INSIGHTS AND LIMITATIONS OF ACOUSTIC STRESS TOMOGRAPHY IN FORESTRY APPLICATIONS

[a)]Miloš Gejdoš, [a)]Katarína Michajlová, [b)]Miroslav Němec

[a)]Technical University in Zvolen, Faculty of Forestry, Department of Forest Harvesting, Logistics and Ameliorations, Zvolen, Slovakia, gejdos@tuzvo.sk, michajlovakatarina@gmail.com
[b)] Technical University in Zvolen, Faculty of Wood Sciences and Technology, Department of Physics, Electrical Engineering and Applied Mechanics, Zvolen, Slovakia, nemec@tuzvo.sk

Abstract: Effective wood evaluation necessitates a thorough consideration of technical parameters, including both quantitative and qualitative features. The study aimed to practically verify the accuracy and applicability of the ARBOTOM acoustic stress tomograph under various forestry operations and research conditions. The tomograph was tested in a forest stand and a poplar plantation. A total of 165 standing tree trunks were evaluated using the acoustic tomograph: 108 oaks, 53 lindens, 4 pines, 1 fir in the forest, and 2 poplar trunks at the plantation. The median value for damage identified in the red color spectrum was 41.4% for oak and 58.3% for linden. In the violet color spectrum, the median values for damage were 13.75% for oak and 9.5% for linden. The results also indicated that the number of sensors did not significantly affect the identification of the extent of red or violet damage zones. The application on poplar trunks showed that the tomograph is not suitable for very thin trunks with naturally thinner wood. Integrating these technologies into forestry operations could help create favorable conditions for the use of modern information technologies in conjunction with the sustainable management of forest resources.

Keywords: quality of wood, acoustic stress wave, impulse tomograph, image analysis

1. INTRODUCTION

Accurately determining the value of wood is essential for the forestry industry, as wood sales constitute a significant portion of its revenue. Effective wood evaluation necessitates a thorough consideration of technical parameters, including both quantitative and qualitative features. Furthermore, it is crucial to account for negative factors such as diseases, damage, and growth abnormalities, which can impact the wood's intended use and overall economic value. These aspects underscore the importance of precise measurement and evaluation in determining the final worth of wood [1].

Various methods are available for the qualitative assessment of wood, categorized by their degree of invasiveness into destructive, semi-destructive, and non-destructive techniques, each employing different operational principles [2]. However, assessing the quality of standing trees poses significant challenges. Current evaluation methods often involve a high degree of subjectivity on the part of the evaluator or rely on time-consuming approaches that necessitate the extraction of wood samples, particularly in the case of destructive methods. This complexity highlights the need for more reliable and efficient strategies for evaluating wood quality, ensuring that all relevant factors are taken into account to enhance accuracy and objectivity in valuation.

A quick and relatively accurate alternative is semi-destructive and non-destructive methods based on acoustic tomography or measuring the resistance of penetration inside the trunk. Both methods demonstrate a relatively high correlation in identifying internal damage in standing trees [3]. However, the complexity of internal qualitative features can significantly impact the accuracy of the results. Tomographs that operate on the same principle but are made by different manufacturers may show considerable differences in accuracy [4]. When used by experienced operators, these devices can achieve an accuracy level of 90% in detecting quality features and 83% in determining their location [5]. Most existing studies focus on the deployment of these devices in forest stands or plantations [6]. Assessing the quality of standing trees remains challenging, often involving a high degree of evaluator subjectivity or requiring time-consuming, destructive methods tied to wood extraction. In some cases, it has been found that the acoustic tomography method tends to overestimate the area affected by damage while underestimating the extent of healthy wood, compared to the real state [7]. This study aimed to practically verify the accuracy and applicability of the ARBOTOM acoustic stress tomograph under different forestry operations and research conditions.

