Basics of micro-resistance drilling for timber inspection

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Mobile resistance recording drilling using thin needles is used to inspect trees, timber and structures since 1987. Profiles of simple machine types reveal voids and severe decay. Electronic high-resolution versions, in addition, show cracks, delaminations, incipient decay and tree-ring density structures of earlywood and latewood. However, knowledge about wood anatomy is pre-requisite in order to be able to interpret the resulting profiles correctly.

Keywords: Resistance drilling, wood anatomy, timber

Introduction

Resistance (recording) drilling with thin needles is used to determine the condition of structural timber and joints by measuring density profiles of wood, in order to detect decay, insect damage, cracks, invisible beams and hidden parts (*Ehlbeck and Görlacher,* 1990; *Kasal et al.*, 2009).

Possibilities and limitations of the method can only be understood by learning the development of its technical specifications because they reflect the different properties of currently available and used machine types and applications. In addition, knowledge about wood anatomy, properties of wood as a material and as member of timber structures is required for proper application and reliable interpretation of results.

Technical basics

Historic development

1984, two German engineers (W. Kamm, S. Voss) developed a drill that recorded the penetration resistance of a thin needle in wood. But, resonance effects of the recording spring mechanism triggered by tree-ring variations often led to wrong readings due to over-tuned profiles (too high in latewood, too low or even zero in soft earlywood). Such misleading spring-resonance effects can be partially reduced by compensation springs for damping. But this introduces stimulus thresholds into the recording system, causing another systematic and inherited error: drill resistance values below this stimulus threshold are suppressed and not displayed or plateaus appear in the profile. If the profile drops down to zero in earlywood, for example, this could be misinterpreted as insect damage. As a consequence, low profiles from intact but soft wood (as common in the centre of most conifers or in the sapwood of many ring porous species) often was misinterpreted as a sign of decay or insect damage. These mechanically recorded profiles had been shown as being nonlinear, non-reproducible and thus unreliable, systematically leading to wrong evaluations. The developers consequently switched to electrically recording mechanisms (*Kamm and Voss,* 1985).

In a joint project of the tree-ring lab at Hohenheim University and the Environmental Physics Institute of Heidelberg University, the resistance drilling method was then further developed with the aim to measure the intra-annual density variations of tree-rings. Early measurements clearly showed that electronic regulation and recording of motor power are prerequisite for obtaining reproducible profiles and reliable results that can linearly be correlated to wood density (*Rinn,* 1988).

Originally, the power consumption of both motors, one responsible for feed and the other for rotation of the needle, was measured individually and recorded while the needle was going forward and backward, delivering four curves per measurement. Detailed comparative analysis showed that the variations of the power consumption of the feeding motor at constant speed and of both motors while pulling the needle backwards did not contain significant additional information (*Rinn,* 1989). Therefore, subsequently resistance drills from then on usually measured and recorded the electrical power consumption of a direct current needle rotation motor. This value is proportional to the mechanical torque at the needle (if the motor acts linear) and mainly depends on wood density (*Rinn et al.*, 1990).

Needle geometry

For both scientific and practical applications, the resistance drilling method had to fulfil several different diverting requirements and it took years to test different materials and needle shapes with thousands of drillings until a solution was found.

As the goal was to determine radial density profiles at highest possible resolution, the drill-resistance had to be measured

