Acoustic guided wave detection of grounding rod corrosion: equivalent circuit model and implementation

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Received 1 August 2019, revised 15 December 2019
Accepted for publication 4 February 2020
Published 8 April 2020

Abstract

Acoustic pulse-echo systems, are effective for corrosion damage detection in buried individual ground rods without any need for excavation. In electric power distribution systems there are large numbers buried ground rods are used in substations to form a grounding networks that is critical for the protection of equipment and personnel working in the vicinity of the substation. Over time, these grounding rods will corrode and cease to provide adequate protection. In this work, we present an equivalent circuit model (ECM) for acoustic pulse-echo corrosion detection systems. The circuit model was used to develop a transducer configuration that effectively launches longitudinal acoustic waves that can accurately detect position and damage severity. We show that our model correctly predicts the temporal response from both undamaged rods and rods with machined simulated corrosion pits. The circuit model also accounts for loss, and the results show strong agreement with simulated soil-loss in laboratory experiments. Evidence of wave mode conversion is found in experimental data that is not captured by the model. Preliminary field measurements of copper-clad steel grounding rods are presented that show strong similarities to modeled results. This ECM is a promising basis for further development of pulse-echo systems for corrosion detection and may be useful for future tomographic analysis of field measurements.

Keywords: equivalent circuit model, ground rod corrosion, acoustic guided waves, piezoelectric transducers, pulse-echo method, PSpice models, defect detection

(Some figures may appear in colour only in the online journal)

1. Introduction

Critical to electric power distribution is the substation, which reduces voltage levels so they are safe for distribution to the consumer. A substation has hundreds of steel rods placed in the ground, connected as a grid, and covered with rock to form its grounding network [1]. It has been estimated that in North America alone there are approximately 70,000 substations [2]. As electric substations age, the integrity of the grounding networks degrade from the effects of corrosion. Maintaining an integral grounding network is central to protecting the substation and its personnel [3, 4]. Grounding networks, and the electrodes which constitute them, protect the substation from electrical disturbances such as lightning strikes or grounding faults of nearby equipment. If a grounding electrode corrodes enough, it may fail to conduct as it should in the event of a fault [5]. Current methods for corrosion detection have been shown to be effective for detecting large-scale corrosion within a grounding network [6–13]. However, detection of corrosion in individual rods requires direct visual inspection by excavation. A utility can
avoid costly and unnecessary excavation of defect-free rods if they can effectively locate corrosion in individual rods. Therefore, an effective technique for detecting corrosion in individual rods would be very advantageous to electrical utilities [14].

### 1.1. Current methods for defect detection in grounding rods and grounding networks

Conductivity methods for detecting large scale corrosion within a grounding network have been well documented. The conductivity between two conductors is measured, and the result is used to gauge corrosion levels within the network [6]. However, conductivity measurements are subject to much uncertainty because of varying soil conditions and network topologies [7]. Zeng et al extended the conductivity method to employ an equivalent circuit model (ECM). They combined theoretical analysis and simulation to correlate field conductivity measurements to the degree of corrosion in a grounding network [8].

Electromagnetic methods have also been investigated for grounding network corrosion detection. Zhang et al investigated a method to locate broken electrodes by injecting medium frequency current into the grid and analyzing the recorded measurements using numerical simulation [9]. Liu et al injected low frequency sinusoidal currents into the grounding network and deduced its corrosion status based on the resulting magnetic induction intensity distribution [10]. They analyzed measured data and determined the network’s corrosion status based on contour maps of equivalent resistivity [11].

Other methods to determine the corrosion status have also been explored. An electrochemical method, presented by Zhang et al, determined the corrosion status through measurements of electrochemical interaction between metal electrodes and the surrounding soil [12]. An electrical impedance tomography technique was presented by Li et al to determine the location and degree of corrosion within the grounding network [13].

These methods have a common drawback in that they do not clearly identify corrosion in individual rods. Another drawback is that they require knowledge of the grounding network’s topology which is not often known. Additionally, insufficient knowledge of the soil conditions can lead to inaccurate or erroneous results due to the pivotal role of soil in the electrical parameters measurement. A method is yet to be demonstrated that can locate corrosion in individual rods, is independent of the network topology, and is not strongly influenced by soil conditions.

