Basics of typical resistance-drilling profiles

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Preface

Basics, potential uses and limitations of the resistance-recording drilling method for tree inspection and risk management can best be understood by reviewing its developmental history and technical specifications. These matters are reflected in the different properties of the currently available models of the instrument. In addition to technical specifications, an understanding of wood anatomy and mechanical material properties is required for proper application of this method and reliable interpretation of results.

Manual resistance drilling used by carpenters since the 1920s is not described here because it does not provide recordable data, and thus is not used by professional tree risk assessors.

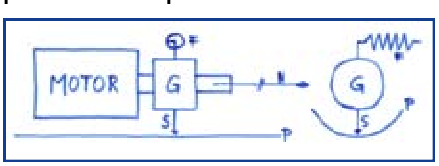
Origin and purpose of resistance drilling

Today, it seems obvious that the penetration resistance of drilling with thin needles (drill bits) can correlate to wood condition. The evolution from concept to development of the first working-prototypes, and finally the current models, however, took quite a bit of time, research, and effort.

Based on the idea of Prof. Gersonde, working at German Federal Material Testing Institute (BAM, Berlin), during the 1970s, the German company WESERHÜTTE AG develop a machine for improving the penetration of preservatives into wooden utility poles by pushing thin needles into the wood to create channels for the chemicals. This method has since become established worldwide, and is known as "In-Sizing". It is especially useful for species like spruce (*Picea*) where wood preservatives do not penetrate well, even under pressure, because the connections between the wood cells close when they dying. The engineer in charge at WESERHÜTTE, Thowald Kipp, observed that some needles broke, while others penetrated quite easily. He concluded that the recorded penetration resistance could tell something about wood condition and strength. WESERHÜTTE, which specialized in large machinery, realized that it was virtually impossible to develop a wood diagnostic method for their application.

Years later, two retired leading engineers of WESERHÜTTE (W. Kamm, S. Voss), got permission from the company to apply for a patent describing the idea of needle resistance-drilling.

Sketch of a KAMM-VOSS-resistance drill from 1984: a scratch pin (S) was fixed at a spring- (F) loaded gear box (G) between the motor and needle (N), creating a 1:1-scaled resistance profile on a wax-paper strip (P) housed within the machine's casing. Resonance and threshold effects due to the spring-loaded recording mechanism delivered systematically incorrect and misleading profiles. Consequently, KAMM and VOSS abandoned this approach and switched to electric recording of the motor's power consumption.

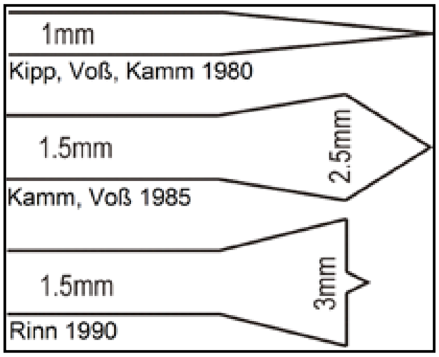


The first series of portable resistance drills were sold to arborists worldwide in 1987. Ehlbeck and Görlacher (1990) proved a linear correlation of its drilling profiles to wood density.

Although this 1985 patent was later declared invalid by the German Patent Supreme Court, it triggered a flurry of development that ultimately led to the first operational resistance drilling machine (Rinn 1986), and the first series of portable drills (Rinn & FEIN 1987).

Although the resistance-drilling method was developed for tree-ring analysis, its ability to detect decay now drives the market.

In 1984, KAMM and VOSS developed a drill that recorded the penetration resistance of a thin needle using a spring-loaded gear box connected to a scratch pin. But, resonance effects of the recording spring mechanism (triggered, for example, by tree-ring density variations) led to inaccurate readings and profiles—too high in late-wood, too low or even zero in softer earlywood. Such misleading spring-resonance effects can be partially reduced by compensation springs. But this introduces stimulus thresholds into the recording system,



A needle shaft diameter of 1.5mm with a flat tip 3mm wide were found to be a good compromise for achieving maximum resolution and stability, while causing the least damage to the sample.

causing another systematic and inherent error—drill resistance values below the threshold are suppressed and not displayed, or plateaus appear in the profile where the curve does not change although the local wood properties are changing.