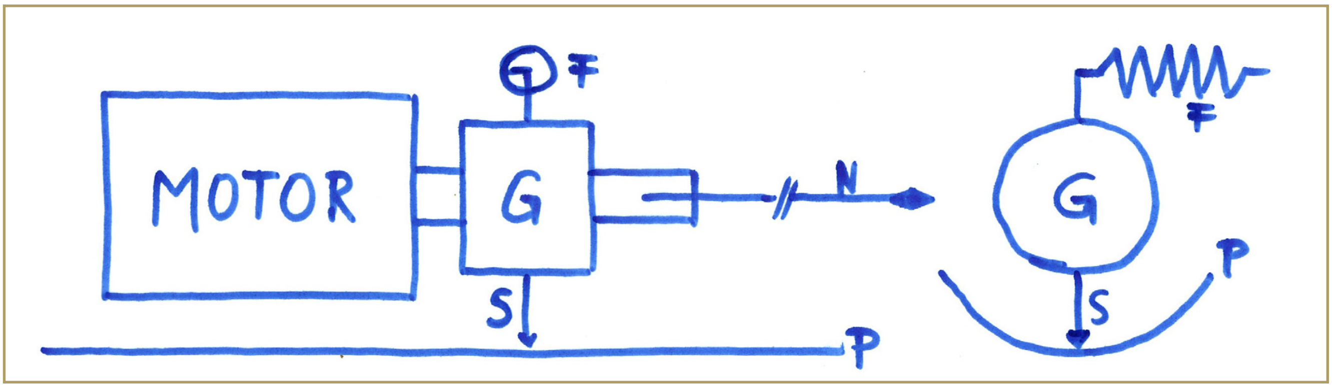

Fig. 1: Sketch of an early resistance drill from 1984: a scratch pin (S) was fixed at a spring (F) loaded gear box (G) between motor and needle (N), creating a 1:1-scaled resistance profile on a wax-paper strip (P); because resonance and threshold effects due to the spring-loaded recording mechanism delivered systematically wrong profiles that were easily misinterpreted, this approach was abandoned and replaced by electric recording of motor power consumption

Abb. 1: Skizze einer frühen Version eines Bohrwiderstandsmessgerätes aus dem Jahre 1984: ein Kratzstift (S) wurde über einen Papierstreifen (P) im Gerätegehäuse geführt und mittels drehbar gelagertem Differentialgetriebe (G) hin und her bewegt; weil Resonanz und Schwelleneffekte des federgetriebenen Aufzeichnungsmechanismus zu systematisch falschen Profilen führten, wurde dieser Ansatz aufgegeben und durch eine elektrische Aufzeichnung der Motorleistung ersetzt

with the highest possible resolution along the drilling path. That means, a flat tip front line would be best. Because tree-ring borders are not linear-laminar but more or less concentric or even waving, the width of the needle's tip determines the resolution by tangential averaging and should be as small as possible.
Because the damage to the inspected sample (tree or beam) should be minimized, the needle had to be as thin as possible. But, thin needles (< 1 mm) were often "misled" by wooden rays, knots or other wood anatomical in-homogeneities and did not drill straight enough. In addition, for penetrating hardwoods, needles had to be thicker and stronger. Finally, a shaft diameter of 1.5 mm and a 3.0 mm tip was found to be a good compromise. All subsequently shown profiles, if not explicitly described as different, have been obtained using an electronically regulated and recording resistance drill using flat tipped 1.5/3.0 mm steel needle.
The method's ability of decay detection was a side-effect of the scientific development for tree-ring analysis. Some thousand drilling devices were already sold worldwide since. Currently, several machine types are available from different manufacturers, varying significantly in size, weight, resolution, precision, applicability and price.

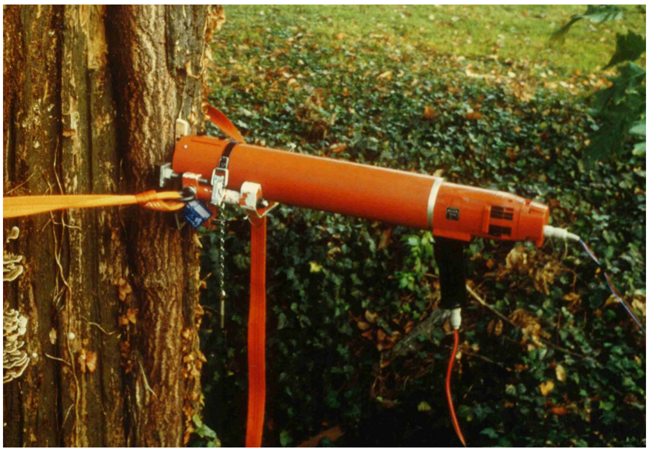

Fig. 2: Resistance drill of the first portable device series from 1987, sold to experts worldwide; using such a machine, *Ehlbeck and Görlacher* proved a linear correlation of the profiles to wood gross density (1990)

Abb. 2: Bohrwiderstandsmessgerät der ersten portablen Geräteserie aus dem Jahre 1987, welches an Experten auf der ganzen Welt verkauft wurde; damit gelang Ehlbeck und Görlacher der Nachweis einer linearen Korrelation der mittleren Kurvenhöhe zur Rohdichte des durchbohrten Holzes (1990)

Basics of profile interpretation

If the needles geometry follows the guidelines as described above, local wood density at the position of the needle's tip is the main factor, influencing the 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 pre-requisite to understand basic wood anatomical properties for appropriate application and proper interpretation of the resulting profiles.

