The primary aim of the expert assessment was to conduct a qualitative analysis of 136 trunks within the forest area of the Center of Excellence LignoSilva. Qualitative features are evaluated either based on their precise size and surface area within the wood, or their direct occurrence is noted. Many features evaluated based on their areal extent consider their coverage from the cross-sectional area, such as rot, wood discoloration, reaction wood, false core, etc. These features are relatively common regardless of the wood type (Gejdoš et al. 2021). However, the methodology prescribed by legislation often leads to a direct overestimation of the areal occurrence of these features compared to their actual area (Gejdoš et al. 2014).

The broad spectrum of damage within standing trees allows for diagnosis using non-destructive, semi-destructive, and destructive methods. Evaluation based on the speed of propagation of an acoustic wave, assessed by an acoustic tomograph, is already a well-known and frequently used method. When tested on samples of extracted tree trunk parts, it showed relatively good agreement with the actual situation, with an average difference of only 0.97% (Gejdoš et al. 2023b). However, when assessing health and quality features, the tomograph may not provide as accurate results due to factors such as the mutual position of sensors, their number during analysis, wood type, etc. To improve these results, optimization mathematical algorithms were tested for some tree species, yielding more precise outcomes (Du et al. 2024). It has also been shown that there are significant differences between computed tomography and acoustic tomography. While both methods can be compared and are complementary to each other, acoustic tomography provides good results even in detecting rods and wood, which differ in cross-section mainly in moisture content (heartwood/sapwood) (Brüchert et al. 2013).

In our study, the tomograph overestimated the area of damage by an average of 15% compared to evaluation according to the standard, which showed a 10% overestimation. The tomograph exhibited greater discrepancies when identifying damage in oak wood. However, this observation holds true only under the specified conditions. In the work by Liang & Fu (2014), it was shown that increasing the number of sensors can significantly improve the accuracy of the results provided by the acoustic tomograph. In the future, the principle should be that the minimum number of sensors used in the analysis should be 10, with more than 12 being optimal. The accuracy of detecting qualitative features located closer to the surface of the tree trunk can also be significantly improved by the hybrid use of the acoustic-laser technique. A new distribution of sensors can be adopted based on the near-surface response detected by the acoustic laser technique, resulting in a more reliable image of the tree trunk using sonic tomography (Qin et al. 2018).

When analyzing palm trees with an acoustic tomograph and verifying the results with micro-drilling, Lin et al. (2011b) found that for deeper internal damage, the tomograph underestimated the damage levels, while for signs of damage near the surface of the trunk, it overestimated them.

5. Conclusions

In our case, the acoustic tomograph tended to overestimate the areas of damage. However, there remains the potential for refining the results by utilizing a larger number of sensors and conducting a more detailed analysis, along with an external visual assessment of the standing tree. The method of qualitative assessment using an acoustic tomograph places high demands on the technician, who must accurately depict the shape of the tested trunk in the cross-section where the measurement is conducted. Additionally, the accuracy greatly relies on the user's experience and the precision of image analysis performed by software. Nevertheless, this does not alter the overall perspective on acoustic tomography, which serves as a valuable predictor in assessing the health status of trees and their susceptibility to potential mechanical destruction from adverse environmental conditions. However, this method exhibits rather unsatisfactory results for a precise and detailed evaluation of the internal qualitative characteristics of the trunk and subsequent classification into quality classes.

Improvements to the method's inaccuracies can be achieved not only through the aforementioned methodical measurement approach but also through optimization using mathematical algorithms. As the evaluation of the qualitative state of standing trees in forest stands becomes increasingly important in the future, this method can serve as a key component of automation methods within precision forestry.

By integrating this method with laser ground scanning, digital evidence, and the development of appropriate mathematical algorithms or trained neural networks, it becomes feasible to establish an automated system for assessing the quality of trees in forest stands. This would subsequently enhance record-keeping, facilitate harvesting activity planning, inform marketing strategies, and streamline the trade process for harvested wood.

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