### 1.2. Pulse-echo method using acoustic guided waves (AGW)

One method that shows great promise is the pulse-echo method using AGW. AGW are transmitted into a material or structure. The presence and location of any defect in the structure can then be extracted from the measured data according to the time of flight method [15]. Approaches based on AGW have been shown to be effective in identifying and locating defects in materials where the guided mechanical waves can propagate easily [16–19]. AGW-based technology has been practiced in detecting flaws/defects in solid materials in the field of non-destructive testing [17]. Considerable interest in AGW has also emerged in the field of structural health monitoring [18]. In the AGW approach, guided waves can propagate long distances in a structure. This characteristic makes it possible to detect the defects in parts of the structure that would otherwise be inaccessible. For example, AGW methods have been investigated for the application of detecting uniform cross-sectional loss in steel bars embedded in mortar and concrete [19–21].

The use of the AGW pulse-echo technique for rods embedded in soil was first presented by Shoji and Higashi [22]. Pulse-Echo AGW were generated in steel rods using shear-mode piezoelectric transducers mounted on the side of the exposed part of the rod. They investigated different longitudinal AGW in steel rods embedded in soil to determine which was most suitable for defect detection. They showed that the attenuation-radius $\alpha_{L-r}$ (dB m m$^{-1}$) is minimum for $L(0, 1)$ in steel rods buried in soil in the frequency-radius $f_{L-r}$ (kHz m) bandwidth of (0, 1) kHz m [22]. Shoji and Hirata extended the foundational work of Shoji and Higashi by investigating the effects of defects on wave propagation in the rod [23]. Axisymmetric defects were machined into the rods and the recorded signals were examined to understand the effect of the machined defect on the pulse-echo response. However, the work by Shoji et al [22, 23] considered only anchor rods which have a significant portion of their lengths exposed above ground. The scope of their work was also limited to considering only the longitudinal wave mode.

Zhao et al extended the work of Shoji et al to the investigation of torsional and flexural wave modes for defect detection. Their experimental results confirmed that the $L(0, 1)$ mode was the best candidate for corrosion detection in rods buried in soil [24]. They simulated rod defects experimentally with machined pits of varying size and location. Their results confirmed that the size and location of simulated corrosion pits could be well correlated with measured pulse-echo signals. They also investigated the lossy effects of soil experimentally by wrapping the test rods in clay (Plainsman M340). They observed that they could not selectively generate the $L(0, 1)$ mode without introducing other non-ideal wave modes into the rod.

Significant advancement of the discussed pulse-echo method could be facilitated by the accompaniment of an ECM. A model of the pulse-echo system would enable the examination of the effect of only the $L(0, 1)$ mode. In turn, this would aid in the interpretation of measured pulse-echo data which are convoluted with other modes. A preliminary version of such a model was presented by Durham et al [25], and was based on the ECM for a piezo transducer presented by Leach [26]. They demonstrated that the measured pulse-echo signal in an idealized setup could be replicated in PSpice using an ECM of the same setup [25]. In this work we present a complete circuit model of the pulse-echo system which incorporates loss and material property characterization. A sensor configuration that efficiently couples the $L(0, 1)$
mode into the rod, conceived from the circuit modeling, is also presented. We present the design and implementation of an ECM of the sensor and the test rods used in accompanying experiments. The circuit model is implemented in PSpice and the results are compared to controlled laboratory tests where clay was used to simulate the effects of the soil. Preliminary results from field testing using the pulse-echo system are also presented.

2. Pulse-echo system design

2.1. Overview of pulse-echo method

In the pulse echo-method, an acoustic pulse, generated by a transducer, is made to propagate in a waveguide. At the defect/waveguide boundary, a portion of the incident wave will reflect off the boundary and propagate back to the transmitter. The location of the defect is extracted from the reflected wave using the time of flight method. If the material properties of the waveguide are known, then the group velocity \( v_g \) of the wave traveling in the material is also known. The position of the defect \( L_{\text{defect}} \) is then determined using equation (1). A schematic diagram of the experimental setup used in this work is presented in figure 1. A magnetic clamp is used to hold the transducer against the test specimen

\[
L_{\text{defect}} = v_g \Delta t / 2. \tag{1}
\]