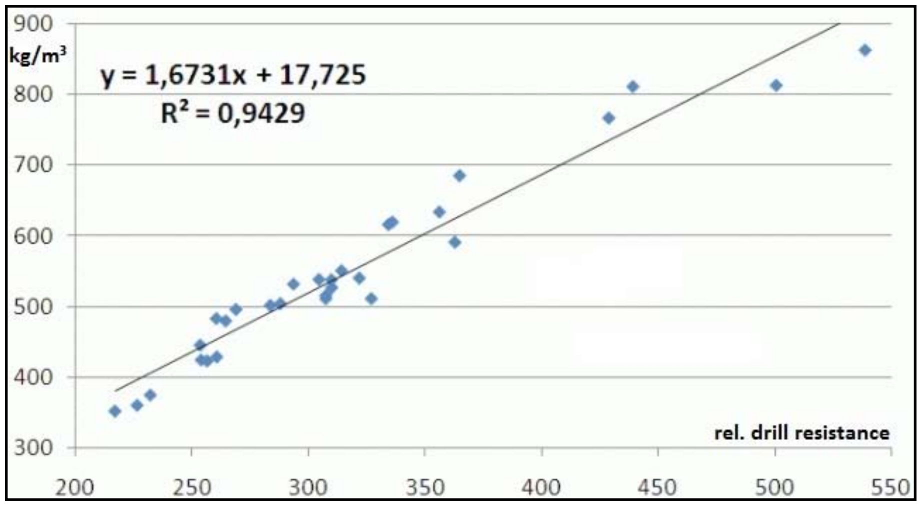
If the spring-recorded profile drops down to zero in soft (but intact) earlywood, for example, this is likely misinterpreted as insect damage or decay. As a consequence, profiles from intact, but soft wood (commonly found in the centers of most conifers or in the sapwood of many other species) are often misinterpreted as being decayed. These mechanically recorded profiles thus had been shown as nonlinear, non-reproducible, imprecise, incorrect and unreliable. And, even more important, such systematically wrong profiles can never be the base for a correct and reliable evaluation of wood condition and stability. Because of that, KAMM and VOSS developed a new drill in 1985 with an electrical recording mechanism, starting with a loud speaker and headphone connected to the drilling motor. They applied for a patent and asked German electric tool companies if they would be interested in buying the intellectual property rights.

With this needle, it was possible to drill up to a depth of 1.5m (~5ft) into old oak trees and still detect tree-rings narrower than 0.5mm (Rinn 1990).

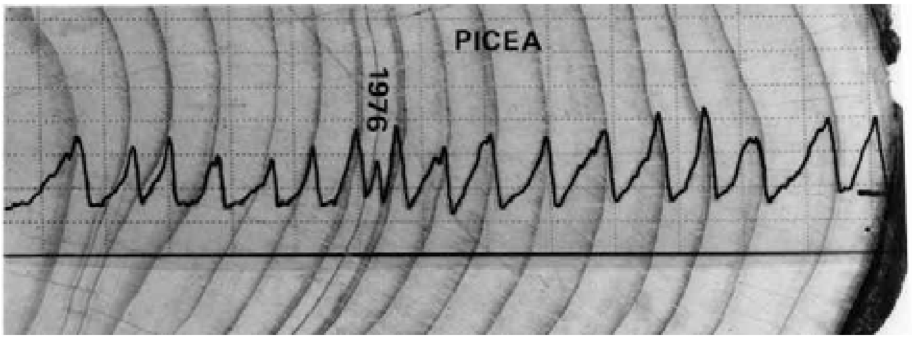
FEIN of Stuttgart/Germany, the company that invented the first electric drilling machine in the 1880s was interested in their offer, but wanted an independent opinion from a University regarding whether the needle resistance method could work. In a joint project of the tree-ring lab at Hohenheim University and the Environmental Physics Institute of Heidelberg University, the resistance drilling idea was then further developed with the aim to measure the intra-annual density variations of tree-rings for climate reconstruction (Rinn 1986-1988). Early measurements clearly showed that electronic regulation and electronic recording of motor power consumption are required to obtain reproducible profiles and reliable results that can be linearly correlated to wood density, as opposed to spring-loaded recordings which were shown to be unreliable and systematically inaccurate.