Wood anatomy

In terms of wood material properties and regarding the cutting mechanism at the needle's tip, local shear strength may be even closer related to the measured drill resistance value. But, comparison with high-resolution radial x-ray density profiles showed that electronically regulated and recorded resistance drilling delivers profiles linearly correlated to local wood density, dissolving tree-rings down to a width of about 1/10 mm, if the needle is equipped with a flat tip and penetrates the tree-ring borders perpendicular (*Rinn et al.*, 1996).
Despite rare exceptions, the combination of the following fac-

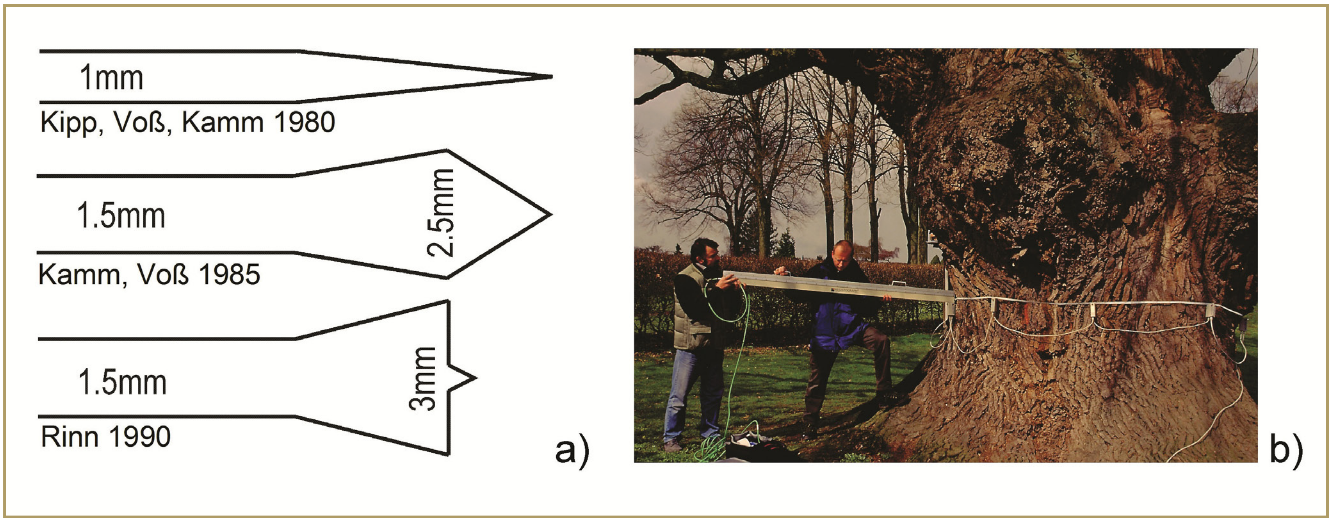

Fig. 3: a) A needle shaft of 1.5 mm and a flat tip of 3.0 mm width were found to be a good compromise for achieving maximum resolution and stability at lowest damage to the sample; b) With this needle, it was possible to drill up to a depth of 1.5 m into old oak trees and still detect tree-rings narrower than 0.5 mm (*Rinn,* 1990)

Abb. 3: a) Ein Schaftdurchmesser von 1,5 mm und eine Kopfbreite von 3,0 mm haben sich als guter Kompromiss zwischen Stabilität, Messwertauflösung und Schädigung erwiesen; b) Mit dieser Bohrnadel gelang es, bis zu 1,5 m tief in alte Eichen zu bohren und dennoch Jahrringe bis zu einer Breite von unter 0,5 mm zu detektieren (Rinn, 1990)

tors determines typical shape of radial resistance profiles:

- Latewood is mostly much denser than earlywood.
- Broad tree rings are mostly dominated by earlywood in conifers and latewood in ring-porous wood.
- Due to the age-trend (*Bräker et al.*, 1981), the average ring width declines with tree age.
- In narrow conifer rings, the relative amount of latewood is higher and consequently the gross density is higher.
- Earlywood width in ring-porous trees does not show strong variations.
- In narrow oak rings, the relative amount of earlywood is higher. The narrowest possible oak rings mainly consist from the very soft earlywood.
- The broader oak rings are, the more latewood dominates and the higher their gross density.