2. MATERIAL AND METHODS

2. 1. Measurement equipment

For field measurements, an ARBOTOM acoustic tomograph from Rinntech (Germany) was used, in a technical version with 24 sensors (further technological modifications can be 6, 12, and 18 sensors) with Arbotom v2 software. The measurements were carried out from 2022 to 2024.

The freely available ImageJ software was used for image analysis and graphic evaluation, and the STATISTICA 12.0 software was used for statistical evaluations.

2. 2. Tested applications

The tomograph was tested under conditions of non-homogeneous and uneven forest stand at the National Forestry Center. The research area is located in the Zvolen - Stráže region, within forest district Budča I., forest stand no. 911, which covers an area of 1.47 hectares and consists of two layers with diverse vegetation. Economically, the area is classified as a forest of special purpose, designated for forestry research and education. The tree composition is predominantly deciduous, including Winter oak (*Quercus petraea*) (63%), Small-leaved linden (*Tilia cordata*) (15%), Hornbeam (*Carpinus betulus*) (15%), Summer oak (*Quercus robur*) (5%), and Scots pine (*Pinus sylvestris*) (2%).

A total of 165 standing tree trunks were evaluated using the acoustic tomograph in this forest: 108 oaks, 53 lindens, 4 pines, and 1 fir.

The second round of testing took place at a purpose-built facility of the Technical University in Zvolen (Arboretum Borová hora) on aspen poplar (*Populus tremula*) clones labeled T-14. The tomograph was verified on two trunks of these clones.

The measurement methodology remained consistent across all experiments, following the procedures specified in the tomograph's operating instructions. The results of the measurements were visualized as tomograms generated by the tomograph's software.

2. 3. Image analysis

The methodology for analyzing qualitative features using ImageJ software was adapted from the paper [8]. The process involves manually marking the area of the cross-section and the area of the qualitative feature depicted in the tomograms.

3. RESULTS

3. 1. Identified areas of damage

The sample size for fir trees (1 specimen) and pine trees (3 specimens) was too small for statistical evaluation. The limited abundance of these species was significantly influenced by the overall tree composition of the forest stand where the experiment was conducted.

The tomograph primarily displays the speed of propagation of the generated acoustic wave using a color spectrum ranging from the highest to the lowest speed. The color code is as follows: green represents healthy wood with high density (where the wave propagation speed is highest), yellow and orange indicate healthy wood with lower density, red signifies the limit value for potentially damaged wood, and purple indicates significantly lower density and wood rot damage (where the wave speed is the lowest) – see Fig. 1.

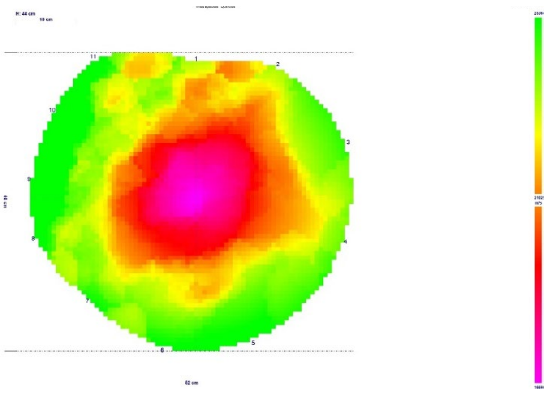


Fig. 1: Image of the assessed tree from Arbotom v2 software

Image analysis of the tomograph output was used to determine the percentages of the cross-sectional areas corresponding to the red and purple zones, which indicate potential internal damage in the trunks of standing trees. The results of the statistical analysis of these proportions are presented in Fig. 2.