2.2. Pulse-echo corrosion sensor design

In the pulse-echo method, the choice of wave-mode is critical to its effectiveness and is specific to each application. Zhao et al and Shoji et al [22–24] showed that the \( L(0, 1) \) mode is the most effective mode for defect detection in a steel rod buried in soil. In grounding rods, the propagating \( L(0, 1) \) mode is largely confined inside the rod [22, 23, 27], and thus will undergo significantly less attenuation than the flexural or torsional modes [22, 23, 28]. The group velocity dispersion curves for the steel grounding rods examined in this work are shown in figure 2(c) [29]. Three different wave modes can propagate in grounding rods below 100 kHz. Figure 2(c) shows that the \( L(0, 1) \) mode will propagate 60% faster than the flexural \( F(1, 1) \) and torsional \( T(0, 1) \) modes. Therefore, the \( L(0, 1) \) mode can be easily distinguished from the other two modes using the time of flight method.

The pulse-echo corrosion transducer (PECS) was designed to selectively generate the \( L(0, 1) \) mode. Figure 2(a) shows how two PZT disks (SMD15T12S412) [30], each with a rated resonant frequency of \( f_r = 1.7 \text{ MHz} \) were used to form the transmitter and receiver ports, respectively. Since the magnitude of the received signal is 50–100 times lower than the transmitted signal, using separate transmitter and receiver disks greatly reduced the dynamic-range requirements of the receiving electronics. The PECS is symmetrical, where the PZT disks are fixed between a pair of steel cylinders. Between the cylinders, the disks are interspaced by three brass electrodes. All the PECS constituents were selected to have the same radius \( r = 7.5 \text{ mm} \). Silver epoxy (Ag-epoxy) was used as an adhesive to bind the components together. The epoxy was allowed to cure for 24 h before tests were conducted, as per the manufacturer’s instructions. The PZT disks have thickness 1.2 mm, the steel rods have length \( L = 20 \text{ mm} \), the brass electrodes have thickness of 0.15 mm, and the epoxy thickness is \( \approx 50 \mu \text{m} \). The disks are fixed to the inner brass electrode which serves as ground. As shown in figure 2(a), the PECS can be thought of as two opposing cylindrical resonators. Each resonator is fixed at the driving end, and open at the other. Thus, the cylinders form quarter-wave resonators whose fundamental frequency \( f_r \) can be approximated from (2) [31]

\[
f_r = \frac{v_{ph}}{4L}, \tag{2}
\]

where \( v_{ph} \) is the phase velocity in the steel cylinders. From equation (2), the approximated resonant frequency of the PECS is 63.8 kHz. Since this approximation only accounts for the length \( L \) of the steel end-pieces, a thorough characterization of the PECS is required, and is presented in
section 4.2. However, this approximation is useful for ensuring that the PECS’ resonant frequency will be within the $L(0, 1)$ bandwidth for grounding rods.

2.3. Pulse-echo test design

The experimental setup shown in figure 1 was implemented for lab testing. A function generator was attached to the PECS transmitting electrode and the receiver electrode was connected to an oscilloscope through an op-amp with gain $G = 100 \, V/V$. For a detailed description of the experimental setup, see our previous work [24]. Acoustic couplant was used between the PECS and the grounding rod to enhance mechanical coupling. For each test, a 5-cycle sinusoidal burst was applied to the transmitter disk, and the pulse-echo response was recorded from the receiver disk. A 5-cycle burst was chosen as a result of the experimental work by Zhao et al [24] who showed that a 5-cycle burst yielded favorable results in comparison to fewer or greater cycles per burst.

Tests were conducted using three different rods: a control rod free of defects, and two rods having machined artificial defects at $L_{defect1} = L_{Rod}/2$ and $L_{defect2} = L_{Rod}/4$. The oscilloscope used an averaging factor of 64.

3. ECM for pulse-echo system

An ECM for the scenario shown in figure 1 was developed that encompassed the acousto-electric properties of the piezoelectric disk. Initially, the lossless system model is derived, with the effects of loss accounted for later. The magnetic clamp was not included in the model.

