Modelling of Resistance-Type Wood Moisture Meters for Three Deciduous Tree Species (Black Alder, Birch, Aspen) in Moisture Contents Above Fibre Saturation Point

VALDEK TAMME[1*], PEETER MUISTE[1], ALLAR PADARI[1] AND HANNES TAMME[2]

[1*] *Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia, Tel.+372 7313108, e-mail: valdek.tamme@emu.ee*

[2] *University of Tartu, Ülikooli 18, 50090 Tartu, Estonia, e-mail: htamme@ut.ee*

Tamme, V., Muiste, P., Padari, A. and Tamme, H. 2014. Modelling of Resistance-Type Wood Moisture Meters for Three Deciduous Tree Species (Black Alder, Birch, Aspen) in Moisture Contents Above Fibre Saturation Point. *Baltic Forestry* 20(1): 157–166.

Abstract

For fast detection of wood moisture content (MC), handheld resistance-type and capacitance-type electrical moisture meters are widely used. In moisture contents above the fibre saturation point (FSP), the measuring accuracy and precision of resistance-type moisture meters starts to progressively decrease as the wood MC increases. The aim of this research was to quantitatively explore this well-known qualitative trend. Three different resistance-type wood moisture meters from leading manufacturers were compared. The display readings of the moisture meters were compared by using the absolute MCs determined for relevant specimens with the oven-dry method. The specimens with the dimensions of 100x60x60 mm (length x width x thickness) were made of three different tree species (black alder, birch, aspen); a total of 60 specimens per each tree species were used. The specimens were dried in a climatic chamber under equal conditions (32°C and 98% RH) until the desired MC was achieved. All wood MC measurements were conducted at a room temperature of 20°C.

Modelling of experiment data confirmed the progressive increase in the absolute error in a single measurement of wood MC with resistance-type moisture meters as the average absolute MC rose. Based on the model, the absolute error on the same confidence level (95%) and for the average MC of 27% was ± 3.9% MC, for the average MC of 60% it was ± 10% MC, and for the average MC of 97% the absolute error was ± 17.5% MC. The best prediction error in wood average MC predicted on the basis of the same model was ± 1.12% MC. The same model was used to predict the resolution of resistance-type moisture meters for the above-mentioned average MCs, which was found to be approximately 1% MC.

Key words: wood drying, wood moisture meter, above FSP

Introduction

Portable electric wood moisture meters can be categorised into two groups based on their operating principle: direct current (DC) resistance-type moisture meters (Stamm 1927, James 1988, 1993) and high frequency alternate current (AC) (2-3 MHz) capacitance-type moisture meters (Ressel 2006). Capacitance-type moisture meters are contact-free, whereas a direct galvanic contact with wood is required for resistance-type moisture meters that uses two electrodes to do the measuring. The reliable measuring range of capacitance-type moisture meters is considered 2–30% MC (Ressel 2006, Bergman 2010). Historically, the main and most accurate measuring range of resistance-type moisture meters has been 7-18% in absolute MC (Norberg 1999, Forsen and Tarvainen 2000) (of dry weight), sometimes also 4–22% (Ressel 2006), and the extended measuring range has been 18–30% (Rozema 2010, Boardman et al. 2011), sometimes also 22–40% (Straube et al. 2002). The range above FSP where wood absolute MC reaches 30-100% is considered non-calibrated mostly due to the high variance in the readings of moisture meters (Vermaas 2002, ASTM Standards 2008). It has even been suggested that "... an indicated MC-reading is more or less a rough guess"(Ressel 2006) and that "readings greater than 30% must be considered only qualitative" (Bergman 2010). A more detailed qualitative assessment of resistance-type moisture meters in the range above FSP is given by manufacturers on their web pages, for example Gann (Gann 2013): "In the range above the fibre saturation point (about 30 % MC) readings become progressively less accurate, depending on the moisture content of the timber to be measured, its specific weight and temperature and the species of wood. … whereas relatively accurate readings can be obtained with oak, beech, white afara, etc. up to range of 60–80 % moisture content". Also Brookhuis (Brookhuis 2009) stated that "Measurements below 7% and above the wood fibre saturation point are not accurate. For a precise determination beyond the measuring range, we recommend using the oven-dry method". These recommendations were taken into account in the source data used for statistical modelling in this research.

Above FSP, substantial discrepancies were documented (Karu 2011) between moisture meter readings and MCs of specimens, which were determined with the oven-dry method. It was also found that numerical differences between meter readings and relative MCs were noticeably smaller than between meter readings and absolute MCs. For wood air drying practices, the research (Tamme et al. 2012a) presented correction formulas for compensating for the differences between absolute MCs and relative MCs and moisture meter readings.

The resistance method as an affordable and reliable method is widely used for monitoring MCs in the wood drying process (Tronstad et al. 2001, Tamme et al. 2010, 2011) as well as in building envelopes (Straube et al. 2002, Onysko et al. 2008). For this reason, it is especially important to quantitatively evaluate the measuring accuracy of the resistance method for MCs above FSP.

It should be mentioned that wood fibre saturation point (FSP) may somewhat differ between tree species (Higgins 1957). If wood FSP has not been accurately determined, the approximate value of 30% MC is used as FSP (Class and Zelinka 2010).

The primary purpose of this research was to carry out a statistically reliable assessment of the progressive decrease in the measuring accuracy of resistance-type wood moisture meters as the wood MC rises above FSP (30-100% MC). In addition, the research also set out to determine the resolution of the moisture meter Gann HT 85T for both resistance (k?) and moisture content (% MC) units above FSP, and to compare the wood moisture meters used in the experiments.

The statistical models developed for wood moisture content also enable a wider interpretation (and not just a quantitative description) of the phenomenon of progressive decrease in the measuring accuracy of a single measurement with wood moisture meters. The greatest benefit of a statistical model describing wood moisture content is the opportunity to predict the average moisture content of a batch of wood with sufficient accuracy for practical needs, by a non-destructive method and within a reasonable period of time without having to use the labour- and resource-intensive oven-drying procedure every time. Sometimes the wood moisture content prediction is required for determining the mechanical properties of wood, such as the modulus of elasticity (MOE) and modulus of rupture (MOR) by a non-destructive ultrasound method (Wang et al. 2004). In fact, both the MOE and MOR are highly dependent on wood density. In turn, wood density correlates strongly with wood moisture content both above FSP and below FSP (Kretschmann 2010, Cai 2008, Carter et al. 2005).