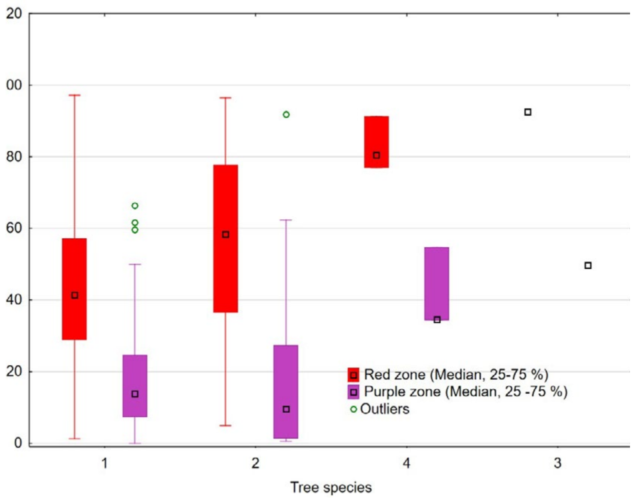


Fig. 2: Analysis of damaged zones detected by tomograph in red and purple zone on standing tree species (1 – Oak, 2 – Linden, 3 – Fir, 4 – Pine)

The median value for the red zone was 41.4% for oak and 58.3% for linden, while the identified ranges for the purple zone were significantly lower. The median value for the purple zone was 13.75% for oak and 9.5% for linden. Based on subsequent verification of some affected individuals and similar research conducted in other studies [1-2], it can be inferred that damage is more likely to occur in the purple zone.

3. 2. Analysis of the effect of the number of sensors on the accuracy and extent of detected damage

Figure 3 presents ternary graphs showing the parameters of the identified zones of potential damage, trunk circumference, and the number of sensors for individual tree species. Individual zones for the fir tree could not be drawn since only one tree was measured.

The results indicate that the number of sensors did not significantly impact the identification of the extent of the red or purple damage zones. The range of these zones increased only slightly with the number of sensors. In most analyzed trees, the number of sensors ranged from 6 to 10 (corresponding to the orange to dark red zones). The extent of damage was more significantly influenced by the trunk circumference; as the circumference increased, so did the extent of the identified red and purple zones in the trunk cross-section.

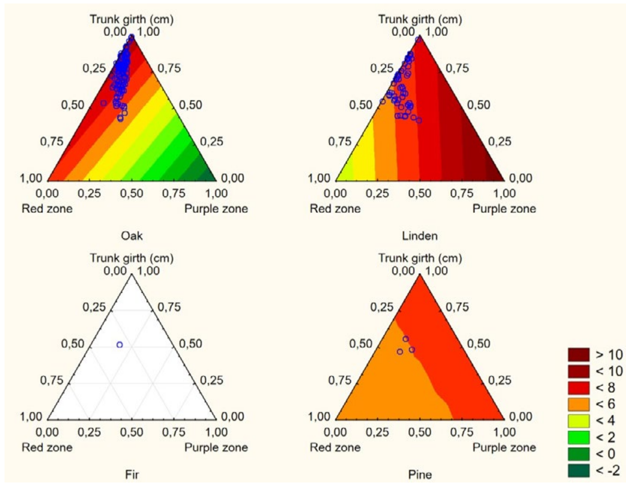


Fig. 3: Ternary plots for the damaged zones and trunk girth according to used number of sensors

3. 3. The use of a tomograph in a plantation of fast-growing trees

To verify the suitability of using the tomograph on thinner individuals of fast-growing trees, two Populus tremula specimens with diameters of 13 cm and 15 cm were selected, representing the average thickness of all individuals in the research area. Four sensors were placed on each trunk. Although these trees were demonstrably healthy, the tomograph indicated a relatively high proportion of damage in the violet spectrum (Fig. 4).

