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# Comparison of voltammetry and digital bridge methods for electrical resistance measurements in wood

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ABSTRACT

The comparison of accuracy and ease of operation was made between voltammetry and digital bridge method for electrical resistance measurement in *Populus davidiana* wood specimens and the factors influencing voltammetry were examined. The results showed that current types, waveforms, voltages and frequency had different effects on the resistance values of voltammetry. The measured DC resistance decreased with the increasing voltage. DC resistance presented a turning point at the voltage of 8 V, while AC impedance remained constant over the entire voltage range. The effects of waveform on resistance was minor. No remarkable difference in resistances was found between the two methods above fiber saturated point (FSP) and voltammetry was relatively stable below FSP. The relationship between MC and resistances confirmed the previous findings from other scholars. Compared to the digital bridge, the voltammetry of AC with 1000 Hz sine waves was found to be the superior method for wood resistance measurement.

## 1. Introduction

The method of electrical resistance measurements was originally applied in the fields of medical examination and geological exploration. It was later introduced to the field of biomass materials in order to study a material's type and structure. As one of the basic means, electronical resistance technique was also used for electrical properties study and its correlation with progressive discoloration and decay rates of wood (Lin, 1965, 1967; Tattar et al., 1972; Tattar and Saufley, 1973; Shortle and Smith, 1987; Wang and Wang, 2016). Electrical properties of wood was found closely correlated with physical (moisture content, water content, and wood density) and chemical properties (mineral ions content and concentration of phenolic and resin acids) (Tattar et al.,1972; Tiitta et al., 1999). In addition, electrical properties were also affected by temperature, grain orientation and testing frequency (Tiitta et al., 1999).

Electrical resistance characteristics can offer information about moisture content (MC) of wood and is continuously used for field measurements and recordings (Tiitta et al., 1999; Guyot et al., 2013). The electrical resistance method has also shown potential for estimating sapwood area in the context of improving whole-tree water use estimates. In recent years, some nondestructive testing methods based on resistance measurement including impedance/resistance tomography and spectroscopy coupled with other techniques have been used to map tree resistivity in field for decay detection, moisture content estimation or wood boundary differentiation (Oliva et al., 2011; Guyot et al., 2013; Martin and Günther, 2013; Gao et al., 2014; Yue et al., 2016).

Electrical resistance was first quantified for trees using a Wheatstone bridge in the early 1900s (Stone, 1903) and the "Shigometer" became the device of choice in the 1970s (Shigo and Shigo,1974). More recently, Rotfinder, and Picus TreeTronic detectors emerged and were used to for outdoor tree decay detection (Oliva et al., 2011; Yue et al., 2016).

However, information about factors influencing accuracy of resistance measurement in wood is very limited and still require additional investigation in the laboratory. This is the necessary foundation for portable resistance-based tools development for field application. Voltammetry and electric bridge are two common methods for wood resistance measurements. The objectives of this study are to investigate the factors influencing voltammetry for laboratory wood resistance measurements and to compare with the digital bridge method for accuracy and ease of operation. This study seeks to determine the superior method between these two commonly used techniques and to provide the most appropriate settings for resistance measurements.

## 2. Materials and methods

### 2.1. Technical background

Electrical resistance measurement of wood should make operations

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as easy as possible on the premise of ensuring accuracy. In general, the resistance value of dielectric material of homogeneous structure can be directly measured by using the ohmmeter. But as for wood, a biomass material of the anisotropy characteristics, the ohmmeter is unable to obtain stable readings. The reason is when using the ohmmeter to measure the resistance of wood directly, the test current of ohmmeter is the direct current (DC) produced by dry cells. Since resistance is affected by the amount of time the DC field is applied, it would typically take 1 min to display the reading after the initial measurement (Li, 2002). Furthermore, the measuring accuracy of resistance type sensors decreases and side effects related to measuring wood moisture begin to occur when moisture contents above fiber saturation point (FSP) in wood. These side effects should be taken into account in the measuring process (Tamme et al.2013). Tamme et al. (2013) demonstrated that time dependence of electrical resistance in wood with MC above FSP can be measured with a high level of accuracy and described mathematically with the electrometric method. The mathematical model was established to describe the dynamics between wood electrical resistance, wood electrical capacitance and relaxation time (Tamme et al., 2014).

The current widely used methods for wood resistance measurements are the voltammetry and electric bridge methods. Both of which are relatively simple and convenient for indoor tests

#### 2.1.1. Voltammetry method

Voltammetry is also called V-A method which uses voltmeter and ammeter to measure the voltage and current in the circuit, and calculates the resistance value of the measured component according to the Ohm's law (Zhao, 2010). According to the ampere meter position placed in the circuit, voltammetry is divided into two kinds: inter-connection and exter-connection as shown in Fig. 1a and b.

The resistance value measured using inter-connected method is generally greater than its actual value. Due to the small ammeter resistance, the inter-connection is more appropriate if the measured resistance element is large. The resistance obtained by exter-connection is less than its actually value. Due to the large internal resistance of voltmeter, the exter-connection method is more suitable for the measurement of minor resistance elements. Although certain system errors cannot be avoided when using the voltammetry method, its advantage is its ease of operation in the laboratory.

