Key to evaluating resistance drilling profiles

Frank Rinn

Introduction

Since its development in the 1980s, resistance-recording drilling using thin needles has become the most popular technique around the world for detailed inspection of urban trees and timber to determine levels of risk or stability. Thousands of tree risk assessors and timber inspectors typically use this method to detect (hidden) defects or voids. Furthermore, specialized experts, risk assessors, and scientists use resistance drilling to assess wood quality (density), decay compartmentalization, and incremental growth rates. Unfortunately, complaints about inaccurate evaluations of trees based on application of this method are increasing. Most incorrect evaluations of trees and timber we analyzed came from misinterpretations of the measured profiles. The key to understanding this method correctly is explained below.

When reviewing resistance drilling profiles, decay often seems obvious at first glance, but this conclusion may be wrong (**Fig. 1**). It becomes evident when you review the developmental background and technical properties of resistance drilling that there is much to be learned by practitioners before profiles can be accurately and consistently interpreted. This problem is made worse because there are significant differences between the various types of resistance drilling devices on the market. Available devices vary in price, practical application, precision, resolution, and repeatability of the obtained profiles (Rinn 2012). Currently, more than 10 different resistance drills from at least four manufacturers are in use, and they differ significantly in many ways. When the same sample is drilled with different machine types, the profiles may look quite different, suggesting contradictory conclusions about wood condition. In addition, it has to be taken into account that proof of accuracy and reliability shown for one type of resistance drill does not necessarily apply to other drilling device types.

The key to evaluating accuracy and reliability

The test results of a diagnostic device that measures properties of a sample can only be understood and interpreted correctly when it is clear what the results represent, what kind of value or curve is displayed, and what it means. Consequently, a manufacturer has to provide clear information about what his product measures, what this means, and how precise it is. These requirements are clearly specified in many national and international standards, such as ISO 17025 ISO 5725, ANSI/NCSL Z540-2-1997, and DIN 1319. What this means is that there needs to be a clear connection between the measured values and the real (physical) properties of the inspected material. "Wood condition", for example, is not a clear property of a tree or piece of timber. In contrast, density or strength are clearly defined material properties and can be used to characterize important aspects of "wood condition".

In the case of decay detection in wood, the aspects are quite clear:

When reviewing resistance drilling profiles, decay often seems obvious at first glance, but this conclusion is often wrong.

Figure 1. Typical example of a resistance drilling profile where incipient decay is often identified although the wood is completely intact (and the profile demonstrates this). In the center of conifers growing in moderate climate with some cold winter conditions, the central rings are mostly dominated by the low density earlywood. Close to the pith, it happens that the needle penetrates a broad tree-ring trough earlywood tangentially, leading to a relatively long and low profile section. However, as long as the tree-ring-structure is clearly visible and the profile does not drop below the level of the surrounding earlywood zones, this indicates intact wood. This shows how important it is to understand wood anatomy before using such a diagnostic method.

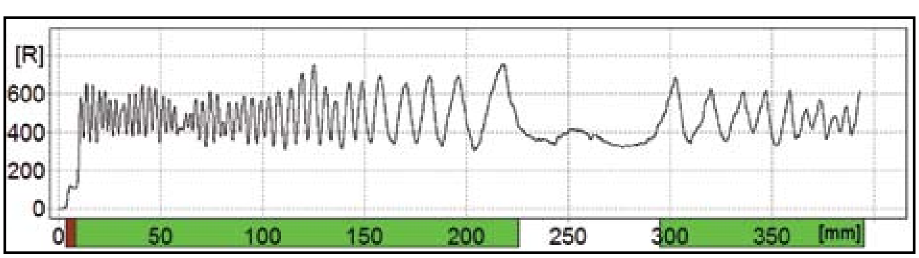


Figure 2. Early stages of brown rot (darker mottling in the light colored earlywood) of *Pinus sylvestris*, caused by *Serpula lacrymans*. Decay often starts by deteriorating earlywood without significantly compromising the latewood. This leads to characteristic local drops in the radial density profiles (Fig. 3). Because even such slight reductions in density can lead to significant strength loss (Wilcox 1977), it is critical that methods for decay detection are able to clearly reveal such alterations of the material. Consequently, such early-stage defects can only be identified by resistance drilling, when the profile highly correlates to wood density and provides a high spatial and signal resolution. The earlywood and latewood zones of tree-rings have to be clearly and correctly differentiated in order to enable the user to identify even incipient decay by changing profile structure.

decomposition of wood due to fungal decay is commonly described by weight-loss of the material, or change in density (Means et. al. 1985). The importance of measuring density precisely becomes clear, considering that with incipient decay, a 10% loss in density can result in 80% loss of wood strength (Wilcox 1977). Unfortunately, strength values of wood can only be measured directly by loading until failure. As this is not practical for tree risk assessors or timber inspection, non-destructive measurements are carried out and strength or load-carrying capacity is estimated from the test results. This estimation is commonly based on correlations. The quality and thus, the precision and reliability of such a correlation is usually characterized by the coefficient of determination (r^2). For linear correlations, r^2=1 means a perfect correlation, r^2~0.5 poor, and 0 indicates no correlation.