Materials and Methods

The research made use of specimens of black alder (*Alnus glutinosa*), birch (*Betula pendula*), and European aspen (*Populus tremula*), each with the dimensions of 100x60x60 mm (height x width x thickness). The specimens were dried in the Feutron climatic chamber (Feutron 2013) under equal conditions (at 32°C, 98% RH and air velocity of 0.4 m/s) until the desired MC was achieved. All wood MC measurements were carried out at a room temperature of 20°C. Resistance type wood moisture meters Gann HT 85 T (Gann 2013), FMD-6 (Brookhuis 2013) and NDT James Moisture Master (Ndtjames 2013) from three different manufacturers were used. The measurement resolution of all moisture meters used in the experiments was ± 0.1% MC. The chosen measuring depth of measuring electrodes was 1/3 of the thickness of a specimen (that is, in the case of a 60 mm specimen, the measuring depth was 20 mm of the surface of the specimen). Measuring electrodes (teflon insulated pins, 60 mm) were tapped with a Gann hammer electrode RAM- IN electrode M18 (Gann 2013) to a depth of 20 mm. The number of specimens per each tree species was n = 60.

A Kern weighing scale (Kern-sohn 2013) was used. The absolute MC of dry weight of the specimens was determined according to the standard ISO 3130:1975. The following methodological assumption was the basis for the comparison test of the moisture meters: only the average MC of the specimens was determined by the oven-dry method and the respective reading of the moisture meter was recorded. The influence of possible moisture gradients in each specimen on measuring results was not taken into account since a non-destructive method could not be used for detecting moisture gradients in the specimens.

Experiment data was statistically processed in two stages. In the first stage, statistical variables were analysed one by one by methods of descriptive statistics, and in the second stage, the variables (measurements) were examined by measures of association by methods of regression analysis.

While processing the experiment data it became clear that although the purpose was to study MCs above FSP, in some cases the trend lines that had been obtained overlapped The best prediction error in wood average MC predicted on the basis of the same model was ± 1.12% MC (for example in the case of FMD-6). Due to this overlap, it can be said that the range of application of the established trend lines is even slightly wider than the MCs above FSP that was suggested in the title of this article.

In the second stage of statistical processing the experiment data, a simple univariate linear regression was used. Inverse regression was applied (Onysko et al. 2008) and therefore the moisture meter reading was chosen as the independent variable. Inverse regression was used because it is better suited for practical needs and because the purpose of this research was not calibration of moisture meters but simply their comparison under under the same conditions. A total of nine regression models were developed for three tree species and three moisture meters. Logarithmic transformation was applied to the actual MC variable. The initial variable was again used for making conclusions based on the model. For testing the reliability of the regression line that was found, the Kolmogorov-Smirnov test was used in all comparisons to evaluate the normal distribution of prediction residuals, and where possible, the Shapiro-Wilk test was also used. The tests were then doubled with visual control methods of normal distribution (a histogram with the density of probability and a Q–Q plot). Statistical modeling was done in the statistical software environment of R (*r*-project 2013).

Statistical modelling of wood moisture content produced the essential parameters of regression models: *R*-squared of the model, (b) standard error (*SE*) of the model, and (*c*) 95% confidence interval (CI) of the regression line. The confidence interval for individual predictors is substantially larger than the one computed above for the predicted mean (Sachs 1982). The most important external parameters in relation to regression models include the optimal number of measurements, repeatability of measurements and the repeatability (reproducibility or validation) of regmodels. Repeatability of results of measurement is defined as closeness of the agreement between the results of successive measurements of the same measuring carried out under the same conditions of measurement (ISO 3534-1:1993). Validation of regression models is based on the following property (Sachs 1982): the variance of a sum or difference of independent random variables (e. g. old and new samples) is equal to the sum of their variables, i.e.

$$D(X + Y) = DX + DY. \quad (1)$$

As rough approximation we can assume that the residual variances DX and DY of two models are equal, $DX = DY$, and the standard error of the new regression model $SE1$ is:

$$SE1 = \sqrt{D(X+Y)} = \sqrt{2DX} \approx 1.4SE$$

(a) *R*-squared:

$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2} \quad (2)$$

The expression (2) is a measure of how well the predicted ($\hat{y}_i$) values fit. The less the observed values depart from the fitted line, the smaller this ratio is and the closer R^2 is to 1. Thus R^2 can be considered a measure for how well the regression line explains the observed values.

(b) Standard error of regression model (*SE*):

$$SE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y})^2}{n-2}} \quad (3)$$

SE is a measure of the inadequacy of fit for the fitted equation $\hat{y} = a + bx$, or of the error which is made in the estimation or prediction of y from given values of x (Sachs 1982).

Wood electrical equivalent resistance method was used for experimental determination of the resolution of the moisture meter Gann HT 85T in electrical resistance units on two moisture levels selected in the beginning and end of the moisture range above FSP (30-100% MC). For simulation of equivalent wood electrical resistances in the moisture meter input, a resistance box type P4002 was used, which had the accuracy class of 0.05 and a selectable resistance range of 10 kΩ–100 MΩ (Metrosert 2013). Different resistances were used in the moisture meter input so that the reading would change ± 0.1% MC on a selected moisture level. The divergence of the resistances in this range is corresponding to the experimentally determined resolution. For calculating the resolution according to the actual MC (that is, gravimetric MC determined with the oven-dry method), the most reliable (confirmed by both the Kolmogorov-Smirnov test and the Shapiro-Wilk test) regression line was used based on the presumption of it being 100% reliable. This way, the regression line obtained a fixed transfer function, that is, it acted as a calibration curve (corrected in the comparison test). It was also noted that resolution is an idealised parameter (a certain limit value) of a measuring device, which actual measuring accuracy never achieves.

