A nondestructive indirect approach to long-term wood moisture monitoring based on electrical methods: experimental verification and statistical evaluation

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Abstract: Wood has a long tradition of use as a building material due its properties and availability. However, it is very sensitive to moisture. Wood components of building structures basically require a certain level of moisture protection, and thus moisture monitoring to ensure the serviceability of such components during their whole lifespan while integrated within buildings is relevant to this area. Moisture is an important issue and it is necessary to increase moisture safety in buildings and reduce the risk of moisture damage. The aim of this study is to investigate two moisture monitoring techniques promoting moisture safety in wood-based buildings (i.e. new structures as well as renovated and protected buildings) and for all uses in buildings. The study is focused on the comparison of two electrical methods that can be employed for the nondestructive moisture monitoring of wood components integrated in the structures of buildings. The principle behind both methods is theoretically introduced, and details are given concerning a comparative experimental campaign utilizing spruce wood samples. The experiments were carried out in order to verify the viability and final application of the methods. The advantages and disadvantages of both methods are highlighted, and a statistical analysis has been conducted to confirm their suitability. Based on the results obtained, both methods can be successfully applied to wood components in buildings for moisture contents above 8%.

Keywords: wood moisture; resistance measurement; wood moisture sensing; non-destructive testing; moisture safety;

1. Introduction

The properties and lifespan of wood strongly depend on many aspects, and therefore the permanent moisture monitoring of wood has a specific application in a wide range of technical fields. Primarily, wood-based wall technologies are widely considered to be suitable building materials for low-environmental impact composites in the building engineering field. Wood framed and composite wood wall technologies that utilize advanced insulation techniques have been well-integrated for several decades in the building sector and specifically meet thermal and environmental requirements [1]. Thermal properties such as thermal conductivity and specific heat are given significant consideration when designing buildings, especially low-energy or passive ones. Building
components that are exposed to the weather outdoors are mainly affected by moisture and temperature-related effects. It has been two decades since exterior building surfaces began to be designed to be monitored by methods for the continuous monitoring of temperature and moisture in the micro-environment of structures, and within the wood itself. A system was introduced that maps the climate index for the decay of wood at various geographical levels via the use of existing climatic data, standards and moisture content measurements [2]. Moisture and temperature can also play an important role indoors and within the structure of a building, i.e. throughout the whole building envelope. The existence of high moisture content can initiate decay or the growth of fungi. Particularly for bio-based building materials such as wood, the use of biological agents should be considered in order to predict service lives, particularly with regard to fungal decay and mould growth risks. The control and reduction of wood moisture content is therefore a key instrument for wood protection [3]. However, the permanent monitoring of wood components may also have relevant role to play in this field, especially when such components are incorporated in the building structure and their continuous physical monitoring is impossible. The correct estimation of timber moisture content and the subsequent initiation of potentially necessary measures are therefore essential tasks during the planning, execution and maintenance of buildings built with wood or wood-based products. This fact has contributed to a recent and considerable rise in interest concerning the in-situ monitoring of the moisture content of structural timber elements [4]. In this connection, the modeling of the outdoor performance of wood products is also attracting specific attention [5]. Furthermore, moisture content measurement has a lot of potential for use in testing the durability of timber products [6]. A technique for the nondestructive evaluation of moisture content distribution during drying using a newly developed soft X-ray digital microscope and absorbometry was investigated by Tanaka et al. [7] and Tanaka and Kawai [8]. X-ray based methodology and diagnostics have already been successfully developed and used in many applications to identify aspects of wood decay [9,10]. In particular, wood temperature and moisture content have a direct impact on fungus and its ability to metabolize and degrade wood cell wall material over time [11]. Moisture requirements for the growth and decay of different fungi and wood species have already been determined, though relationships between wood moisture content, wood temperature and fungal decay play an important part when applying the method in specific climates [12]. In addition, the interrelationship between microclimate, material climate, and decay is being studied in order to achieve a better understanding of issues concerned with the service life prediction of wood and wood-based products. Dietsch et al. [4] describes common methods of determining wood moisture content and evaluates them with respect to their applicability in monitoring concepts. Continuous moisture measurements using calibrated load cells and a data logger coupled with a weather station are an efficient way to record moisture in all kinds of material [13]. Unfortunately, the most accurate direct methods, which use oven drying and distillation, are time-consuming and cause the destruction of specimens. Many non-direct methods have been developed based on electric conductance or dielectric properties which allow results to be obtained fast and with satisfactory accuracy. In this relation, wood moisture measurement has a long history. Dunlap [14] discusses twelve commercial electrical moisture meters. Most of them are based on resistance (conductance) measurement. The Wood Handbook [15] states that the resistance of wood ranges from a few petaohms for oven-dry wood to a few kiloohms for wood with fiber saturation. In the range between fiber to complete saturation the change of resistance is not so significant. Williams [16] mentioned that the conductance and dielectric properties of wood vary consistently with moisture content when it is less than 30% with a roughly linear relationship between the logarithm of conductance and the logarithm of moisture content. Thanks to this relationship the moisture content can be determined. The measurement principle is based on the application of direct or alternating current, but higher resistances than a few hundred megaohms are not so easy to measure. Electric-current through such huge resistance is often very small and direct current measurement in a simple electrical circuit with an appropriate error is not possible. Moisture content is not the only phenomenon which has an effect on the conductance of wood material; another significant factor is temperature dependency. Williams [16] mentioned that an increase of ten degrees Celsius causes an approximately twofold increase in
conductance in regions with more than 10 percent moisture content. Another problem is the
anisotropy of wood in the direction of the grain. Conductance measured parallel to the grain is
approximately double that of perpendicular conductance.