Because even slight alterations of wood density can lead to significant strength loss, any method used to determine wood density has to be able to evaluate density as precisely and reliably as possible to assess the stability of trees or timber. Otherwise, the user cannot consistently distinguish between intact and decayed wood. This is not only valid for resistance drilling, but for all technical diagnostic devices. Although 10% weight-loss can lead to 80% loss in tension or bending strength, the change in compression strength is similarly low as for density (**Fig. 2**). Thus, such early stages of decay cannot, in principle, be detected by sounding with a mallet or with sonic-tomography. Even pull-tests (load-tests) cannot detect such decay stages when present on the compression side of loading (because compression strength is little affected until decay is advanced). Therefore, resistance drills have to correctly measure, record and reveal profiles along the drilling path in high signal and spatial resolution, and with a clear and reproducible correlation to wood density in order to enable the user to reliably identify decay.

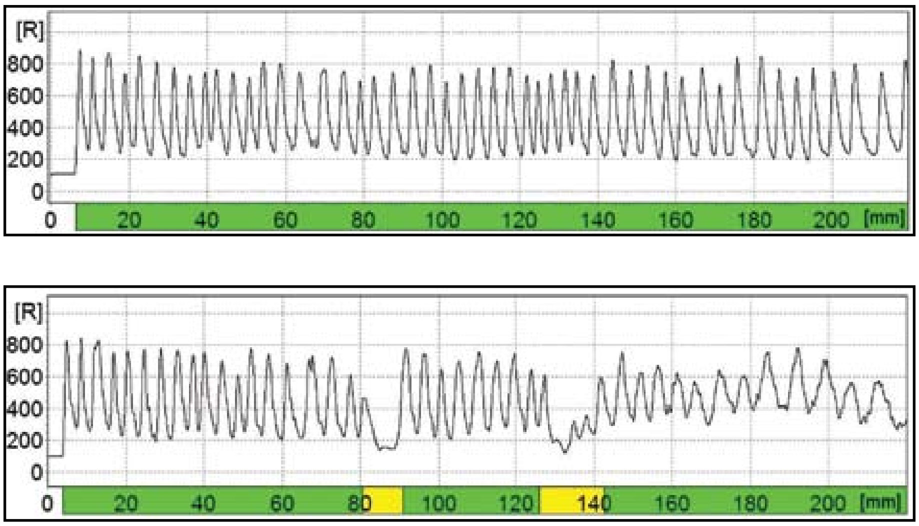
Equally important, the user has to be able to read the profiles and to identify decay by the characteristic changes in the profile curves: the identification of profile sections representing decay is commonly done by comparison with natural and undisturbed curves derived from drillings through intact wood (**Fig. 3**). But, these typical curves are species specific (Rinn 1994) and also depend on drilling location and angle (Rinn 2013). Consequently, learning resistance-drilling starts with understanding wood anatomy and the consequences it has on density, in both typical radial, and tangential planes, as well as in intra-annual fluctuations between earlywood and latewood zones (Rinn 2012).

Fortunately for arborists, the development of the drill-resistance method got pointed in this direction after the two German inventors Kamm and Voss contacted scientists at the Universities of Heidelberg and Hohenheim. They wanted to see if resistance drilling could be used to distinguish earlywood and latewood sections within oak growth increments. The only way to clearly differentiate these intra-annual structures was to measure radial density profiles with the highest possible spatial and signal resolution. The ability of modern resistance drilling devices to detect defects (including incipient decay), thus, was a side effect of a scientific project in dendrochronology. However, modern resistance drill devices have come a long way since the early prototypes. It is important to understand the steps this development had to go through to be able to provide reliable results.