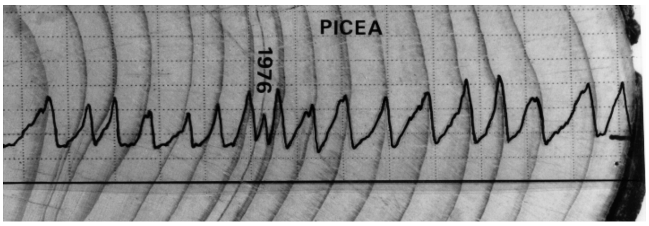

Fig. 4: If the needle penetrates the tree rings of conifers nearly perpendicular, the profile reveals differences in density between earlywood and latewood; in this profile of a spruce tree, felled in 1986, the extremely dry summer of 1976 can be identified by the correspondingly narrow tree-ring with only a few latewood cells

Abb. 4: Wenn die Bohrnadel Jahrringe in Nadelholz senkrecht durchbohrt, zeigen die Profile die Unterschiede in der Dichte von Früh- und Spätholz; in diesem Profil einer 1986 gefällten Fichte ist das Trockenjahr 1976 deutlich am engen Jahrring mit wenig Spätholz zu erkennen

- Thus, the quicker a tree is growing, in general, the higher the wood's gross density in ring porous species and the lower in conifers.

There are many consequences of the combination of these aspects for timber inspection: wood of full size conifer beams, for example, is commonly stronger in the outer areas of the cross section and the opposite applies to oak beams. Most important for resistance drilling is that radial profiles derived from conifer beams tend to drop down in the centre by nature (because of broader tree rings dominated by earlywood in the centre in the juvenile wood). This 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 in intact rings, this indicates decay, a crack, or the pith.

Typical profiles reflect wood anatomical structure

In ring-porous wood, such as oak (*Quercus*) or chestnut (*Castanea*), the profiles commonly rise up in the centre of the beams and then drop down again when the needle is coming closer to the other side. This drop-down effect can only be distinguished from decay or insect damage in profiles that are linearly correlated to density and provide a high resolution. Although this applies to the detection of early stages of decay, it is important, because early decay stages can strongly affect bending strength. If a beam is affected by brown rot fungi (*Serpula lacrymans,* for example), incipient stages of decay can lead to 80 % strength loss while the wood lost only 10 % of its density (*Wilcox,* 1978). Consequently, a small drop in the resistance profile can correspond to a big strength loss. Such early stages of decay can only be identified within high resolution resistance profiles clearly revealing tree ring structures and showing slight differences by

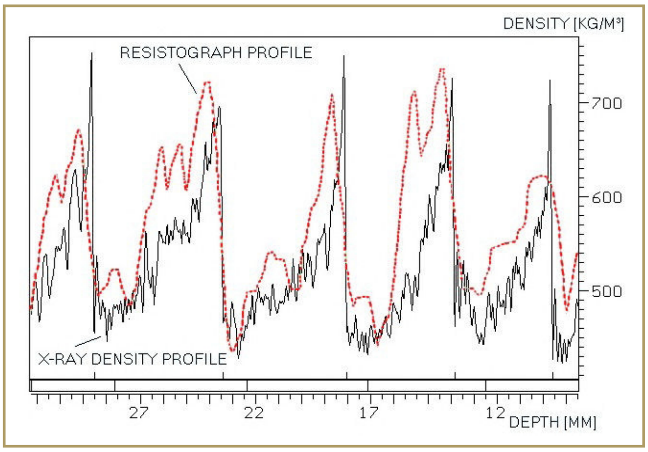

Fig. 5: This superposition of a radial x-ray density profile (resolution 1/100 mm) of larch with a resistance drilling profile shows that local wood density is the main factor determining drill resistance; the slope of the resistance profile at the tree-ring border represents the step function response of the method and thus represents the resolution limit of tree-ring detectability when penetrated perpendicular