Technical basics

The power consumption of both electrical motors, one responsible for feed and the other for rotation of the needle, was measured individually and recorded while the needle was moving forward and backward, producing four curves per measurement. Detailed comparative analysis showed that the variations of the power consumption of the feed- motor at constant speed, and of both motors, while pulling the needle backwards did not contain significant additional information (Rinn 1989). Consequently, resistance drills from then on usually measured and recorded the electrical power consumption of a direct-current, needle-rotation motor while penetrating wood. This value is proportional to the mechanical torque at the needle, assuming the motor acts linearly. This requires a correspondingly linear type of electric



Such a high linear correlation between mean value of the resistance-drilling profile and mean density of the penetrated wood (kg/m³) is the basis for reliable evaluation of wood condition by interpreting the displayed curves. It was proven that only drills using electronic regulation and electronic, linear recording without resonance and damping effects (as common in the original spring-recording devices) can accurately measure wood density and deliver profiles that can reliably be interpreted.



If the needle penetrates the tree rings of conifers radially inward (perpendicular to the stem), the profile clearly reveals differences in density between earlywood and latewood. In this profile of a spruce tree felled in 1986, the extremely dry summer of 1976 can be identified by the correspondingly narrow tree-ring with only a few latewood cells.

direct-current motor. If the needle's tip is flat and twice the diameter of the shaft, the torque mainly depends on density at the major point of contact at the needle's 'front line' while penetrating the wood at a high rotational speed (Rinn et.al. 1991). The ratio between rotational speed and thrust was shown to be critical to achieve a high linear correlation to wood density. Only this allows a reliable interpretation of the obtained profiles.

Since the goal was to determine radial density profiles at the highest possible resolution, drill resistance must be measured at one point of the drilling path at a time. Therefore the end of the needle had to be flat. A thin centering tip was added to the end of the needle to guide it along a straight path. Because tree-ring borders are not linear-laminar (arranged in a linear or flat manner, but are concentric or even undulating, the width of the needles tip determines the radial resolution by tangential averaging, and therefore should be as small as possible. A wider needle would not allow the method to detect thin tree rings because the tip would rotate in earlywood and latewood of two or even more rings at the same time. As a result, the measured resistance cannot differentiate between the density of individual earlywood and latewood zones, and it would be impossible to identify thin tree rings. Therefore, for tree ring identification, the needles should be as thin as possible.

The needle had to be kept as narrow as possible to minimize damage to the tree being tested. Unfortunately, thin needles (<1mm) are often deflected by wood rays, knots or other wood anatomical features, and did not maintain a straight path. And for being able to penetrate hardwoods, needles had to be thicker and stronger anyway. After thousands of tests, a shaft diameter of 1.5mm and a 3mm tip was found to be a good compromise between minimizing damage and maximizing information in the profiles (Rinn 1989a; Rinn et.al. 1990).

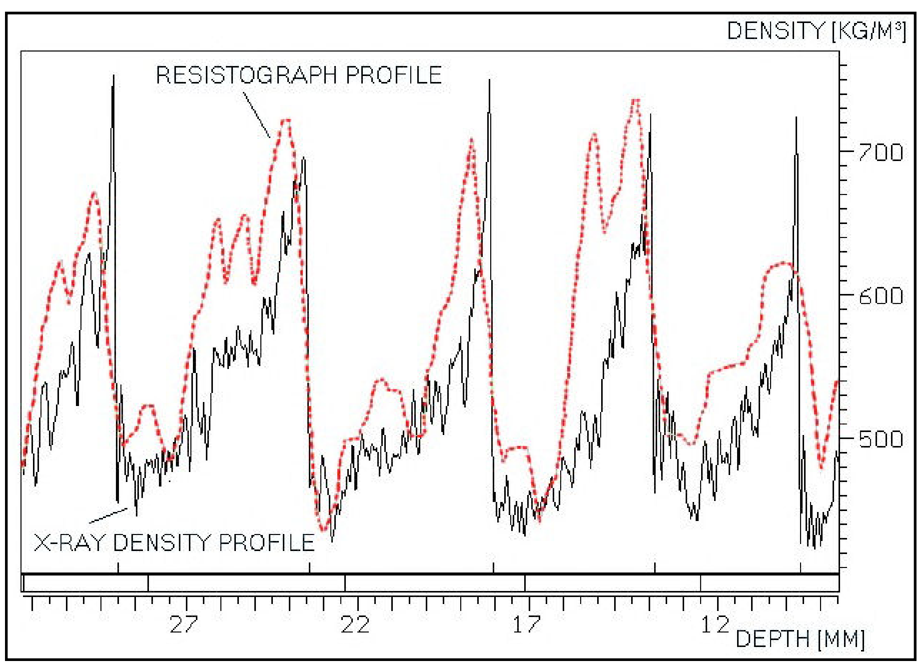
All subsequent profiles used in this document have been obtained using a resistance-drill that records and is regulated electronically. It was also equipped with a flat tipped 1.5/3mm steel needle as described above.