Many methods, complex electrical circuits and devices have been developed in past decades.
Typical devices are equipped with probes and a display for showing measured values. They are
portable, and very useful for taking technical measurements or conducting on-site inspections of
materials. A long-term moisture measuring and data logging method for wood exposed to weather
conditions was developed by Brischke et al. [17]. The method involves measuring the electrical
resistance with glued electrodes for a sustainable connection. The measuring points at the tips of the
electrodes are glued conductively into the wood while the remaining outer parts of the electrodes are
glued with insulating adhesive. For this purpose, special conductive and insulating glues and
electrodes were developed and comparatively evaluated in laboratory tests. Nowadays with
innovative approaches in many fields of our lives, we often use technologies which allow us to
monitor the whole process of evolution. Portable independent devices often cannot be integrated into
structures for a long time or connected to networks. For that reason, there are potential future
applications for sensors which could be connected to a network and placed into a composite structure
containing wood for a long period of time. The sophisticated circuits used in commercial portable
devices are often trade secrets of their producers and are not so easy to adapt for use in automatized
systems. If the resistance measurement approach is used, there are two methods which are applicable:
they are subjected to further analysis here. Both of the analyzed methods use the capacitor charge
principle in a different way.

This study describes experimental work which aimed to obtain wood moisture monitoring data
indirectly using two electrical methods. The main aims of this research work are first to introduce the
theoretical principles of both measurement methods used, second to evaluate their applicability and
finally to verify them based on the experimental results obtained. Both methods are applied to
samples made of spruce wood. The experimental results were evaluated via a statistical approach
based on Bland-Altman plots. Originally, the Bland-Altman procedure [18] was used in medicine to
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2. Description of the Circuits, Theoretical Principles and Applications

As mentioned above, basically there are two methods which can be used for long-term wood
moisture monitoring using electrical resistance and direct current. The first method uses a resistor–
capacitor (RC) circuit which has been improved by transforming it into a digital device using a 555
timer chip [20,21]. The second applicable method uses capacitor charging via an operational amplifier
connected as an integrator circuit. This method was originally applied to other problems requiring
the measurement of high resistance by Aguilar et al. [22]. Both methods can be usefully implemented
in small sensor packages as illustrated in Figure 1. This shows small sensor prototypes which were
assembled based on this research work and directly attached to wood samples in a climatic chamber
during a test involving long-term monitoring.