Results

Research results are presented in the following Tables and Figures. Tables 1, 2 and 3 are presenting the results of processing of the experimental data by the method of descriptive statistics for three hardwood species. Tables 4, 5 and 6 are presenting the results

Table 1. Testing of moisture meters on black alder specimens

Statistical parameter	Oven dry actual MC %	Moisture meter readings		
		Gann (MC %)	NDT James (MC %)	FMD – 6 (MC %)
Range 1	68.6 – 124.8	32.6 – 39.2	30.4 – 33.3	29.8 – 33.5
Range 1, mean	105.7	35.9	31.6	31.8
Range 1, st. dev.	12.154	1.299	0.819	0.908
Range 2	52.7 – 65.5	26.8 – 30.9	25.4 – 30.7	26.4 – 28.7
Range 2, mean	59.5	28.6	27.7	27.4
Range 2, st. dev.	3.66	1.104	1.259	0.577
Range 3	27.3 – 37	19.9 – 23.8	23 – 29	21.4 – 24.7
Range 3, mean	31.56	21.8	25.6	23.1
Range 3, st. dev.	2.031	0.793	1.52	0.718

Table 2. Testing of moisture meters on birch specimens

Statistical parameter	Oven dry actual MC %	Moisture meter readings		
		Gann (MC %)	NDT James (MC %)	FMD – 6 (MC %)
Range 1	69.4 -91.5	38.3 – 46.8	32 – 36.6	31.3 – 36.8
Range 1, mean	85.2	42.4	34	33.8
Range 1, st. dev.	3.85	2.129	1.067	1.22
Range 2	44.5 – 60.3	31.9 – 36.6	27.3 – 31.2	27.2 - 31
Range 2, mean	49.8	34.1	29.4	28.8
Range 2, st. dev.	4.44	1.312	1.167	0.914
Range 3	26.4 - 37	22.5 -28.8	23.3 – 29.5	23.2 – 28.7
Range 3, mean	30.3	24.9	26.6	25.2
Range 3, st. dev.	2.355	1.423	1.409	1.069

Table 3. Testing of moisture meters on aspen specimens

Statistical parameter	Oven dry actual MC %	Moisture meter readings		
		Gann (MC %)	NDT James (MC %)	FMD – 6 (MC %)
Range 1	86.5 – 117.2	43.7 – 50.1	34.8 – 39.7	31.5 – 35.7
Range 1, mean	107	47.4	37.6	32.6
Range 1, st. dev.	7.745	1.327	1.018	0.885
Range 2	39.2 – 70.5	33.6 – 37.6	28.2 – 33.4	24.9 – 30.1
Range 2, mean	56.5	35.9	30.5	27.2
Range 2, st. dev.	7.866	1.07	1.251	1.25
Range 3	23 – 40.6	20.5 – 29	21.8 - 29.2	20 – 29.3
Range 3, mean	29.9	24.3	25.3	23.5
Range 3, st. dev.	3.482	1.911	1.753	1.856

of modelling of moisture metres for three hardwood species and Figures 1, 2 and 3 display the results graphically. Figures 4 and 5 present the regression residuals histogram and Q-Q plot (propability paper) corresponding to positive Shapiro-Wilk test results. According to the Kolmogorov-Smirnov test, the distribution of prediction residuals in the regression model may be considered close to normal. The regression models used in all comparisons fit this definition. According to the Shapiro-Wilk test, the distribution of residuals in the regression model may be considered normal. The regression models in two comparisons (black alder – Gann HT 85T and birch – NDT James Moisture Master) fit this definition.

The resolution of the moisture meter Gann HT 85T according to resistance was experimentally determined (the wood group switch was in the 3rd position and the temperature switch in the 20°C position) with the resistance simulation method for two wood MCs: wood MC of 85.4% ± 0.1% MC produced the resolution of

Table 4. Modelling of moisture meters on black alder specimens. Independent variable in regression model is moisture meter reading in MC %

Parameter	Meter		
	Gann HT 85T	NDT James	FMD-6
No. of observations	134	133	134
Intercept (Int.)	0.711	-0.358	0.573
Lower 95% of Int.	0.675	-0.514	0.458
Upper 95% of Int.	0.748	-0.201	0.688
p-value of Intercept	$p < 0.001$	$p < 0.001$	$p < 0.001$
Slope (Sl.)	0.03640	0.0743	0.0427
Lower 95% of Sl.	0.0352	0.0688	0.0387
Upper 95% of Sl.	0.0376	0,0798	0.0468
p-value of Slope	$p < 0.001$	$p<0.001$	$p < 0.001$
R-squared (R^2)	0.963	0.847	0.765
Standard Error of Regmodel (*SE*)	0.04836	0.09783	0.1213
p-value of Regmodel	p < 0.001	$p < 0.001$	$p < 0.001$
*) ks. test of residuals, *p*-value	$p = 0.5412 > 0.05$	$p = 0.4156>0.05$	$p = 0.1224>0.05$
Shapiro-Wilk test of residuals, *p*-value	$p = 0.2274 > 0.05$	$p = 0.0177<0.05$	$p = 3.0e-5<0.05$

*) ks.test – Kolmogorov-Smirnov test of residuals

Table 5. Modelling of moisture meters on birch specimens. Independent variable in regression model is moisture meter reading in MC %

Parameter	Meter		
	Gann HT 85T	NDT James	FMD-6
No. of observations	134	134	134
Intercept (Int.)	0.8673	0.0437	0.2468
Slope (Sl.)	0.0249	0.05504	0.0495
R-squared (R^2)	0.968	0.920	0.942
Standard Error of Regmodel (*SE*)	0. 0385	0.0604	0.0514
ks. test of residuals, *p*-value	$p = 0.1069 > 0.05$	$p = 0.7638 > 0.05$	$p = 0.1995 > 0.05$

Table 6. Modelling of moisture meters on aspen specimens. Independent variable in regression model is moisture meter reading in MC %

Parameter	Meter		
	Gann HT 85T	NDT James	FMD-6
No. of observations	140	140	140
Intercept (Int.)	0.894	0.399	0.155
Slope (Sl.)	0.0239	0.0432	0.0568
R-squared (R^2)	0.982	0.946	0.936
Standard Error of Regmodel (*SE*)	0.0361	0.0619	0.0676
ks. test of residuals, *p*-value	$p = 0.4579 > 0.05$	p = 0.1469 > 0.05	$p = 0.09119 > 0.05$

10 kΩ ± 0.104 kΩ, b) wood MC of 30% ± 0.1% MC produced the resolution of 370 kΩ ± 5 kΩ. The resolution of a wood moisture meter according to resistance is significant when a resistance meter is added in the moisture meter comparison test.