Abb. 5: Diese Überlagerung zweier radialer Röntgendichte- und Bohrwiderstandsprofile belegt, dass vor allem die Dichte des Holzes den Bohrwiderstand bestimmt; die Steigung des Bohrwiderstandsprofils an der Jahrringgrenze zeigt die Sprungantwort des Verfahrens und damit die Auflösungsgrenze für die Jahrringerkennung bei senkrechtem Durchbohren

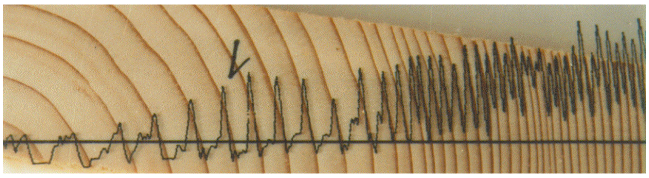

Fig. 6: In contrast to narrow rings, broad conifer rings are usually dominated by soft earlywood; due to age trend in ring width, conifer beams and poles are mostly softer in the centre; the corresponding decline in drill resistance can only be distinguished from a decline by internal decay if the intra-annual density structures are revealed correctly; this requires a high resolution profile, measured and recorded electronically linear, otherwise it will lead to misinterpretation and wrong evaluation of timber

Abb. 6: Im Gegensatz zu schmalen Jahrringen, bestehen breite Nadelholzjahrringe meist hauptsächlich aus dem weicheren Frühholz; gemäß Alterstrend in der Jahrringbreite sind Balken oder Masten aus Nadelholz im Inneren meist deutlich weicher; der entsprechende Abfall im Bohrwiderstandsprofil kann von einem fäulebedingten Kurvenabfall unterschieden werden, wenn die Jahrringstruktur korrekt wiedergegeben wird; dies erfordert einerseits eine entsprechend hohe Auflösung des Profils und andererseits eine lineare Abbildung der Rohdichte, sonst kommt es zu Fehlbeurteilungen

early decay stages (10 measurement points per mm at 10 bit resolution, in minimum).

Resistance profiles derived from tropical species without distinct tree-rings show similar behaviour as many diffuse-porous species from moderate zones and mostly slightly rise up in the centre. Thus, in general, three types of wood have to be distinguished in terms of typical profile shape: temperate conifers, temperate ring-porous wood, diffuse-porous wood and tropical wood without distinct annual tree-rings.

Shaft friction

Depending on the machine and needle type, there is a more or less disturbing source of systematic errors in the profiles, caused by friction to the needles shaft while drilling. For many machines, as soon as the density of the penetrated wood exceeds 600 kg/m³, the profile tends to incline with depth even if the wood is soft or decayed.

This effect disturbs both qualitative as well as quantitative evaluation of the profiles and can make reliable decay detection im-

Fig. 7: In contrast to narrow rings, broad ring porous tree-rings are dominated by dense latewood; due to age trend in ring-width, oak beams are denser in the center, leading to an increasing drill resistance; narrow oak rings are dominated by soft earlywood, leading to a drop in density and drill resistance profiles; high resolution electronic drills with an ordinate axis linearly correlated to wood density are mandatory for distinguishing such zones of narrow but intact rings from areas of decay

Abb. 7: Im Gegensatz zu engen, sind breite Jahrringe in ringporigen Hölzern meist dominiert vom dichteren Spätholz; gemäß Alterstrend der Jahrringbreite führt dies zu einem systematischen Anstieg der Bohrwiderstandsprofile im Inneren von Bäumen; eine hohe messtechnische Auflösung und eine lineare Korrelation zur Holzdichte ist notwendig, um den Kurvenabfall durch enge Jahrringen von dem durch Fäule zu unterscheiden

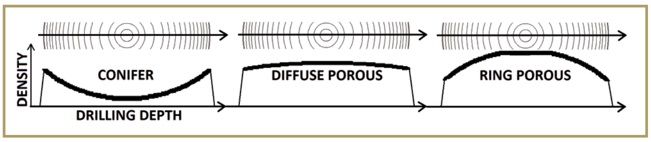

Fig. 8: Typical mean trends of drill resistance profile trends from radially drilled cross section (of calibrated machines without shaft friction), reflecting typical radial stem density trends as confirmed by x-ray measurements (*Read et al.,* 2011)