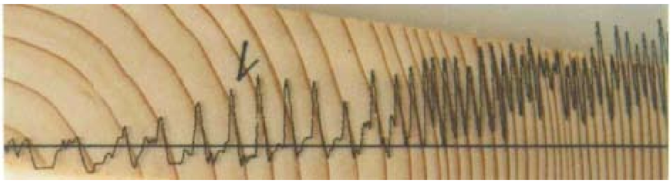
Although the resistance-drilling method was developed for tree-ring analysis, its ability to detect decay now drives the market. Several thousand drills have been sold worldwide since 1987 by different manufacturers, but they differ dramatically in size, weight, resolution, precision, applicability and price. A linear correlation to wood density (as a mandatory pre-requisite for reliable profile interpretation) was demonstrated only for electronically regulated and electronically recording device types (Winnistorfer and Wimmer 1995).

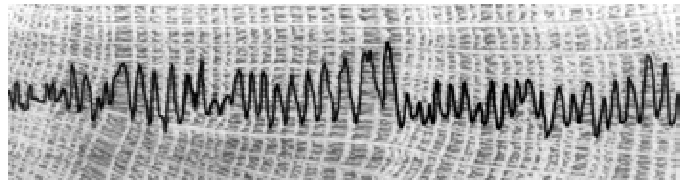
Ability to detect tree rings and decay

If the needle's geometry follows the

This superposition of a radial x-ray-density profile (resolution 1/100mm) of larch (Larix) with a resistance drilling profile shows that local wood density determines the resistance value. The slope of the resistance profile at the tree-ring border represents the resolution limit of detecting tree-ring (~1/10mm) when penetrated perpendicular (Rinn et.al. 1996).







(Left) Wide conifer rings are usually dominated by soft early-wood. Due to an age trend in ring width (Bräker et.al. 1978), conifers (trees, beams and poles) are mostly much softer in the center. The corresponding decline in drill resistance can only be distinguished from a decline due to internal decay if the intra-annual density structures are revealed correctly. This requires a high resolution profile that is linearly correlated to density, which can only be achieved by measuring and recording drill resistance electronically. Otherwise it would lead to misinterpretation and an inaccurate evaluation of trees and timber. Therefore, only machines that provide high resolution and linearly scaled profiles, can be used for reliable evaluations. The use of the early spring-loaded versions had to be abandoned because they lack these capabilities.

(Right) Because earlywood width usually does not vary much, the wider rings of oak (*Quercus*) have denser latewood, leading to a higher mean profile level. In ring-porous trees, narrow rings may consist entirely of earlywood, and thus provide low density readings. Consequently, the resistance-drilling profile is lower for thinner tree rings, and higher for wider tree rings. This reflects the fact that ring-porous trees have a higher density if they are growing faster.

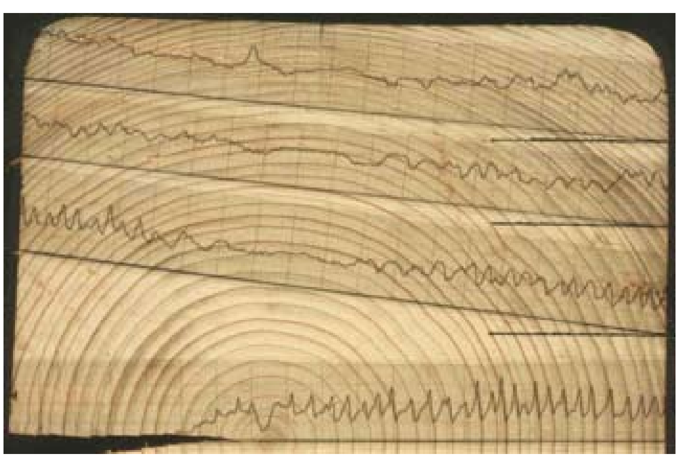
guidelines as described here, local wood density at the point of the needle's tip is the main factor influencing mechanical penetration resistance. Consequently, due to density variations between earlywood and latewood, tree-ring structure and penetration angle determine the shape of the obtained profiles. Therefore, it is necessary to understand basic wood anatomical properties in order to interpret resistance profiles correctly.