According to a statistical model, the resolution of the moisture meter Gann HT 85T was calculated at wood actual MC as follows: a) 97% MC produced the resolution of 0.82% MC, and b) 27% MC produced the resolution of 0.23% MC. According to the actual MC

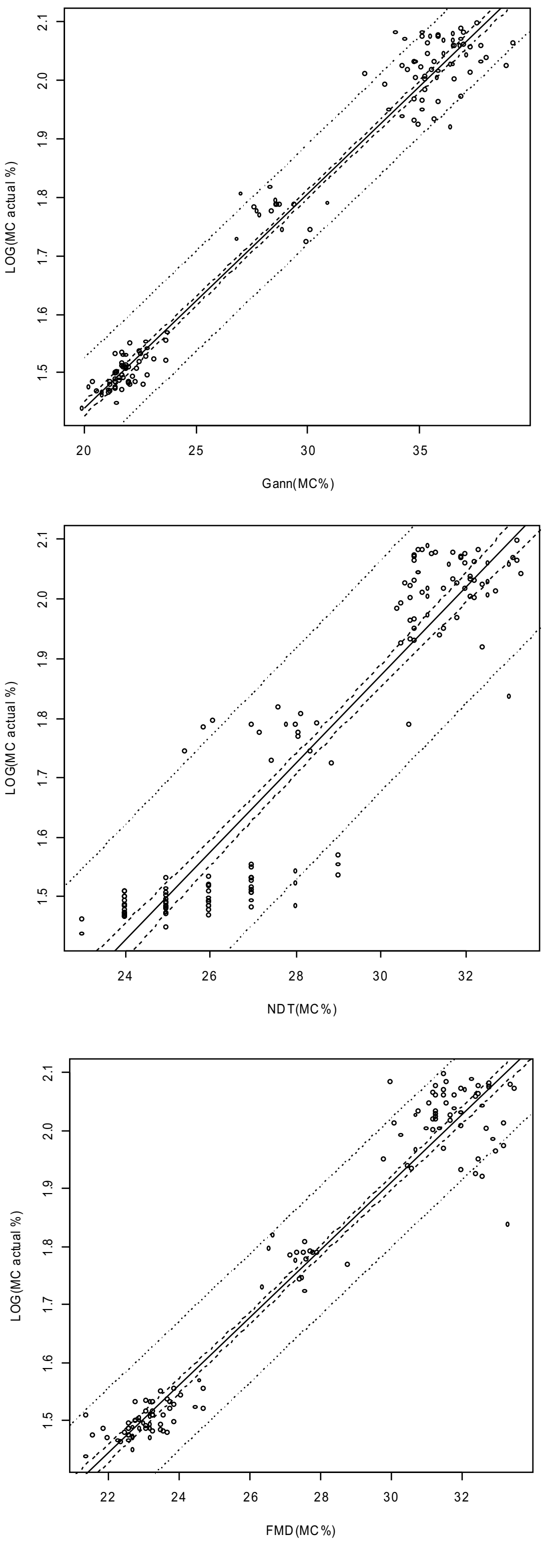

Figure 1. Regression lines of testing wood moisture meters Gann HT 85T, NDT James Moisture Master and Brookhuis FMD-6 on black alder specimen with their 95% confidence and tolerance bands (LOG(MC actual %) – actual MC in log_{10}; Gann, NDT, FMD – meter reading MC, %)

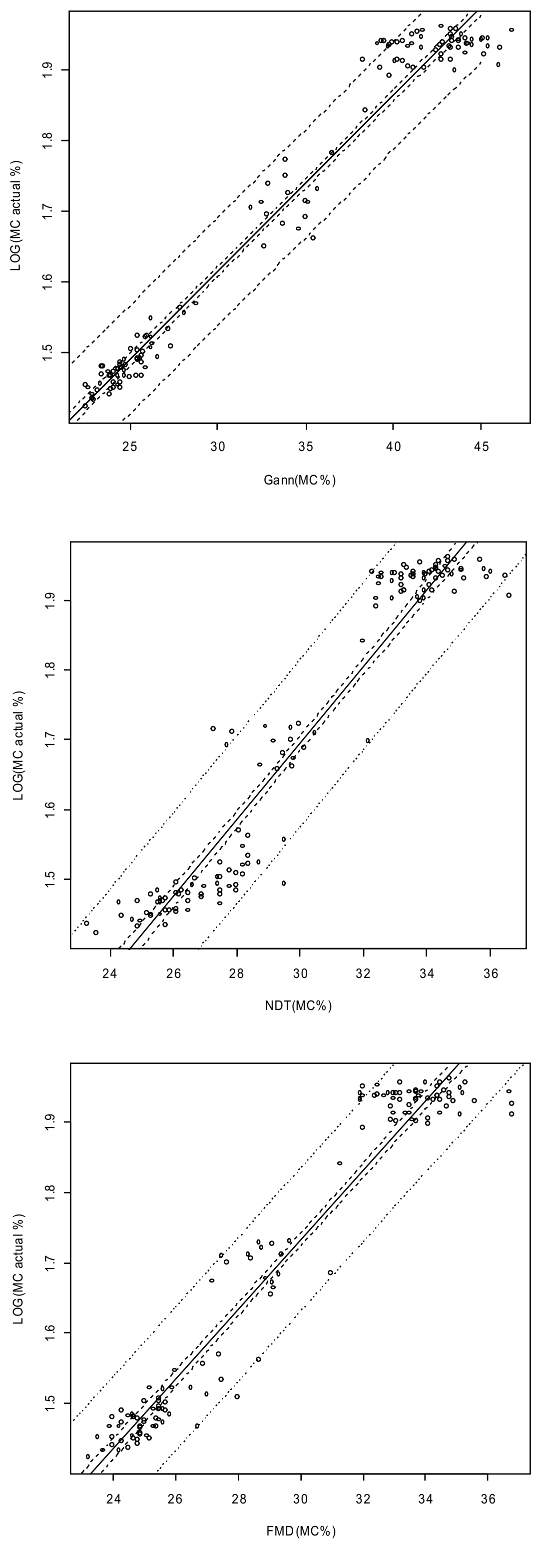

Figure 2. Regression lines of testing wood moisture meters Gann HT 85T, NDT James Moisture Master and Brookhuis FMD-6 on birch specimen with their 95% confidence and tolerance bands (LOG(MC actual %) – actual MC in log_{10}; Gann, NDT, FMD – meter reading MC, %)