The application of circuits was tested on spruce wood samples. Several wood samples with
electrodes attached in various orientations relative to the fibers of the wood were measured with both
methods. The samples were fitted with electrodes and placed into a desiccator where humidity and
temperature were controlled. The measurements were obtained via a digital oscilloscope at intervals
during conditioning, and the weights of the samples were measured. The results from both circuits
were compared to each other using the obtained data.
2.1. The RC Circuit Method

This type of circuit is also known as an RC network or RC filter. It combines a capacitor with a resistor in series and is driven by voltage or a source of current. The main principle of RC circuits is based on the relationship between capacitor and resistor values and the voltage level in the capacitor over time. In a simple example with direct current and a rise in voltage from zero to a particular voltage level at the input rail of the resistor, the time of capacitor charging is proportional to the time constant of the circuit. The time constant is defined by the value of the resistor and capacitor.

At zero time the capacitor $C$ is discharged. If the input voltage is applied at resistor $R$, the voltage charge of capacitor $C$ starts rising over time until it reaches the maximum value, as is displayed in Figure 2. The time constant (1) represents the time taken by the capacitor to charge to approximately 63.2 percent of its final voltage value. At a known and stable capacitance and a known time of charging the resistance can be estimated, and vice versa. The relation between the voltage of capacitor $V_C$ and the stable input voltage $V_{IN}$ on the left resistor rail can be described by equation (2).

$$\tau = RC$$  \hspace{1cm} (1)

$$V_C = V_{IN}\left(1 - e^{-\frac{t}{\tau}}\right)$$  \hspace{1cm} (2)

The described idea is applied in the first method. The charging and discharging of the circuit is managed by a timer integrated circuit. The most well-known timer, the 555 timer chip, has many applications, from circuits with a blinking LED to circuits which use it to generate an AC signal. The use of this chip for wood moisture measurement was mentioned by Vodicka [20]. It is a logical application in which the chip is used as a monostable timer. This simply means that if a trigger input is pulled to a logical zero, the capacitor is discharged, and then charging starts with the output of the
chip set to a high logical level. If the voltage of the capacitor reaches 63 percent of the input voltage level, the output is set to the zero logical level.

![RC circuit improved by a 555 timer chip](image)

**Figure 2.** RC circuit improved by a 555 timer chip

\[ t = 1.1RC \quad [s] \]  

The time of the output pulse is proportional to the RC constant and can be calculated with Eq. 3. Testing was performed with an oscilloscope; the circuit was triggered by a push button. Triggering and time counting could be handled by a small microcontroller in a real world sensor. The problem standard timer chips have with leakage current, which is often higher than the current through a wood sample with a moisture content of under 10 percent, has been solved by the use of the ICM7555 chip. Its leakage current is within the range of a few picoamperes according the producer’s specifications.

2.2. The Integrator Method

Operational amplifiers have various uses in electronics. The most common functions are as comparators, amplifiers, differentiators and integrators. The last of these is the most relevant to high resistance measurement and the second method implements operational amplifiers in that mode. A TLC71 amplifier in integrator mode has already been used to measure high resistance at the level of hundreds of megaohms [22]. Most operational amplifiers need a symmetric power supply, which is the main disadvantage of these devices in digital electronics.