In addition to needle geometry and electronic regulation, the drilling angle determines the ability to detect tree rings. Maximum resolution of tree-ring structures is provided by radial drillings so that the needle penetrates the tree-ring borders radially inward (perpendicular to the stem). The more the drilling angle deviates from 90°, the less clear tree rings appear in the profiles.

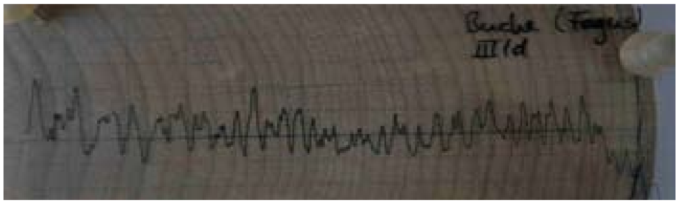
Wood anatomy

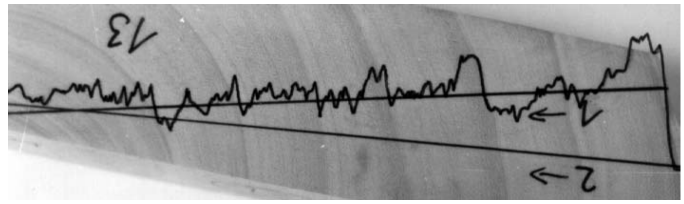
Regarding wood material properties and the cutting mechanism at the needle's tip, local shear strength may be even more closely related to the measured drill resistance value. But, comparison with high-resolution radial x-ray density profiles showed that electronically regulated and recorded resistance-drills produce profiles linearly correlated to local wood density, revealing tree-ring density variations down to a width of about 1/10mm or even less. That is assuming the needle is equipped with

The angle between penetration direction and tree ring borders influences the ability to detect tree rings as shown here for spruce (*Picea*). In areas penetrated tangentially, the profiles cannot show differences between earlywood and latewood. Decay or insect damage can be identified by the drop of the profile below that for the earlywood level. It can be seen here in the bottom profile when the needle penetrates the soft pith and subsequently the crack.



Wide rings of ring-porous trees are dominated by dense latewood. Due to an age-related trend, the wood of ring-porous trees, including stems, branches and beams, is denser in the center. This leads to a corresponding increase drill resistance. Narrow oak (*Quercus*) rings are dominated by soft earlywood, leading to a drop in density and drill resistance profiles. High resolution electronic resistance-drills, thus are mandatory for distinguishing such zones of narrow but intact rings from areas of decay, where the profile drops below that for earlywood. The spring driven recording mechanisms of the early resistance drill models led to resonance fluctuations where the profiles dropped down to zero in earlywood, making it impossible to distinguish between intact but soft and decayed parts.





(Left) In diffuse-porous species, such as beech (*Fagus*), tree ring structures can be clearly visible in the profiles due to changes in wood density between earlywood and latewood. But, there can be tree rings where the tree did not build significant latewood layers thus leading to small or even no variations in parts of the profile. Therefore, it is impossible to determine number and width of tree rings.

(Right) Sometimes, density variations within the ring may be in the same order of magnitude as at the tree ring border, and sometimes latewood is very thin or even absent, so that no peak is obvious in the profile to identify the tree ring as seen in this example from a drilling in poplar (*Populus*).

a flat tip that penetrates the tree-ring borders radially (Rinn et. al. 1996).