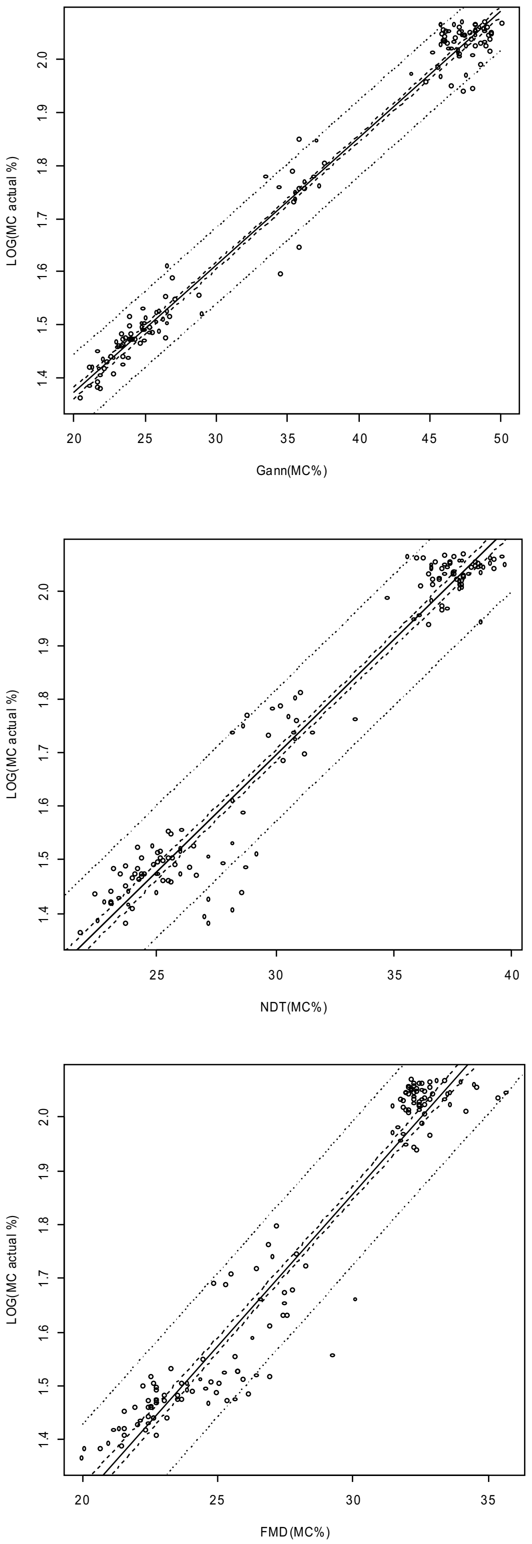

Figure 3. Regression lines of testing wood moisture meters Gann HT 85T, NDT James Moisture Master and Brookhuis FMD-6 on aspen specimen with their 95% confidence and tolerance bands (LOG(MC actual %) – actual MC in $\log_{10}$; Gann, NDT, FMD – meter reading MC, %)

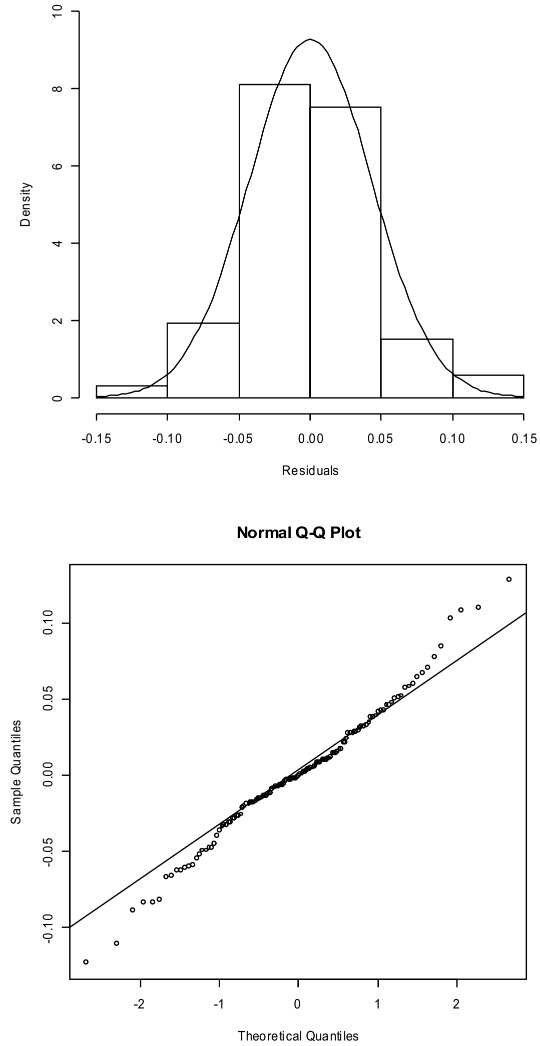

Figure 4. Black alder – Gann HT 85T histogram of residuals with curve of density of probability of normal distribution and Q-Q plot of regression model

above FSP, the total resolution based on a robust approach, is approximately 1% MC.

From a practical standpoint, it is vital to answer the question of up to which MC the moisture meters can reliably be used. In using moisture meters, the upper MC limit has been determined with an electrical resistance value at which the meter still displays a stable reading. Depending on the tree species, this value may be different. For example, the research (Tamme et al. 2012b) found the minimum electrical resistance to be 10 kŁ, which corresponded to the average oven-dry MC of 146% of the pine sapwood specimen.