Steps of the technical development

In the early 1980s, the two German engineers Kamm and Voss tried to develop a mobile timber inspection method, starting with an electric motor driving a long, thin, and rotating needle into wood. They used a spring-loaded mechanical recording mechanism to create a penetration resistance profile in 1:1 scale by moving a scratch pin attached to the gear-box between motor and needle over a sheet of pressure sensitive wax paper within the device. As mentioned in their patent application, similar ideas had already been described in the 1960s. But, Kamm and Voss soon realized, that their drill produced systemati-

Figure 3. Two relatively scaled resistance drilling profiles obtained with an authentic RESISTOGRAPH® in Douglas fir (*Pseudotsuga menziesii*). The top profile represents the typical curve derived in an intact cross section. The bottom profile shows early stages of decay like that shown in Fig. 2. The decayed sections (marked in yellow) can clearly be identified by the different profile shape of the tree-ring structure. This is only possible when the resistance drill provides sufficient spatial and signal resolution, and, even more important, is highly and clearly correlated to wood density along the drilling path. For most applications, the profiles do not need to be calibrated, but clearly correlated to density so that the identification of early stages of decay is possible (by comparing with typical tree-ring structures). This is not only important because early decay stages can already be related to significant strength loss (Wilcox 1978). In many applications, detection of incipient decay is even more important for estimation of potential future risk (to quality, strength, or stability). Knowing about the presence of incipient decay and its potential impact on current or future stability, is important to make correct and reliable recommendations on pruning and many other aspects of tree-risk management.

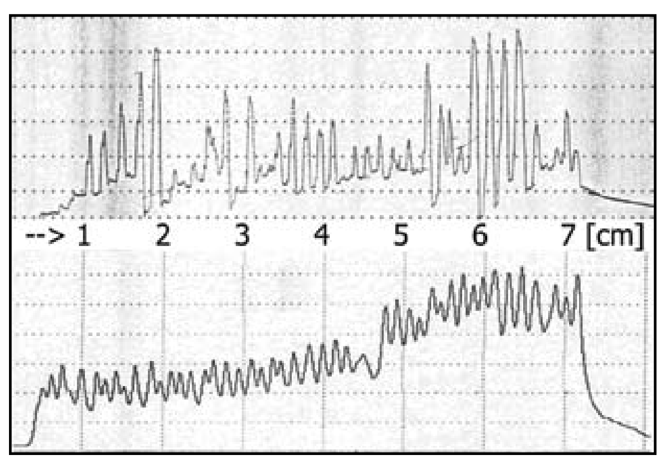


cally incorrect results: "*results obtained with this method are quite inaccurate and allow only rough conjecture about on the internal condition of the tested sample*" (Kamm and Voss 1985). Spring-resonance effects led to fluctuations not correlated to the condition of the penetrated wood. When Kamm and Voss damped misleading resonance effects of the spring-loaded recording mechanism by adding counter springs, this induced damping effects leading to plateau sections in the profiles: the curve stayed on one (mostly low) level without significant fluctuations and did not reflect the real wood condition - both in terms of the absolute level as well as in the intra-annual density variations. This was an additional reason for inevitable misinterpretations with the potential of significant consequences, such as unnecessary felling of trees or unnecessary replacements of utility poles or timber structures.

The two inventors, recognizing these limitations of their early device, understood why scientists and experts were unlikely to accept it and why it would have been irresponsible to market it, considering systematically incorrect results and missing scientific proof of accuracy and reliability. In addition, it would have exposed experts to the risk of being held responsible for consequences of incorrect decisions regarding tree or timber safety due to inaccurate profiles.

Accordingly, Kamm and Voss developed an electrical recording resistance drill, submitted a corre-

Figure 4. Two resistance drilling profiles measured at the same spot in coniferous wood. The bottom profile was measured by a resistance drill using electronic regulation and recording. Following the high correlation to wood density (r^2>0.9), this profile clearly reflects earlywood and latewood zones within the tree-rings. Thus, the profile can be interpreted reliably in terms of growth rates and density, thus wood condition. In contrast, the upper profile fluctuates in a non-systematic way both in trends and in local variations - not clearly correlated to wood density along the drilling path, due to resonance and other effects of the spring-driven mechanical recording mechanism that Kamm and Voss used until 1984. Because similar fluctuations happen when there is decay in the earlywood, cracks or insect damage, it was impossible for Kamm and Voss to correctly interpret profiles using the mechanical spring-driven recording device. This explains why the two engineers developed the electrical regulating and recording resistance drilling (1985).