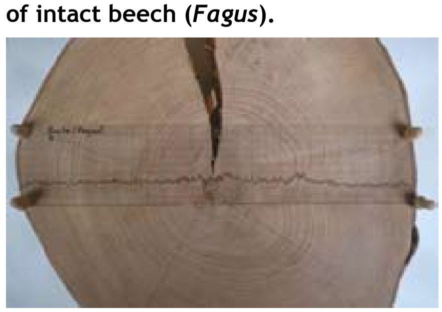
The combination of the following wood anatomical properties determines the appearance of typical radial resistance profiles, which are correlated with density profiles:

- In general, latewood is much denser than early-wood. Wide tree rings are dominated by:
  - earlywood in conifers
  - latewood in ring-porous spe cies
- Due to the age trend, the average ring width declines with tree age and remains at a relatively low level throughout maturity.
- In the case of narrow conifer rings, the relative amount of latewood is higher, and density, as a result, is also higher. Consequently, slow growing conifers are mostly denser and stronger.
- Width of earlywood in ring-porous trees mostly does not show strong variations. Therefore, the relative amount of earlywood is higher in narrow oak rings. The narrowest of oak rings are composed primarily of very soft earlywood. Consequently, the wood of slow growing ring-porous trees is low in density and lacking in strength.
- Wider oak rings contain more latewood and are higher in density. Thus the faster ring-porous trees are growing, the higher their density and the higher the strength of their wood.
- The consequence of slow or fast growth in terms of density is opposite in conifers and ring-porous species.

There are many other consequences of the combination of these wood anatomical properties for tree inspection: conifer stems, for example, are commonly soft in the center and stronger in the outer areas of the cross section, and the opposite applies to oak and all other ring-porous species. Most important for resistance drilling is that radial profiles derived from conifers naturally tend to drop down in the center. This is not a sign of decay and can only be distinguished reliably from a profile drop caused by internal decay, if the profile is linearly correlated to density, and the resolution is high enough to clearly differentiate between earlywood and latewood zones. If the profile drops down below the lowest earlywood resistance level, this indicates decay, a crack, or the pith as shown above.

In ring-porous wood, such as oak (*Quercus*), the profiles commonly are very low in the wet and soft sapwood with narrow rings, containing primarily soft earlywood. They rise up in the center of the cross sections. Again, a high resolution and linear correlation to wood density is required to differentiate between intact but soft sapwood and decay.

Typical radial resistance drilling profile of intact beech (*Fagus*).



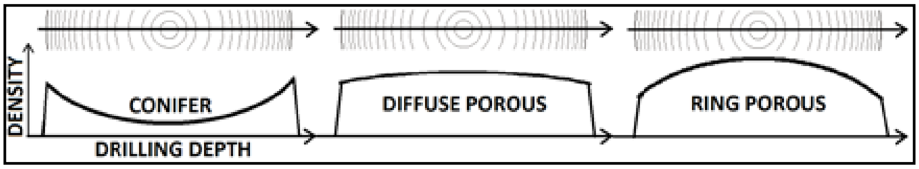
Resistance profiles derived from tropical species without distinct tree rings are similar to most diffuse-porous trees from moderate climate zones, but tend to rise up slightly in the center. Thus, in general, three types of wood have to be distinguished in terms of typical profile shape:

1. temperate conifers
2. temperate ring-porous wood
3. diffuse-porous wood and wood of tropical trees without distinct tree rings

These typical trends have to be taken into account while interpreting resistance-drilling profiles. At the same time, the influence of the angle of the needle's path in relation to the tree-ring borders has to be considered. If a drilling profile cannot be interpreted, a reference drilling further up the stem may help, although the number of drillings should be limited in order to minimize damage to the tree.

Summary

Needle penetration angle in relation to tree-ring borders and wood anatomical properties of the tree species determine the typical shape of the resulting resistance drilling profiles. Only profiles of electronically regulated and electronically recording resistance-drilling machines have been shown to linearly correlate to wood



The anatomical properties for the three wood-type groups (conifers, ring-porous and diffuse-porous trees), in combination with the trend for decreasing ring width with age, are important factors determining the typical radial density trend across stems and branches: These trends lead to typical mean resistance profiles because drilling resistance mainly reflects wood density along the drilling path. This aspect has to be taken into account while interpreting every profile and it underscores how important it is to know the species being tested, and the angle of the needle's path in relation to the tree rings. Individual trees can have different mean profiles, for example if the tree was growing suppressed in early years. When in doubt, a reference drilling at another point on the tree may help. Reference drilling should be done in the same fibers further up or down the stem.