Statistical modelling of experiment data confirmed the progressive increase in the absolute error in a single measurement of wood actual MC as the average absolute MC rose. The absolute error found by the moisture meter Gann HT 85T on the basis of the mod-

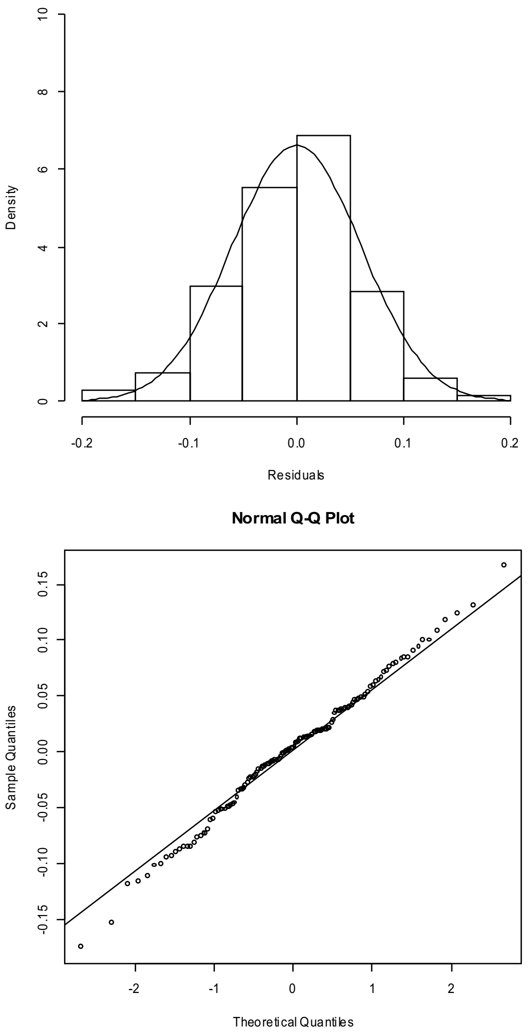

Figure 5. Birch – NDT James Moisture Master histogram of residuals with curve of density of probability of normal distribution and Q-Q plot of regression model

el on the same confidence level (95%) and for the average MC of 27% was ± 3.9% MC; for the average MC of 60% it was ± 10% MC and for the average MC of 97% the absolute error was ± 17.5% MC. The absolute error with a "+" sign was determined on the basis of the upper 95% confidence limit of regression parameters and the absolute error with a "-" sign was determined on the basis of the lower 95% confidence limit of regression parameters.

When comparing the moisture meters used in the experiments, it can be suggested based on tables 4, 5 and 6 that the SEs of the regression models developed for the moisture meter Gann HT 85T are, in the case of all three tree species, approximately two times smaller than those for moisture meters NDT James and FMD-6. Moreover, R-squared values of the models produced for Gann HT 85T are the greatest in the case of all three tree species compared to the other two moisture meters NDT James and FMD-6 used in the experiments.

Discussion

The standard deviation (st. dev.) in the empirical distribution of the MCs determined in the specimens with the oven-dry method indicates a downward trend when the specimens are slowly dried under equal conditions (see Tables 1, 2 and 3). This trend emerged in case of the specimens of all three dried tree species. The fact that a slow drying mode evens out the differences between the average MCs of the specimens is, most likely, one of the manifestations of Fick's law.

Modelling of wood MC above FSP improves the accuracy of determining wood MC. This quality can be best illustrated by (figuratively) transferring the modelling results obtained in this research to a real production situation (in sawmills, treatment plants and so on).

Example (of a figurative construction): 60 boards (i.e. the sample) have been randomly selected from a batch of black alder boards (e.g. the population). The task is to estimate the average moisture content of the batch of wood based on the sample. First, the oven-drying method is used. If the moisture content of a single board is determined by oven-drying, the average possible error is 12.2% (see row "St. dev. of range 1" Table 1 in the case of an average MC of 97% chosen for the example calculated by the parameters of regression model described in the Table 4). However, determining the moisture content of all 60 boards by oven-drying enables detecting the average moisture content (97% MC in this specific example) with great accuracy (see Table 1 data, at least 1.58% MC). In spite of the high accuracy of the oven-dry method, it also has a few flaws. Firstly, it will take a few days to get the results. During this time, the wet wood has continued to dry on the storage site and thus, the results may no longer be reliable. Secondly, this method is a destructive one as sawing the specimens out of the boards reduces the quality of the remaining board parts. Thirdly, the cost of electric energy, labour force and equipment (high-quality drying chambers and precise scales) is high. All in all, using the oven-dry method in practice is only justifiable in certain cases and for the purpose of developing statistical models. In the following segment, the average moisture content of 60 boards (sample) is predicted on conditions equal to those of the oven-dry method. Data in Table 1 is applied separately to variables and data in Table 3 is used for the regression model of the moisture meter Gann HT 85T. By measuring the moisture content of a single randomly selected board with the moisture meter Gann HT 85T, the average possible margin of error is 17.5% MC (the margin of error, in this case, is somewhat larger than in the case of the oven-dry method where it is 12.2% MC). If the average moisture content of the 60 boards (which as in the previous examples was 97% MC) is predicted on the basis of the SE of the regression model, the possible average margin of error is 1.12% MC. Therefore, the prediction of the average moisture content of the wood batch based on the model has proven to be surprisingly accurate. To confirm this prediction, the 60 boards of the sample must be actually measured. If a wood moisture meter has a memory for recording readings (as in FMD-6 or Gann model 2050), the actual measuring speed is two measurements per minute and the entire procedure would take half an hour. Let us assume that instead of 60 measurements we limit ourselves to 30 measurements, thereby halving the number of measurements. In that case, the *SE* of the model would increase by four times based on the equation (3), and in predicting the average moisture content, we would have on average a margin of error of 1.56% MC. According to the model repeatability principle, the measuring series of the next 60 measurements (that is, the new sample) should result in a 1.4 time increase in the *SE*. This would mean that in the next moisture content prediction based on the previous model and new measuring data, we would on average have a margin of error of 1.17% MC.