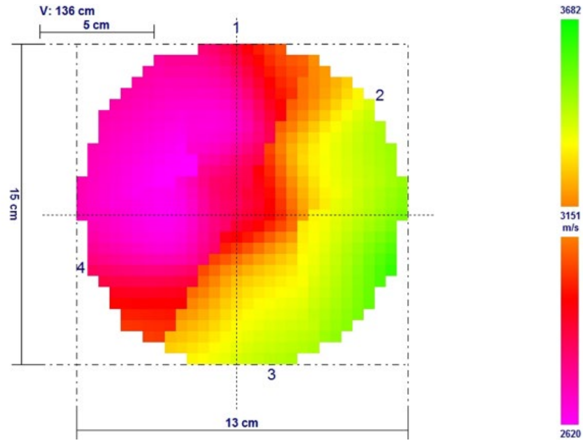


Fig. 4: Analyzed poplar trunk with 13 cm thickness

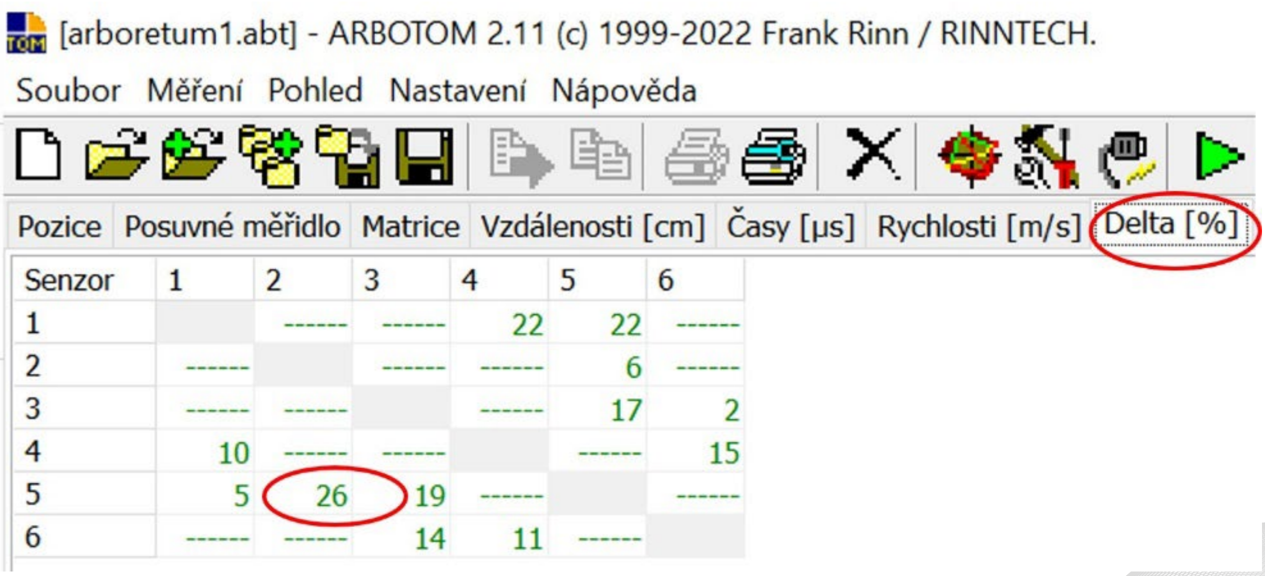
The Arbotom software evaluates statistical deviations in acoustic wave propagation speeds between individual sensors (Delta in %). According to the manual, if this deviation exceeds 10%, the measurement cannot be considered valid. In both cases, the measurements showed statistical deviations exceeding 20% (with maximum deviations of 26% and 22%), rendering the tomograph unreliable for small tree diameters (Fig. 5).

This application demonstrates that the tomograph is unsuitable for use on very thin trunks, which also have physiologically thinner wood. Therefore, it is not recommended to use the tomograph for qualitative analysis of individuals with a trunk thickness of less than 20 cm.

The reliability of the acoustic tomograph method can also be influenced by the software algorithms used to calculate wave speeds for different wood types. In addition to wood types, factors such as relative humidity, season, atmospheric conditions, provenance, and variations among wood species and subvarieties can also affect wave propagation speed.