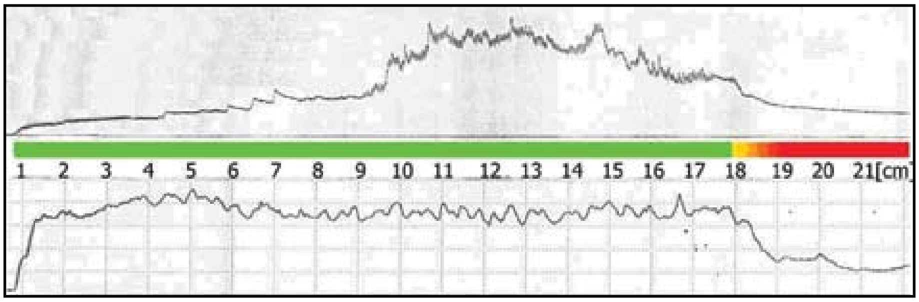


Figure 5. Resistance drilling profiles obtained in *Tilia cordata* with internal decay behind 18cm of intact wood. The bottom profile, which came from an electronically regulating and recording drill, clearly and reliably revealed the intact nature of the outer shell (green) to the point where the profile begins to drop in density (yellow) into the decayed area (red). The top profile shows both plateau and resonance effects typical for the spring-driven, mechanical recording device used by Kamm and Voss in the early 1980s. In the outer section, this mechanically recorded profile stays on the same low level as the profile does in the central part (with totally rotten wood). Consequently, such profiles often led to incorrect interpretations as an indication of sapwood decay (although the outer wood section was intact).

sponding patent (1985) and tried to get this updated version accepted by scientists. In 1986, the Universities of Heidelberg and Hohenheim decided to investigate whether this method, as described in the Kamm and Voss patent application, would enable scientists to analyze earlywood and latewood zones within tree-rings (Rinn 1988; Rinn et. al. 1990).

Based on the first laboratory prototype built during this scientific project in 1986, a first series of mobile resistance drills using electric recording was developed and sold to scientists and experts the following year. The use of these new resistance drills on building timber showed a correlation of r^2>0.8 between the profiles and the gross density of dry timber (Görlacher et. al. 1990). This clearly showed the method's potential for decay detection and wood quality analysis. However, the technical resolution of the drill was not sufficient for assessing intra-annual density profiles of narrow tree-rings (Rinn 1988). As a result, these machines were quite limited in detecting incipient decay, fine cracks or ring-checks (Rinn 2015).

Assessment of narrow tree rings, incipient decay or other fine defects requires a higher resolution of measured values along the drilling path and a clearer and stronger correlation to local wood density at each position of the needle while penetrating the wood. Consequently, a specific electronically regulating and recording drill was developed and patented (Rinn 1990), including a new geometry for the needle's tip (**Figs. 6-7**).

As a result of these changes, the overall resolution increased by a factor of more than 10 (Rinn et. al., 1996). The 5th generation of these electronically regulating and recording resistance drills was released in 2006. It achieved a correlation of r^2>0.9 to wood density, even in green timber (Brashaw 2013). Consequently, the profiles obtained during testing accurately represent the level of wood density along the drilling path, allowing a correspondingly reliable evaluation of wood condition by distinguishing between intact and decayed parts, including differentiation between intact (but soft) areas and those with incipient decay.

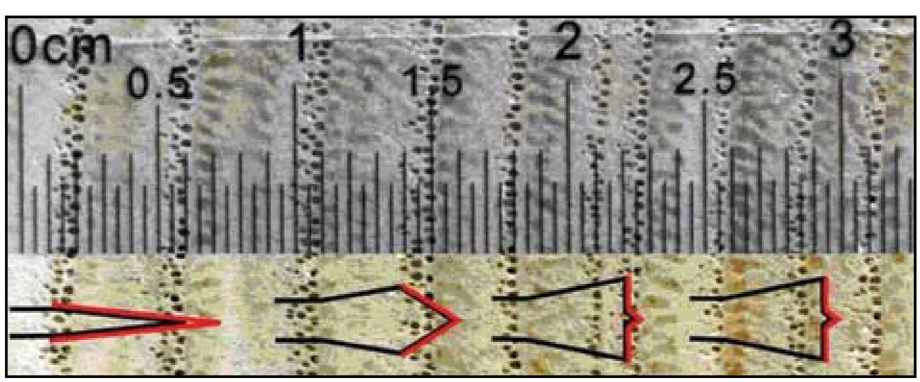


Figure 6. Three different needle tip geometries plotted to scale on a wood surface of chestnut (*Castanea sativa*). The first needle used by the German engineers Kipp, Kamm, and Voss for timber inspection in 1980 was pointed and ~1mm in diameter (left). The second version by Kamm and Voss in 1985 changed in tip geometry (shaft 1.5mm, tip 2.5mm) in order to get higher resolution and better correlation to wood density. For achieving maximum possible spatial resolution and highest possible correlation to wood density, a new tip geometry was later introduced (tip ~3mm, shaft 1.5mm; Rinn 1990). The red lines indicate the areas at the needle's tip of maximum penetration resistance while drilling, leading to torque of the motor (and measured electronically as power consumption). The shorter the extension of the red line in drilling direction, the higher the spatial resolution of the profile. If the red line fits into a thin band of vessels of a ring-porous wood, for example, this is clearly revealed in the profile by a corresponding drop, representing the low density in earlywood (Fig 7).