In the modelling of wood moisture content, it is important to keep in mind that there is no real need to use calibrated measuring instruments such as wood moisture meters. Therefore, the metrological parameters that were significant for calibrated wood moisture meters (e.g. accuracy, repeatability, reliable measuring range, etc.) take on a new meaning in a statistical model even from the point of view of the model as a whole. For example, an analogy could be drawn between the terms *accuracy* and *quality of the model* and *confidence interval of estimated regression parameters*, and *reliable measuring range* could be similar to *reliable model domain*, and *repeatability* could be compared to *model reproducibility*, etc. If this research had made use of three electrical resistance meters (that is, if their scale readings would have been given in kΩ) instead of three calibrated wood moisture meters, there would probably not have been any noticeable changes in the obtained regression model parameters. The only prerequisite for measuring instruments used for modelling is their sufficient moisture sensitivity (that is, upon a single-unit change in wood moisture content their output signal should be reliably detected). Linearity of the output signal of the used measuring instruments as well as time stability would also improve the essential parameters of the statistical model. The methodology applied in this research does not require according to Vermaas (Vermaas 2002) "attempts to "calibrate" resistance moisture meters for use above f. s. p.".

Conclusions

To acquire the calibration curve, the *in situ* calibration method is used, which is characteristic of non-destructive methods. It is presumed that an individual measurement is non-reliable; essentially the pre-calibration of the moisture meters by the manufacturer is also ignored. The statistics procedure automatically adapts to the pre-calibration and produces correct parameters of the model. With this, the pre-calibrated wood moisture meters are recalibrated. The recalibration curve is found for the average values of a large number of measurements, as is the practice in non-destructive methods.

Modelling of experiment data confirmed the progressive increase in the absolute error in a single measurement of wood MC with resistance-type moisture meters as the average absolute of MC rose. Based on the model, the absolute error on the same confidence level (95%) and for the average MC of 27% was ± 3.9% MC, for the average MC of 60% it was ± 10% MC and for the average MC of 97% the absolute error was ± 17.5% MC. The predicted error of wood average MC by the same model was ± 1.12% MC. The model was also used to predict the resolution of resistance-type moisture meters, which was found to be approximately 1% MC. It was found that in the modelling of wood moisture content, utilization of measuring instruments previously calibrated into wood moisture meters is not necessary. Necessary prerequisites include moisture sensitivity of measuring instruments, linearity of output signal, and time stability.

Acknowledgements

This research was supported by grant No. 906 of the Environmental Investment Centre of Estonia.

References

ASTM D4444-08. 2008. Standard Test Method for Laboratory Standardization and Calibration of Hand-Held Moisture Meters, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, 10 pp.

Bergman, R. 2010. Drying and Control of Moisture Content and Dimensional Changes. Wood Handbook, General Technical Report No. FPL-GTR-190, Forest Service, Forest Products Laboratory, U. S. Dept. of Agriculture, Madison, WI, 2010: 20 pp. (Cited 14.12.2013). Available: http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr190/chapter_13.pdf

Boardman, C. R., Glass S. V. and Carll, C. G. 2011. Moisture Meter Calibrations for Untreated and ACQ-Treated Southern Yellow Pine Lumber and Plywood. *Journal of Testing and Evaluation* 40(1): 1 – 10

Brookhuis Micro- Electronics BV.2009. Moisture measuring manual Version 1.4, 27 pp.

Cai, Z. 2008. A new method of determining moisture gradient in wood. *Forest products journal* 58(7/8): 41-45

Class, S.V. and Zelinka, S. L. 2010. Wood Handbook, Chapter 04. Moisture Relations and Physical Properties of Wood. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA. 19 pp.

Carter, P., Briggs, T., Ross, R.J. and Wang, X. 2005. Acousting testing to enchance western values and meet customer wood quality needs. - Productivity of western forests: a forest products focus. Portland, OR :U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General technical report PNW; GTR-642; 121-129. (Cited 14.12.2013). Available: http://www.fpl.fs.fed.us/documnts/pdf2005/fpl_2005_carter 001.pdf

Edwards, N. C. 1974. Procedure for the determination of species correction data for electrical resistance type moisture meters. CSIRO Div. For. Prod. (Unpublished divisional report), 10 pp.

Forsén, H. and Tarvainen, V. 2000. Accuracy and functionality of hand-held wood moisture content meters. VTT (Espoo 2000), VTT Publications 420: 102 pp. (Cited 14.12.2013). Available: http://www.vtt.fi/inf/pdf/publications/2000/P420.pdf

ISO 3130:1975. 1975. Wood – Determination of moisture content for physical and mechanical tests. International Organization for Standardization, Switzerland, 2 pp.

ISO 3534-1:1993. 1993. Statistics – Vocabulary and symbols – Part 1: Propability and general statistical terms. Geneva: International organisation for standardization, 105 pp.

Higgins, N. C. 1957. The EMC of selected native and foreign woods. *Forest Product Journal* 7(10): 371 - 377

James, W. L. 1988. Electric moisture meters for wood, *General Technical Report No. FPL-GTR-6,* U. S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI: 19 pp. (Cited 14.12.2013). Available: http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr06.pdf

James, W. L. 1993. In: Fundamentals of hand held moisture metes: An outline. Proceedings. ASTM Hand Held Moisture Meter Workshop, Madison, WJ, Forest Product Society, 5 May 1993: 13 – 16

Karu, M. 2011. Accuracy of moisture meters at different moisture levels. Bachelor thesis. Estonian University of Life Sciences. Tartu, 46 pp.

Kretschmann, D. E. 2010. Wood Handbook, Chapter 05. Mechanical Properties of Wood. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA. 41 p.