3.1. Modeling the piezoelectric element

Different methods for modeling piezoelectric elements have been widely reported in literature [26, 32–37]. These techniques include RLC ECMs [33, 35, 38], finite element methods [32], and electrical analogous circuits using transmission lines [25, 33, 35]. Leach’s ECM, using controlled sources, presents an intuitive method for modeling the piezoelectric element [26], and is easily combined in PSpice with other model elements using transmission line theory [36, 37, 39]. Here we present the derivation of Leach’s model for a thickness-extensional-mode (TE) piezoelectric disk [26].

The acoustoelectric behavior of a piezoelectric disk, vibrating in the $z$ direction is presented in figure 3. In this model, force, $f_z$, and particle velocity, $u_z$, are represented in the electrical domain as voltage and current, respectively. The Laplace variable, $s$, is used to represent time differentiation. This model assumes that electromechanical coupling between $z$ and the other orthogonal directions, $x$ and $y$, can be neglected. Thus, only the tensor components in the $z$ direction, denoted by the index 3, are needed to describe the motion of the disk. The equations of motion are then given by equations (3)-(5) in table 1. The direct and indirect piezoelectric effects are given by equations (3a) and (4a), respectively [40]. Stress, $\sigma_3$, is related to strain, $\epsilon_3$, through the open-circuit stiffness, $c_{33}^{0}$, and the piezoelectric constant, $h_{33}$, $\epsilon_3$ is related to the electric flux density, $D_3$, through the electric field intensity, $E_3$, clamped permittivity, $\epsilon^3_\infty$, and piezoelectric constant, $\epsilon_{33}$. Equation (5a) relates the force, $f_z$, to density, $\rho$, thickness, $t$, cross-sectional area, $A_z$, and particle acceleration, $a_z$. Substituting $f_z/A_z$ for $\sigma_3$, and $d\zeta_z/dz$ for $\epsilon_3$, where $\zeta_z$ is the particle displacement, gives equations (3b) and (4b). $f_z$ is expressed in terms of particle velocity, $u_z$, according to equation (5b). An ECM which models equations (3)–(5) requires that $E_3$ and $D_3$ be expressed in terms of the voltage, $v_z$, and the electric current, $i_z$ (figure 3), respectively. Making the substitutions presented in table 2, equation (3b) becomes equation (6), and equation (4b) becomes equation (7). Since $D_3/dz = 0$, the zero term $-h_{33}i_z/s$ can be added to equation (5b) to obtain equation (8).
The telegraphers equations in (9b) and (10b) are then found by replacing \( (f_z - h_{33}i/s) \) and \( u_z \) in equations (9a) and (10a), with the distributed transmission line voltage \( V_z \) and current \( I_z \), respectively. The per unit length inductance, \( L_z \), and per unit length capacitance, \( C_z \), on the transmission line are then given as \( \rho A_z \), and \( 1/c_0^2 A_z \), respectively, and the per unit length resistance \( R_z \) is initially assumed zero. Integrating equation (7) along \( z \) from 0 to \( \ell_z \), yields \( v \), where \( u_z = u(0) \) and \( u_z = u(\ell_z) \).

The scenario depicted in figure 3 can now be represented by the ECM shown in figure 4. The model is divided into a mechanical side, denoted by blue text, and an electrical side, denoted by red text. Two controlled sources couple electrical to mechanical energy according to equations denoted by red text. Two controlled sources couple electrical and mechanical side, denoted by blue text, and an electrical side, denoted by red text.

\[
\begin{align*}
\frac{d}{dz} \left( I_z - \frac{h_{33}i}{s} z \right) & = -\rho A_z u_z, \quad (9a) \quad \frac{dV_z}{dz} = -L_z I_z, \quad L = \rho A_z, \quad (9b) \\
\frac{dm}{dz} - s \frac{1}{z A_z} \left( I_z - \frac{h_{33}i}{s} z \right) & = 0, \quad (10a) \quad \frac{dl}{dz} = -C_z V_z, \quad C = \frac{1}{x_0 A_z}, \quad (10b) \\
v & = \frac{h_{33}m}{s} (u_n - u_z), \quad (11a) \quad v = \frac{h_{33}f_z}{s} + \frac{i}{s C_0}, \quad C_0 = \frac{c_0^2 A_z}{\ell_z}, \quad (11b)
\end{align*}
\]

(9b) – (11b) are then given as \( \rho A_z \), and \( 1/c_0^2 A_z \), respectively, and the per unit length resistance \( R_z \) is initially assumed zero. Integrating equation (7) along \( z \) from 0 to \( \ell_z \), yields \( v \), where \( u_z = u(0) \) and \( u_z = u(\ell_z) \).