density, allowing the user to interpret correctly and evaluate reliably. Thus, technical properties of resistance drills have to be taken into account before purchasing and using a resistance drill. Proper evaluation requires knowledge about the species-specific typical density trends within the tree rings and along the drilling path. Wood anatomical properties differ strongly between the three wood-type groups (conifers, ring-porous and diffuse-porous trees). These properties influence the resistance-drilling profiles, as well as the mechanical behavior of trees in general. Ring porous trees have the highest strength values in the center, and are much weaker outside. Conifers are just the opposite. This aspect influences all technical measurements of mechanical properties and behavior of trees, not only by resistance drilling but also stress-wave-timing (sonic tomography) and static-load tests. It has to be taken into account while estimating strength and eventual strength loss due to decay (while moisture content plays an important role, too). Thus, high-resolution resistance drilling profiles reveal valuable information about intact and decayed areas, increment growth rates and mechanical properties of wood.

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Some references and further reading:

Bräker, O. U. 1981: Der Alterstrend bei Jahrringdichten und Jahrringbreiten von Nadelhölzern und sein Ausgleich. Mitteilungen der forstlichen Bundesversuchsanstalt Wien 142, S. 75-102

Ehlbeck J., Görlacher, R. 1990: Bohrwiderstandsmessungen an eingebautem Konstruktionsholz. Sonderdruck Sonderforschungsbereich (SFB) 315 (Erhalten historisch bedeutsamer Bauwerke) Universität Karlsruhe.

Görlacher R., Hättich, R. 1990: Untersuchung von altem Konstruktionsholz. Die Bohrwiderstandsmethode. Bauen mit Holz, Juni 1990. Erneuerte Auflage: 1992, Holzbaustatik-Aktuell Juli 1992/2.

Rinn, F. 1988: A new method for measuring tree-ring density parameters. Physics diploma thesis, Institute for Environmental Physics, Heidelberg University, 85pp.

Rinn, F. 1989a: Eine neue Bohrmethode zur Holzuntersuchung. Holz Zentralblatt Nr. 34 (20.3.1989). S. 529 - 530.

Rinn, F. 1989b: Neue Messmethode für Baumuntersuchung und Holzprüfung, Garten und Landschaft 6/89 (3).

Rinn, F. 1990: Device for material testing, especially wood, by drill resistance measurements. German Patent 4122494.

Rinn, F., Becker, B., Kromer, B. 1990: Ein neues Verfahren zur direkten Messung der Holzdichte bei Laub- und Nadelhölzern. Dendrochronologia 7.

Rinn, F., Becker, B., Kromer, B. 1990: Density Profiles of Conifers and Deciduous Trees. Proceedings Lund-Symposium on Tree Rings and Environment, Lund University.

Rinn, F. 1992: Chancen und Grenzen bei der Untersuchung von Konstruktionshölzern mit der Bohrwiderstandsmethode. Bauen mit Holz 9 (1992): S. 745 - 748.

Rinn, F. 1993: Catalogue of relative density profiles of trees, poles and timber derived from RESISTOGRAPH micro-drillings. Proc. 9th Int. Meeting Non-destructive Testing, Madison 1993.

Rinn, F. 1994: Resistographic visualization of tree ring density variations. International Conference Tree Rings and Environment. Tucson, AZ, 1994. Printed in: Radiocarbon 1996, pp. 871-878.

Rinn, F. 1994: One minute pole inspection with RESISTOGRAPH micro drillings. Proc. Int. Conf. on wood poles and piles. Ft. Collins, Colorado, USA, March 1994.

Rinn, F. 1994: Resistographic inspection of building timber. Proc. Pacific Timber Engineering Conference. Gold Coast, Australia, July 1994.

Rinn, F., Schweingruber F.-H., Schär, E. 1996: RESISTOGRAPH and X-Ray Density Charts of Wood. Comparative Evaluation of Drill Resistance Profiles and X-Ray Density Charts of Different Wood Species. Holzforschung Vol. 50 (1996) pp. 303-311.

Winnistorfer, Paul M., Wimmer, Rupert 1995: Application of a drill resistance technique for density profile measurement in wood composite panels. Forest Products Journal, Vol. 45, No. 6, p. 90-93, June 1995.