Norberg, P. 1999. Monitoring wood moisture content using the WETCORR method. *Holz als Roh- und Werkstoff*, V. 57: 448 – 453

Onysko, D. M., Schumacher, C. and Garrahan, P. 2008. Field Measurement of Moisture in Building Materials and Assembles: Pitfalls and Error Assessment. In: Best 1 Conference – Building Enclosure Science& Technology, Minneapolis, 10 – 12 June 2008: 30 pp.

http://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BEST/BEST1_005.pdf

Ressel, J. B. 2006. Fundamentals of Wood Moisture Content Measurement. Cost E53, Training School, 17. 10 pp. (Cited 14.12.2013). Available: http://www.coste53.net/downloads/TrainingSchool/1stTraining_School/1st_COST_E53_Training_School-all.pdf

Rozema, P. 2010. Do's and don'ts in respect to moisture measurement. In: „The Future of Quality Control for Wood&Wood Products", 4 – 7th May 2010, Edinburgh. The Final Conference of COST Action E 53: 9pp. (Cited 14.12.2013). Available: http://www.coste53.net/downloads/Edinburgh/Edinburgh-Presentation/72.pdf

Stamm, A. J. 1927.The electrical resistance of wood as a measure of its moisture content. *Industrial and Engineering Chemistry* 19(9): 1021 -1025 (Cited 14.12.2013). Available: http://pubs.acs.org/doi/abs/10.1021/ie50213a022

Straube, J., Onysko, D. and Schumacher, C. 2002. Methodology and Design of Field Experiments for Monitoring the Hygrothermal Perfomance of Wood Frame Enclosures. *Journal of Thermal Envelope and Building Science* 26(2): 123-151

Tamme, V., Muiste, P., Polyachenko, R. and Tamme, H. 2010. Determination of Dynamics of Moisture content, Temperature and Mechanical Stress of Pine Wood During Convective Drying. Proceedings of 11th International IUFRO Wood Drying Conference, Skellefteå, Sweden, 2010: 147 – 154.

Tamme, V., Muiste, P., Mitt, R. and Tamme, H. 2011.Determination of Effective Diffusion Coefficient and Mechanical Stress of Pine Wood During Convective Drying. *Baltic Forestry* 17(1): 110 – 118

Tamme, V., Kask, R., Muiste, P. and Tamme, H. 2012a. Comparison of wood moisture meters in extended measuring range. Proceedings of 14th Conference "Investigation and Usage of Renewable Energy Sources", Tartu, Estonia, 2012**:** 98 – 108.

Tamme, V., Muiste, P., Kask, R., Padari, A. and Tamme, H. 2012b. Experimental study of electrode effects of resistance type electrodes for monitoring wood drying process above fibre saturation point. – *Forestry Studies* 56, 42 – 55 (Cited 14.12.2013). Available:http://mi.emu.ee/teadusinfo/metsanduslikud-uurimused/contents/2012/vol-56/

Tronstad, S., Sandland, K. M. and Toverød, H. 2001. Drying quality of softwood based on 140 industrial tests in Norwegian sawmills and actions to improve the quality. Proceedings of 3rd Workshop on softwood drying to specific end-uses, COST Action E15, Advances in the drying of wood (1999-2003). VTT Building and Transport, Espoo, Finland, 2001.: 13 pp.

Vermaas, H. F. 2002. State of the Art and Latest Technological Advances in the Drying of Fast- grown Eucalyptus. Proceedings of 4th COST E 15 Workshop „Methods for Improving Drying Quality of Wood", Santiago de Compostela, Spain, 2002.: 17 pp.

Wang, X., Ross, R. J., Brashaw, B. K., Punches, J., Erickson, J. R., Forsman, J. W. and Pellerin, R. E. 2004. Diameter effect on stress-wave evaluation of modulus of elasticity of logs. *Wood and fiber science* 36(3): 368-377

http://www.brookhuis.com/ (Cited 14.12.2013)

http://www.feutron.de/(Cited 14.12.2013)

http://www.gann.de/(Cited 14.12.2013)

http://www.kern-sohn.com/ (Cited 14.12.2013)

http://www.ndtjames.com/ (Cited 14.12.2013)

http://www.metrosert.ee/ (Cited 14.12.2013)

http://www.r-project.org/ (Cited 14.12.2013)

Received 12 July 2013
Accepted 15 May 2014

МОДЕЛИРОВАНИЕ ПРИБОРОВ ИЗМЕРЕНИЯ ВЛАЖНОСТИ ПО СОПРОТИВЛЕНИЮ НА ПРИМЕРЕ ТРЕХ ЛИСТВЕННЫХ ДЕРЕВЬЕВ (ОЛЬХА ЧЕРНАЯ, БЕРЕЗА, ОСИНА) ПРИ СОДЕРЖАНИИ ВЛАЖНОСТИ ВЫШЕ ТОЧКИ НАСЫЩЕНИЯ ОДНОГО ВОЛОКНА

В. Тамме, П. Муйсте, А. Падари и Х. Тамме

Резюме

Для измерения содержания влажности древесины широко используются портативные электрические приборы сопротивления. При увеличении влажности древесины в пределах выше точки насыщения волокна точность измерения таких приборов начинает прогрессивно снижаться. В данной работе представлена квантитавная характеристика даннои хорошо известной квалитативной тенденции. Показания трех приборов от ведущих производителей для измерения влажности сравнивали с абсолютной влажностью определенной методом взвешивания высушеных образцов. Из каждого вида древесины (ольха черная, береза, осина) были изготовлены 60 образцов с размерами (60×60×100) мм^3. Образцы сушили до желаемого содержания влажности в климатической камере при одинаковых условиях (температура 32^{o}C и относительная влажность воздуха RH 98%). Все измерения проводили при комнатной температуре 20 ^{o}C.

На основе статистического моделирования при одиночном измерении MC (moisture content) древесины подтвердилось прогрессивное снижение точности измерения приборов влажности на основе измерения сопротивления при увеличении средней абсолютной влажности древесины. При 95% доверительном уровне и при среднем MC=27% абсолютная ошибка измерения статистической модели была ±3,9% MC, при среднем MC=60% абсолютная ошибка измерения статистической модели была ±10.0% MC и при среднем MC=97% абсолютная ошибка измерения статистической модели была ±17.5% MC. Наименьшая ошибка прогноза среднего MC для древесины по данной модели была ±1.12% MC. На основе представленной модели был составлен прогноз предела разрешения использованных приборов для изученной древесины при средних MC, соответствуюшее значение получили в пределах 1% MC.

Ключевые слова: сушка древесины, измеритель влажности древесины, выше FSP.