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3.2. Modeling non-piezoelectric elements

The buried grounded rod and steel cylinders of the PECS (figures 1 and 2) are cylindrical acoustic waveguides, and can be modeled as transmission lines with distributed \( R_z, L_z \), and \( C_z \) [41]. A component’s material properties is related to its equivalent per unit length \( L_z \) and \( C_z \) by [41]:

\[
L = \rho A_z, \quad (12)
\]

\[
C = E A_z, \quad (13)
\]

Here, \( \rho \) is the component’s mass density, \( E \) is its Young’s Modulus, and \( A_z \) is the cross-sectional area in the \( z \) direction.

4. System element characterization

4.1. Piezoelectric element

Leach’s model (figure 4) will reproduce the behavior of a piezoelectric disk if its physical parameters (table 3) are known. While \( \rho, A_z \), and \( \ell_z \), are straightforward to determine, determining \( h_{33}, c_{33}^3 \), and \( c_{33}^D \) is less straightforward. One approach that can accurately yield these parameters is piezoelectric characterization using impedance spectra [32, 34]. According to this method, one obtains \( c_{33}^S, c_{33}^D \) and \( h_{33} \) by applying curve fitting to a measured impedance spectrum, according to the equations shown in table 4. For a TE-mode piezoelectric disk, equations (14)–(17) model how \( h_{33}, c_{33}^S \) and \( c_{33}^D \), relate to the resonant frequency \( f_z \), anti-resonant frequency \( f_p \), electromechanical coupling coefficient \( k_{33} \), and the resonant impedance \( Z_m = Z(2\pi f_z) \). The mechanical quality factor \( Q_m \) quantifies the strength of the resonator, and the loss factor \( \delta_m \) is a measure of the resonator’s mechanical losses [34]. A variety of softwares are available to perform curve fitting, but one software that is specifically designed for piezoelectrics is the Piezoelectric Resonance Analysis Program (PRAP) [42]. PRAP was used to perform curve fitting to the measured impedance spectra of the PZT disk shown in figure 5. The measured resonant frequency \( f_z \), anti-resonant frequency \( f_p \), electromechanical coupling coefficient \( k_{33} \), and the resonant impedance \( Z_m = Z(2\pi f_z) \). The mechanical quality factor \( Q_m \) quantifies the strength of the resonator, and the loss factor \( \delta_m \) is a measure of the resonator’s mechanical losses [34]. A variety of softwares are available to perform curve fitting, but one software that is specifically designed for piezoelectrics is the Piezoelectric Resonance Analysis Program (PRAP) [42]. PRAP was used to perform curve fitting to the measured impedance spectra of the PZT disk shown in figure 5.
frequency (∼1.55 MHz) of the disk is in close agreement with the rated resonant frequency (1.7 MHz). The multiple resonance modes in the measured impedance spectrum of the PZT disk are characteristic of piezoelectric disk transducers [43]. However, a fit was applied only to the fundamental TE mode, and the proximal modes were ignored. The results obtained from the PRAP fitting are summarized in table 5. The derived parameters \( C, L, \) and \( C_0 \) were calculated using equations (9b)–(11b).

### Table 5. Summary of parameters extracted from PRAP software for use in ECM of pulse-echo corrosion detection system.

| Parameter | Value |
|-----------|-------|
| Given \( \rho = 7700 \text{ kg m}^{-3} \) | \( \ell_x = 1.2 \text{ mm} \) |
| Given \( A_t = 177 \text{ mm}^2 \) | \( h_{33} = 2.44 \times 10^{9} \text{ N C}^{-1} \) |
| Fitted \( C_{33}^0 = 1.71 \times 10^{11} \text{ Pa} \) | \( k_{33} = 0.489 \text{ N m}^{-1} \) |
| Fitted \( \varepsilon_{33}^0 = 9.8 \times 10^{-9} \text{ F m}^{-1} \) | \( h_{33} = 2.44 \times 10^{9} \text{ N C}^{-1} \) |
| Calculated \( C = 33.0 \text{ nF m}^{-1} \) | \( L = 1.36 \text{ H m}^{-1} \) |
| Calculated \( C_0 = 1.44 \text{ nF} \) | \( C = 33.0 \text{ nF m}^{-1} \) |