4. DISCUSSION

Current research focuses primarily on developing optimization algorithms to enhance the accuracy of identified qualitative features and on creating neural networks to improve the results provided by the tomograph. The work of the authors [3] confirmed that an appropriately chosen mathematical algorithm can significantly enhance the tomograph's results. In their study of acoustic tomography on oak trees in Croatian conditions, the authors found an 80-90% agreement between the identified internal damage in standing trees and the actual extent of damage after felling.



Senzor	1	2	3	4	5	6
1		------	------	22	22	------
2	------		------	------	6	------
3	------	------		------	17	2
4	10	------	------		------	15
5	5	26	19	------		------
6	------	------	14	11	------	

Fig. 5: Detected error by tomograph on poplar trunk

The acoustic tomography method tended to underestimate the area of healthy wood and overestimate the presence of incipient wood rot compared to the actual cross-section conditions, while accurately representing the area of active degraded wood and cavities [7].

When using a different type of PICUS® tomograph, it was found that the structure of the individual qualitative features detected by the device can significantly impact its accuracy. Acoustic tomography tends to underestimate heartwood decay when it is the primary structural quality feature of tree trunks. Conversely, when internal cracks are present, acoustic tomography often overestimates their size. The presence of exfoliating cracks in the cross-section creates acoustic shadows, which can mimic the appearance of extensive heartwood decay and lateral cracks [9].

Another study confirmed that increasing the number of sensors and their positioning can enhance the accuracy of identifying quality features, particularly in cases of centric defects [10].

Acoustic tomographs commercially available for tree assessment have two main disadvantages [11]. First, the properties of the 'input signal' of the acoustic shock wave are unknown due to variable hammer impacts on the sensors and frequencies that may not always provide the necessary resolution [12]. Although higher frequencies are expected to yield better resolution, they are attenuated by the anisotropic and highly elastic behavior of wood and frequency dispersion [13]. Consequently, the frequency response is influenced by filtering (transfer functions) from both the transmitting and receiving transducers in the sensors, as well as the coupling medium.

Wang et al. (2007) [14] recommend using at least 12 sensors for trunks between 20 cm and 40 cm in thickness to ensure 'high accuracy.' They suggest 10 sensors for assessing the possible localization of quality features, while 6 sensors are sufficient to detect the existence of a quality feature without determining its location or size. In our case, we consistently used at least 6 sensors; however, they did not always reliably confirm the presence of a quality feature. To enhance accuracy, interpolation methods can be employed, which operate on the principle of image interpolation after reconstruction or projection data interpolation before inversion [15]. For effective interpolation, the data must be precise, and the number of experimental measurements must be sufficient to observe the desired properties, as interpolation does not create new information.

The number of sensors should be selected to maximize the number of measurements taken from the tree trunk, thereby ensuring a rich data set. If the number of acquisitions is low, the output resolution may need enhancement, making interpolation necessary. From a practical perspective, the optimal inversion algorithm should be chosen based on its performance and time efficiency. The goal is to achieve outputs with higher resolution—characterized by fewer artifacts and a higher signal-to-noise ratio—despite a low number of acquisitions. Therefore, reconstruction algorithms should be tailored to the specific experimental conditions and technical capabilities of the device [11].

5. CONCLUSION

Practical deployments of the acoustic tomograph for detailed assessments of the quality state and features of standing trees have revealed certain limitations in identifying the extent and location of specific quality features. The accuracy of the device in determining the range of quality features and classifying potential assortments into quality classes appears insufficient for this application. However, this equipment was primarily developed to detect the existence of qualitative features and assess their potential impact on the stability and overall health of the evaluated tree.

Several factors can influence accuracy, including the frequency used, the signal-to-noise ratio, the number of sensors and their placement, and the inverse algorithms employed. In addition to a methodical approach and practical field applications, utilizing optimization algorithms and trained neural networks can further enhance accuracy.