Abb. 8: Typische mittlere Trends von kalibrierten Bohrwiderstandsprofilen ohne Schaftreibung in Nadelhölzern, zerstreut- und ringporigen Laubhölzern; diese Kurven geben die art-typischen radialen Dichtetrends wieder, die durch Röntgendichtemessungen bestätigt wurden (Read et al., 2011)

Fig. 9: Beside the geometry of the needle's tip and the technical resolution of the machine, the drilling angle referring tree-ring borders determines the visibility of intra-annual tree-ring density structures; if the profile remains low in the center, this does not indicate decay as long as the level equals the earlywood of the surrounding tree-rings; thus, for distinguishing soft but intact wood and decay, especially from incipient stages, a high resolution machine with linear ordinate by electronic recording is required

Abb. 9: Neben der Geometrie der Nadelspitze sowie der technischen Auflösung des Bohrwiderstandsmessgerätes bestimmt der Winkel zwischen Bohrrichtung und Jahrring die Erkennbarkeit von Früh- und Spätholzzonen; wenn das Profil im Inneren auf niedrigem Niveau verbleibt, zeigt dies keine Fäuleschäden an, solange es nicht unter das Niveau der umliegenden Frühholzbereiche fällt – hierfür sind eine ausreichend hohe technische bzw. elektronische Auflösung und eine lineare Ordinate erforderlich

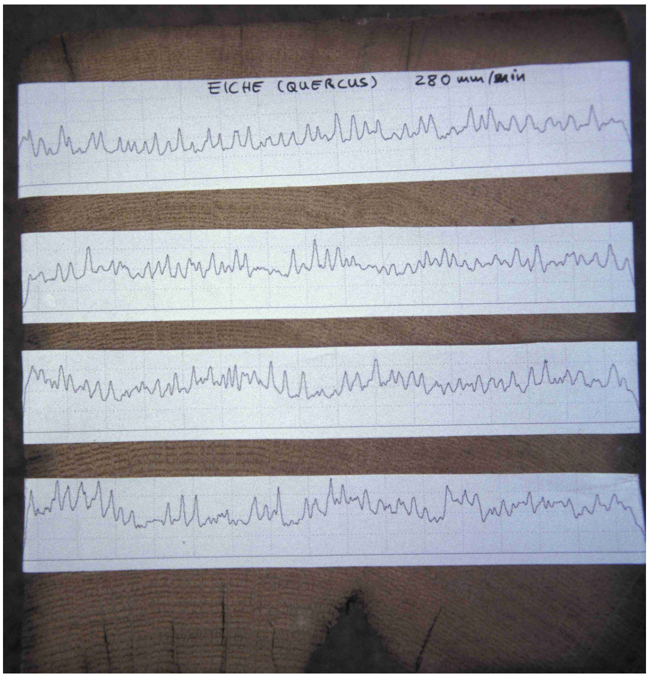

Fig. 10: Profiles of tangential drillings in oak often look like radial drillings in spruce and stay on one level due to the missing change in density in this direction; therefore, without knowing the species, drilling point and drilling direction, it is impossible to interpret the profiles correctly

Abb. 10: Bohrwiderstandsprofile tangentialer Messungen in Eiche verbleiben oft auf einem mittleren Niveau und sehen oft aus wie radiale Profile aus Nadelhölzern; ohne Kenntnis der Holzart und Bohrrichtung relativ zu den Jahrringgrenzen können Bohrwiderstandsprofile demnach nicht korrekt ausgewertet werden

possible. To avoid this disturbance, calibrated machines types are required or manual subtraction of this trend with software.