The integrator works on the principle of capacitor charging. The voltage at the capacitor changes over time according to the voltage value applied to the negative rail of the amplifier. The positive rail of the amplifier is grounded. If a negative voltage level is reached at input through the resistor, which represents measured resistance, the capacitor voltage grows to a positive supply voltage and vice versa. The slope of voltage change is proportional to the resistance and capacity. The output voltage is measured via an oscilloscope and the resetting of the integrator is triggered by a switch. In the case of a real-world sensor, this could be handled by a transistor managed by a microcontroller which is equipped with an analog to digital convertor for output voltage measurement.
3. Materials and Methods

An experimental investigation was conducted using the two abovementioned electrical resistance-based methods and the measurement results were statistically evaluated. In the initial part of this research, the spruce wood samples were prepared, and test circuits were developed for their calibration using resistor fields. Then, the samples were conditioned, measured and weighed on a continuous basis over three months. Finally, the obtained data were analyzed and statistically evaluated. Through this approach, a complex characterization of resistance could be comprehensively obtained from the measurements to verify the applicability of both methods used. All of the information on time dependent moisture parameters measured from the samples was expected to show that a clear picture of the evolution of moisture content can be provided if these test circuits are integrated within wood-based material or a real-world structure.

3.1. Sample Preparation Procedure

Three samples were prepared in the form of blocks with a cross section of 47.0 x 27.5mm and a length of 90.0 mm. They were made of planed spruce wood (Figure 5).

Figure 4. Integrator method circuit diagram and working principle.

Figure 5. Sample preparation (a) procedure and conditioning (b).
3.2. Circuit Setup and Calibration Procedure

Test circuits were built on test printed circuit boards (PCBs) with through-hole technology (THT) and surface-mount device (SMD) electronic parts. The trigger pulses for measurements were initialized by push buttons. The voltage response of the trigger and the output of the circuits were measured by a digital oscilloscope with a 25MHz bandwidth. The RC circuit with a 555 timer chip used a 12V single power supply, while the integrating circuit had a dual power supply with -12V and +12V rails. A polypropylene capacitor was chosen with the value 1nF.

Both circuits were calibrated with two resistor fields. The first test field consisted of 15 resistors with 10MΩ resistance and the second test field had 50 resistors with 20MΩ resistance. Each resistor was measured separately with two digital Ohmmeters and the results were averaged. The total resistance of the first field was set to 148.87MΩ with a maximum error of 1.5MΩ and 993.4 MΩ with a maximum error of 9.9MΩ. Several combinations of resistors were tested by both experimental circuits. The proportional constants of the circuits were identified according to the obtained data using statistical analysis: see Figure 6.

![Calibration data](a) ![Approximation](b)

**Figure 6.** Calibration data (a) and approximation (b).

3.3. Sample Conditioning and Measurement Procedure

The samples were conditioned in a desiccator above a solution of salt in accordance with technical standard EN 12751. Sodium chloride and potassium chloride were used. Relative humidity at laboratory temperature (21 degrees Celsius) reached approximately 76% with the first solution and about 86% with the second. The environment in the desiccator was monitored by a temperature and relative humidity probe. The resistance and weight of the samples was measured at specified intervals by the circuits and a laboratory balance with a resolution of 0.01 g and an accuracy of 0.05 g. Each measurement was taken three times for each electrode location and the results were averaged. The whole conditioning period lasted for roughly three months. The evolution of sample moisture content identified by weighing and the relative humidity in the desiccator is displayed in Figure 7.
Figure 7. Evolution of moisture content over time.

3.4. Sample conditioning and measurement procedure

In the real world, every value measured at a given assembly or sensor often differs slightly thanks to variations in the repeatability and accuracy of methods. The methods used in this research are no exception, and they can be expected to provide slightly varied results, sometimes with higher and sometimes with lower differences. The comparison of both methods requires statistical analysis, which was attempted via the application of the Bland-Altman procedure, which allows the identification of any systematic difference between measurements, as well as possible outliers. The mean difference is the estimated bias, and the standard deviation (SD) of the differences measures the random fluctuations around this mean. The 95% limits of agreement, i.e. $\pm 1.96$ SD of the difference, are computed to determine the most likely difference between two measurements conducted using two methods. If the differences within the $\pm 1.96$ SD are not physically important, the two methods may be used interchangeably. The 95% limits of agreement are often unreliable estimates of population parameters especially for small sample sizes. For small sets of data, like those in the presented study, it is appropriate to use a two-sided $1-(\alpha/2)$ value of Student’s t-distribution with $(n-1)$ degree of freedom as a constant, which multiplies the standard deviation when calculating the limits of agreement.