Evaluating the internal qualitative state of standing trees in precision forestry will present a technological challenge in the future, particularly regarding the simplicity and speed of device use. A combination of various technological and technical approaches—

such as integrating laser ground scanning with acoustic tomography—will be necessary for improved accuracy. This integration could automate the qualitative assessment process and reduce errors stemming from subjective human evaluations. However, the necessary technical resources remain relatively high in acquisition costs.

This approach has the potential to improve timber records, enhance strategic planning and logging interventions, and optimize business strategies in the trade of quality raw wood assortments. Integrating these new technologies into forestry operations could foster the sustainable use of forest resources while leveraging modern information technologies.

ACKNOWLEDGEMENT

This research was funded by the Slovak Research and Development Agency (Grant Numbers APVV-22-0001) and Ministry of Education, Science, Research and Sport of the Slovak Republic (Grant Number KEGA 004TU Z-4/2023 and KEGA 003TU Z-4/2024).

REFERENCES

[1] Gejdoš, M., Suchomel, J., Danihelová, Z.: Analysis of Qualitative Features of Beech and Oak Trunks as a Determinant of the Quality Assessment, FORESTS, ISSN 1999-4907, MDPI, Basel, VOLUME 12(1), p. 15, 2021, DOI: 10.3390/f12010015

[2] Ondrejka, V., Gergeľ, T., Bucha, T., Pástor, M.: Innovative methods of non-destructive evaluation of log quality, CENTRAL EUROPEAN FORESTRY JOURNAL, ISSN 2454-034X, National Forest Centre, Zvolen, VOLUME 67, p. 3-13, 2020 ,DOI: 10.2478/forj-2020-0021

[3] Papandrea, S. F., Cataldo, M. F., Zimbalatti, G., Proto, A. R.: Comparative evaluation of inspection techniques for decay detection in urban trees, SENSORS AND ACTUATORS A-PHYSICAL, ISSN 0924-4247, Elsevier, Lausanne, VOLUME 340, p. 113544, 2022, DOI: 10.1016/j.sna.2022.113544

[4] Cristini, V., Tippner, J., Vojácková, B., Paulic, V.: Comparison of Variability in Results of Acoustic Tomographs in Pedunculate Oak (Quercus robur L.), BIORESOURCES, ISSN 1930-2126, North Carolina State University, Raleigh, VOLUME 16(2), p. 3046-3058, 2021, DOI: 10.15376/biores.16.2.3046-3058

[5] Ostrovsky, R., Kobza, M., Gazo, J.: Extensively damaged trees tested with acoustic tomography considering tree stability in urban greenery, TREES-STRUCTURE AND FUNCTION, ISSN 0931-1890, Springer, Heidelberg, VOLUME 31(3), p. 1015-1023, 2017, DOI: 10.1007/s00468-017-1526-6

[6] Angulo-Ruiz, W. E., Fasabi-Pashanasi, H., Rengifo-Pérez, C. P., Valdivia-Marquez, L. N.: Non-destructive technique based on acoustic tomography for the identification of internal defects in trees, SCIENTIA AGROPECUARIA, ISSN 2077-9917, Univ. Nacl. Trujillo, Trujillo, VOLUME 12(1), p. 65-71, 2021, DOI: 10.17268/sci.agropecu.2021.008

[7] Paulic, V., Skarica, T., Drvodelic, D., Orasnic, M.: Acoustic tomography assessment of decay in sessile oak trees, SUMARSKI LIST, ISSN 0373-1332, Croatian Forestry Society, Zagreb, VOLUME 146(1-2), p. 19-30, 2022, DOI: 10.31298/sl.146.1-2.2

[8] Gejdoš, M., Suchomel, J., Potkány, M.: Software „Image J" Application in Evaluating the Quality of Extracted Raw Wood Assortments, DRVNA INDUSTRIJA, ISSN 0012-6772, Faculty of Forestry, Zagreb, VOLUME 65(2), p. 105-113, 2014, DOI: 10.5552/drind.2014.1348