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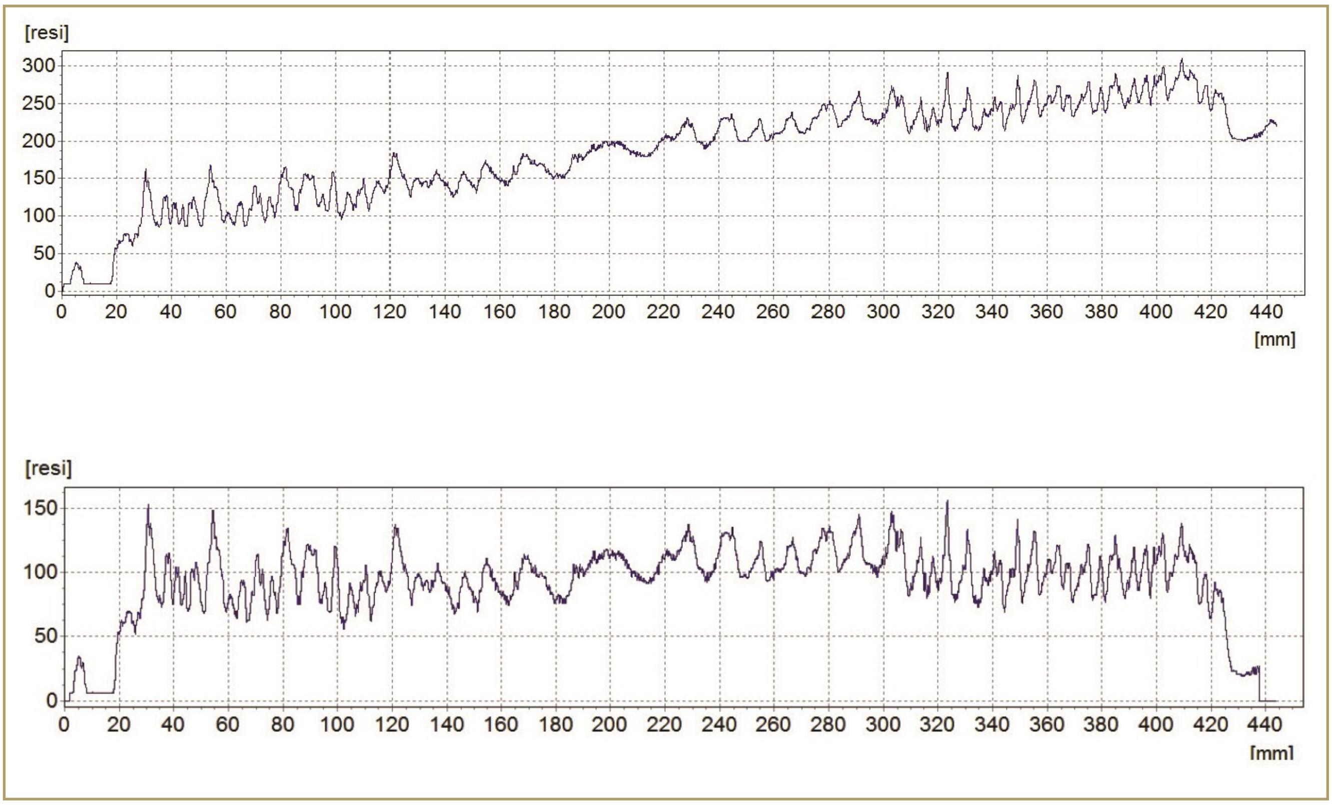

Fig. 11: Depending on machine and needle type, shaft friction may lead to a more or less strong increase of the profile as the needle penetrates the wood (top profile); this effect can mask profile decline by decay and make interpretation more difficult; in case of doubt, reference drillings are required; the profile can be de-trended with a software, shown in the lower profile or a calibrated machine has to be used

Abb. 11: In Abhängigkeit von Gerätetyp und Bohrnadelgeometrie kann Schaftreibung zu einer mehr oder weniger störenden Überlagerung führen (oberes Profil); dieser Effekt kann Profilabfälle durch Schäden überlagern und deren Identifikation erschweren; im Zweifelsfalle sind daher Referenzprofile notwendig; im Computerprogramm kann der Trend durch Schaftreibung eliminiert werden, oder es wird eine auf Holzdichte kalibrierte Variante des Gerätes verwendet

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ABSTRACT

Grundlagen der Bohrwiderstandsmessung zur Holzuntersuchung

Bohrwiderstandsmessungen mit dünnen Nadeln werden seit 1987 für die Untersuchung von Bäumen und Holzkonstruktionen verwendet. Profile einfacher Gerätetypen zeigen Hohlräume und starke Fäulen; elektronisch hochauflösende Geräte zeigen darüber hinaus auch Risse, Delaminationen, frühe Holzabbaustadien sowie Jahrring-Dichteschwankungen zwischen Früh- und Spätholz. Holzanatomische Kenntnisse sind notwendig, um die Profile korrekt zu interpretieren.

***Keywords:** Bohrwiderstandsmessung, Holzanatomie, Holzuntersuchung*