4. Results

The resistance of the wood samples was obtained from the integrator method circuit based on the slope of the rise in voltage. The resistance in megaohms was calculated based on data obtained from the calibration procedure; the values are shown in Table 1. The obtained results for each electrode position slightly differ. Electrodes A and B obtained very similar values, but the values for electrode C were roughly double those measured by A and B. This is in accordance with Williams [16]. Based on the proportional constant identified during the calibration procedure performed for the RC circuit, the resistance of samples was calculated using Table 2. Positions A and B provided quite similar values whilst those gained by position C were nearly two times higher.

The results calculated for the tops of the samples at the “A” electrodes are shown in Figure 8. The values measured from the “B” probes placed on the right sides of the samples are displayed in Figure 9. The values measured with the “C” probes placed in the cross sections are displayed in Figure 10. Linear regression lines have been added to the plots of individual measurements. The values obtained for each probe orientation have quite similar tendencies and sizes. Figure 11. displays the range of all measured values from Figures 8, 9 and 10. It can be seen that the influence of the probe orientation and the direction of the wood grain is about 2%. The curves obtained by the A and B probes are close to each other and lie below the curves obtained by the C probes, which are shifted horizontally by roughly around 2%.
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<td>10.20%</td>
<td>10.51%</td>
<td>11.43%</td>
<td>11.86%</td>
<td>12.13%</td>
<td>12.19%</td>
<td>13.66%</td>
<td>14.28%</td>
</tr>
<tr>
<td>A</td>
<td>19681</td>
<td>13700</td>
<td>6558</td>
<td>2833</td>
<td>1496</td>
<td>747</td>
<td>340</td>
<td>213</td>
<td>209</td>
<td>156</td>
<td>97</td>
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</tr>
<tr>
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<td>23737</td>
<td>15293</td>
<td>6945</td>
<td>3019</td>
<td>1437</td>
<td>695</td>
<td>304</td>
<td>194</td>
<td>184</td>
<td>156</td>
<td>92</td>
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</tr>
<tr>
<td>C</td>
<td>30981</td>
<td>21213</td>
<td>11066</td>
<td>5170</td>
<td>2612</td>
<td>1328</td>
<td>559</td>
<td>379</td>
<td>359</td>
<td>271</td>
<td>171</td>
<td>99</td>
</tr>
</tbody>
</table>

Figure 8. Obtained resistances from both methods for probe “A”.
5. Statistical Evaluation of Results

A study by the authors Bland and Altman [23] revealed that any two methods designed to measure the same parameter should show good correlation when a set of samples are chosen for which the parameter to be determined varies considerably. Therefore, a high correlation coefficient obtained for any two methods designed to measure the same property is just a sign that the sample chosen for measurement has a parameter which varies widely. It does not necessarily imply that there is a good agreement between the two methods. Hence, the analysis below was conducted to provide deeper insight into the differences between the two sets of measurements obtained by the two presented methods.

5.1. Construction of Bland-Altman Plots
The plot has two axes. The x axis represents the mean of the values measured by the RC method and the integrator method. The y axis represents the differences between the values obtained by the two described methods. If there is agreement between two methods, the values in Figure 12 are expected to cluster around the mean of the differences (called the bias), and certainly within the limits of agreement. The dashed lines in the plots represent the lower and upper limit of agreement. It is evident that only two points lie outside the limits of agreement.

Figure 12. Bland-Altman plot for all samples measured at probe “A”

5.2. Proportional Measurement Bias

Proportional bias can also be investigated via Bland-Altman plots, which indicate that the methods do not agree equally through the range of measurements. The limits of agreement are then dependent on the actual measurements. When the relationship between differences is identified, e.g. via regression analysis, the regression-based 95% limits of agreement should be provided, or proper transformation of the differences should be conducted. The range of measured differences between both methods is dependent on the average value of both methods. It is evident from the regression coefficient ($R^2 = 0.73$) shown in Figure 12 that the dependence is present with higher scattering for the higher resistances. In other words, the limits of agreement are underestimated (too wide) for low values and overestimated (too narrow) for high values. In such cases logarithmic data transformation can be used. The goal of transformation is to determine the limits of agreement that are valid for the entire range of values. The Bland-Altman plot for the transformed data measured at probe A for all samples is shown in Figure 13.