A contemporary reliable alternative to the voltammetry method is Electrical impedance spectra (EIS) which is not only fit for measuring various parameters of the alternating current, but also allows perfect equivalent circuit modelling (Zelinka et al., 2007, 2008).

#### 2.1.2. Traditional electric bridge method

Electric bridge method can be divided into Wheatstone bridge (single-arm electric bridge) and Kelvin bridge (double-arm electric bridge). For Wheatstone bridge, three variable resistors ($R_1$, $R_2$ and $R_3$) and the measured element (R) constitute a quadrilateral circuit (Fig. 1**c**), in which the diagonal placing in a galvanometer is called the

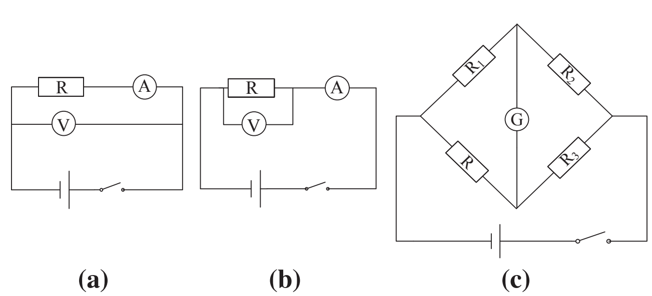


**Fig. 1.** Circuit diagram of voltammetry and Wheatstone bridge. (a) Inter-connection of voltammetry. (b) Exter-connection of voltammetry. (c) Circuit diagram of Wheatstone bridge.

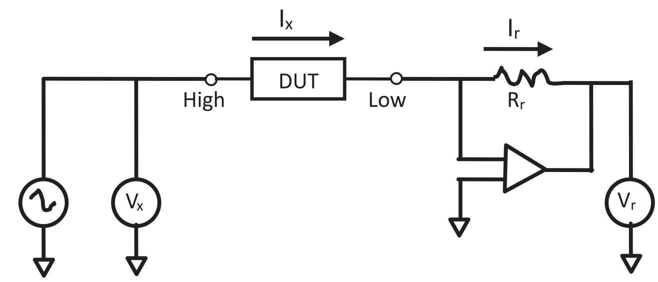


**Fig. 2.** Schematic diagram of fundamentals of digital bridge method.

bridge and each side of quadrangle is called the arm of the bridge. The fundamentals of measurement is using galvanometer to test the current on the bridge and adjusting the resistance of variable resistor to make the bridge balanced. The resistance of measured element is thereby calculated according to the principle of capacitive divider and the known resistance value of the resistor on each arm. Wheatstone bridge method is generally suitable to measure medium value resistance (Fig. 1**c**) while the Kelvin bridge method is suitable for resistance measurements less than 1 Ω. As for wood, whose resistance is almost more than 100 kΩ, the Wheatstone bridge method is the more appropriate of the two.

#### 2.1.3. Digital bridge method

Digital bridge is a recently used method combined with the analog circuit, digital circuit and microcomputer technology. Although it continues to use the "bridge" nomenclature, the circuit principle is different from the traditional bridge circuit but still complies with Ohm's law at a higher level. The fundamentals of digital bridge method is shown in Fig. 2. The DUT is the element to be measured; $R_r$ is a standard resistor. $U_x$ and $U_r$ are respective corresponding voltages of DUT and $R_r$. The resistance of DUT, $Z_x$, can be calculated using the following equation:

$$Z_x = \frac{U_x}{I_x} = \frac{R_r U_x}{U_r} \tag{1}$$

Eq. (1) is a phase expression. Phase-Sensitive Detector (PSD) was used to measure in-phase and quadrature components $U_x$ and $U_r$ corresponding to a certain reference vector, and the components were converted to digital values by the analog-to-digital converter (A/D). Afterwards the resistance and reactance values of the measured $Z_x$ were obtained by means of complex operation using a computer. A contemporary reliable alternative to the digital bridge method is the electrometric method. Tamme et al. (2013) used the Keithley Model 6517B precise electrometer conducting the wood electronical resistance measurement. Electrometer enables selecting between four measuring modes: voltage, current, resistance and charge (Tamme et al.,2013). As for the modern measuring equipment, many handheld resistance meters and wood resistance-type moisture meters have operational amplifiers with LMC or OPA electrometric inputs in their DC circuits.

### 2.2. Materials and moisture content equilibrium

Small clear poplar (*Populus davidiana*) specimens were cut from 1-m-long green log sections. The logs were taken from a 46-year-old poplar tree harvested from Great Young forest stand in Grand Khingan Mountain (52°20′N, 124°42′E, 412 m asl.) located in northeast China. The log section was taken at the height of 1.3 m ( ± 0.13 s.d.) of the tree and was produced into specimens (ca. 20 × 20 × 50 mm$^3$) with the length direction along the wood grain (Fig. 3). Thirty-five freshly-cut specimens were then selected and divided into two groups, one is the experimental group consisting of thirty specimens and the other is the control group consisting of five specimens. Each group covers heartwood and sapwood specimens. Before the resistance measurements, the