[9] Wang, X. P., Wiedenbec, J., Liang, S. Q.: Acoustic Tomography for Decay Detection in Black Cherry trees, WOOD AND FIBER SCIENCE, ISSN 0735-6161, Society of Wood Science and Technology, Monona, USA, VOLUME 41(2), p. 127-137, 2009

[10] Espinosa, L. F., Arciniegas, A. F., Prieto, F. A., Cortes, Y., Brancheriau, L.: Standing tree decay detection by using acoustic tomography images, TWELFTH INTERNATIONAL CONFERENCE ON QUALITY CONTROL BY ARTIFICIAL VISION, ISSN 0277-786X, Society of Photo-Optical Instrumentation Engineers (SPIE), Bellingham, USA, VOLUME 9534, 953404, 2015, DOI: 10.1117/12.2182915

[11] Arciniegas, A., Prieto, F., Brancheriau, L., Lasaygues, P.: Literature review of acoustic and ultrasonic tomography in standing trees, TREES-STRUCTURE AND FUNCTION, ISSN 0931-1890, Springer, Heidelberg, Germany, VOLUME 28(6), p. 1559-1567, 2014, DOI: 10.1007/s00468-014-1062-6

[12] Nicolotti, G., Socco, L. V., Martinis, R., Godio, A., Sambuelli, L.: Application and comparison of three tomographic techniques for detection of decay in trees, ARBORICULTURE & URBAN FORESTRY, ISSN 2155-0778, International society of Arboriculture, Atlanta, USA, VOLUME 29(2), p. 66-78, 2003, DOI: 10.48044/jauf.2003.009

[13] Bucur, V.: Acoustics of Wood, ISBN 978-3-540-30594-1, Springer Berlin, Heidelberg, Germany, p. 394, DOI: 10.1007/3-540-30594-7

[14] Wang, L. H., Xu, H. D., Zhou, C. L., Li, L., Yang, X. C.: Effect of sensor quantity on measurement accuracy of log inner defects by using stress wave, JOURNAL OF FORESTRY RESEARCH, ISSN 1993-0607, Springer Nature, Berlin, Germany, VOLUME 18(3), p. 221-225, 2007, DOI: 10.1007/s11676-007-0045-5

[15] Tomikawa, Y., Iwase, Y., Arita, K., Yamada, H. Non-destructive inspection of a wooden pole using ultrasonic computed tomography, IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, ISSN 1525-8955, Institute of Electrical and Electronics Engineers, Piscataway, New Jersey, USA, VOLUME 33(4), p. 354-358, DOI: 10.1109/t-uffc.1986.26842

Miloš Gejdoš

Working as Associated professor in specialization „Forestry technique and wood processing“ at the Department of Forest Harvesting, Logistics and Ameliorations at the Faculty of Forestry at the Technical University in Zvolen and as a Researcher at the National Forest Centre in Zvolen. He specializes in research of wood quality, raw-wood assortments assessment and development the market with wood. He is a member of the Slovak Acoustical Society and a full member of the European Acoustics Association.

Katarína Michajlová

Is a graduate of the Faculty of Forestry. She works as Assistant professor at the Department of Forest Harvesting, Logistics and Ameliorations. In the scientific work she deals with the issue of qualitative wood analysis. It analyzes the issue of qualitative features of wood with the new non-destructives methods.

Miroslav Němec

He is working as Associated professor in specialization „Acoustic“ and „Theory of Education of Physics“ at Department of Physics, Electrical Engineering and Applied Mechanics at the Faculty of Wood Sciences and Technology at Technical University in Zvolen. He specializes in research in fields of building acoustic, environmental noise and theory of education of physics. Each year he organizes an international conference with colleagues „Material-Acoustic-Place“ in Zvolen (SK). He is a full member of the Slovak Acoustical Society and of the European Acoustic Association.