Figure 13. Bland-Altman plot for all samples measured at probe “A” – logarithmic transformation
The regression coefficient decreased ($R^2 = 0.34$) for the transformed data and the points are more evenly distributed between the new limits of agreement. Nevertheless, three points still lie outside the limits of agreement. Bland-Altman plots for the transformed data measured at probe B and C for all samples are displayed in Figures 14 and 15. When the position of the electrode is ignored, all realizations are within the calculated limits of agreement (see Fig. 16).

**Figure 14.** - Altman plot for all samples measured at probe “B” – logarithmic transformation

**Figure 15.** - Altman plot for all samples measured at probe “C” – logarithmic transformation

**Figure 16.** - Bland-Altman plot for all samples and all probes – logarithmic transformation
6. Discussion

The main advantage of RC circuits is the simplicity of adapting timer circuits to emit digital signals. It is easier to integrate this kind of circuit in the sensors utilized by today’s digital electronics devices. The key limitation of such circuits is their long capacitor charge period at lower moisture contents. Sometimes it may be necessary for a capacitor to charge for a relatively huge time; this would not be recorded by the controller which evaluates the signal from the 555 timer chip at low moisture contents. The second problem is the resolution of charging time, which could be very small at higher moisture contents and thus could cause higher repeatability errors to affect measurements.

The integration method shows voltage changes, which allows the identification of lower moisture content much faster than an RC circuit. The main disadvantage of the integration method is the need for a symmetric power supply, as well as other circuits for the postprocessing of analog signals. Postprocessing circuits for analog signals are expensive and sensitive. The sensitivity of these circuits could lead to worse measurement repeatability and accuracy at lower moisture contents.

The range of differences between the two proposed methods is statistically important for small moisture contents of approximately below 8% (which correspond to high resistances) if the direction of fibers is taken into account. At moisture contents under 8% wood has very high resistance and these methods of measurement are affected by significant errors. Based on the results of the statistical analysis, it is recommended that the threshold moisture content for the use of the proposed methods be set at 8%. Both of the proposed methods show good agreement for a range of moisture contents above this threshold. The measured value corresponding to a moisture content of approx. 9.5% is outside the limits of agreement in the case of all three of the probes, which indicates there is a problem with this individual measurement. The measured value corresponding to the moisture content \( w = 13.66\% \) in the case of probe B also seems not to be a systematic error, but rather an isolated measurement error.

7. Conclusions

The aim of the study was to compare two electrical methods in order to identify their differences and assess their final suitability. As can be seen based on the data obtained, both methods can successfully identify moisture changes within the range of 8 to 15 percent with a resolution and accuracy of about 0.5 percent of moisture content. Furthermore, the advantages and disadvantages of the methods have been analyzed. The RC-circuit is easier to implement thanks to the digital signals of the 555 chip, whilst the integration method allows faster measurement at lower moisture contents.

The RC method seems to be more suitable for intelligent sensors integrated within the structure of a building to perform its long-term monitoring. Low moisture content significantly limits the effectiveness of the two methods due to the high resistance of the wood, and both methods can fail in this situation. At moisture contents higher than 8% both methods seem to be adequately suitable. Based on an analysis of the results of both methods, moisture values ranging from 8 – 15 percent also reach similar levels from the statistical point of view (the differences between both methods are within the limits of agreement for this moisture content range).

It is planned that further research will focus on the improvement of circuits and signal processing from the electrical point of view. Further measurements with higher moisture contents and various kinds of wood need to be analyzed using the two methods to expand the options for their application in buildings.

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