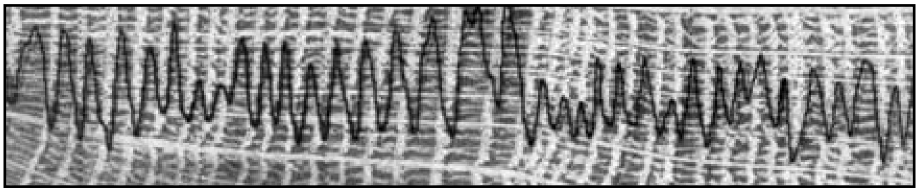


Figure 7. Density profile of a ring-porous oak (*Quercus* spp.), obtained with an electronically regulating and recording resistance drill. The clear correlation to wood density and the spatial resolution (of the machine and the needle's tip geometry) result in a corresponding reliability that both the level and local variations of the profile are reflecting the density at each position of the needle's path while penetrating the wood (Rinn et.al 1996). This contrasts to the profiles produced by the old Kamm-Voss mechanical spring-driven resistance recording device, (Figs. 4,5) and this explains why Kamm and Voss abandoned the old recording principle in order to achieve a reliable method.

However, it has to be understood that this proof is only valid for this one particular kind of resistance recording drill: 10 sampling points per millimeter (better 50 or 100), linearly measured values with more than 10Bit signal resolution and a correlation to wood density with at least $r^2>0.9$. Only then, are profiles accurate in assessing wood density, allowing a correspondingly reliable identification of decay potentially having a significant impact on wood strength and probability of failure. The same is true especially for distinguishing intact but soft wood from decayed sections, for example, in the center of fast growing conifers (trees or poles) or in the sapwood of many broadleaf trees. Otherwise, misinterpretations are unavoidable as previously discussed. This is why these thresholds regarding resolution and precision are required for an application for an official license on the trademark RESISTOGRAPH®, internationally registered in more than 30 countries under IR#646811. The resistance drills that meet these conditions, are licensed and legally labeled with this trademark, can be seen on www.resistograph.com. There is more information on the scientific background of this method available on this website, too.

References and further reading

Brashaw, B.K. 2013: Nondestructive Testing and Evaluation of Wood-Research and Technology Transfer in North America. Proceedings of the 18th international Nondestructive Testing and Evaluation of Wood Symposium, Madison, Sept 2013.

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

Kamm, W., Voss, S. 1985: Drill resistance method and machine. German and international patent application (DE3501841A1). [This patent was later declared invalid because of previous publications from Japan, USA, & Germany].

Means, J.E., Cromack, K. Jr, MacMillan, P. C. 1985: Comparison of decomposition models using wood density of Douglas-fir logs. Canadian Journal of Forest Research, 1985, 15(6): 1092-1098, 10.1139/x85-178.

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

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

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. 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., 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.

Rinn, F. 2012: Basics of typical resistance-drilling profiles. Western Arborist. WCISA Winter 2012, 30-36.

Rinn, F. 2013: Typical Trends in Resistance Drilling Profiles of Trees. ArboristNews. Feb 2013, 42-47.

Rinn, F. 2015: Central defects in sonic tomography. Western Arborist. Spring 2015, 38-41.

Wilcox, W.W. 1978. Review of literature on the effects of early stages of decay on wood strength. Wood and Fiber 9(4):252-257.

Summary

Density is one of the most important material properties of wood, characterizing several basic aspects of quality and stability. Because even slight density changes can lead to significant strength loss, and because incipient decay can quickly develop into severe decomposition, density has to be measured precisely and at high resolution. Understanding the historical development of the resistance drilling method helps in understanding why and how the correlation to wood density in combination with a high spatial and signal resolution is the key parameter for characterizing quality and reliability of such devices and their results. However, learning resistance drilling starts with studying and understanding wood anatomy and species-specific density profiles (radial, tangential, and longitudinal).

Frank Rinn
Heidelberg, Germany