4.2. PECS sensor and ground rods

The grounding rods used in this work were 1018 carbon steel rods with radius \( r = 19 \text{ mm}, \ \rho = 7870 \text{ kg m}^{-3}, \) and \( E = 205 \text{ GPa} \) [27]. The PECS was composed of four different materials: the PZT disks, the brass electrodes, steel end pieces, and the silver epoxy. The length of the steel end pieces and the thickness of the brass electrodes were measured using callipers. The thickness of the silver epoxy was approximated using a microscope. To simplify modeling, \( \rho \) and \( E \) for the PECS constituents were approximated based on available material datasheets.

The resonance behavior of the PECS was analyzed using an impedance analyzer (Agilent E4990A). The measured impedance spectra (black) is shown in figure 6, and a summary of the measured resonance properties is given in table 6. A discrepancy is observed between the measured resonance and the predicted resonance from equation (2). This discrepancy is reasonable since equation (2) was derived from a simplified model (figure 2(b)) of the PECS. The modeled response is shown in red, and is discussed in section 5.2.

### Table 6. Summary of measured resonance characteristics for PECS.

| Characteristic | Value |
|---------------|-------|
| Series resonance \( f_s \) (kHz) | 40.1 |
| Parallel resonance \( f_p \) (kHz) | 41.1 |
| Series resonance impedance (Ω) | 916 |
| Parallel resonance impedance (Ω) | 3652 |
| Mechanical quality factor \( Q_m \) | 33.5 |

5. PSpice implementation of pulse-echo system model

5.1. ECM of piezoelectric disk

The conceptual circuit presented in figure 4 is shown implemented in PSpice in figure 7. The right side represents the electrical side, with electric potential \( v \), and the left the acousto-mechanical side. The two sides are coupled via the ELAPLACE blocks \( E_1 \) and \( E_2 \). Since the dependent voltage sources in figure 4 integrate their control inputs, they are most easily implemented in PSpice using ELAPLACE blocks. The zero-volt sources \( V_1 \) and \( V_2 \) are ammeters whose outputs control blocks \( E_1 \) and \( E_2 \), respectively. The resistors \( R_B \) and \( R_F \) model the air impedance at the front and back faces of the piezo transducer, respectively [36]. The transmission line parameters and the capacitance \( C_0 \) were calculated based on equations (9)–(11), and the parameters given in table 5.

The model was verified by comparing the simulated impedance spectrum against the measured impedance spectrum for the PZT disk. The results of the simulation are shown in figure 5. The multiple peaks and valleys present in the
measured response of figure 5 are the result of other resonant modes that are neglected in the ECM. However, the dominant resonant frequency of the measured response (1.55 MHz) is in strong agreement with the simulated impedance response. To account for mechanical losses, $R$ of the transmission line $T_1$ was adjusted until the simulated quality factor was in agreement with the measured quality factor.

5.2. PECS ECM

The PSpice implementation of the PECS device, shown in figure 8, closely resembles its physical implementation (figure 2(a)). For each physical layer of the PECS there is an equivalent transmission line to represent it. The PECS ECM is built on top of the PZT ECM (figure 7). In figure 8(b), the center unit is formed from two PZT circuits joined between nodes 1 and 2, respectively. The top and bottom circuits of figure 8(c) represent the electrical ports for the transmitter and receiver disks, respectively. $V_{\text{pulse}}$ is formed by multiplying a square-wave pulse, having pulse-width $PW = 5/f_r$ and unity amplitude $A_1$, with a sinusoid excited at frequency $f_r$ (from equation (2)) and amplitude $A_2$. The received signal is measured at $V_{\text{echo}}$ in the bottom circuit across $R_t$. An operational amplifier circuit (not shown) amplifies the simulated pulse-echo response by the same factor used in lab experiments.

5.2.1. Mechanical losses in PECS ECM. To account for mechanical losses we made three simplifying assumptions. First, we assumed that each disk has the same $R$ value, as obtained from figure 5. Second, we assumed that $R$ is unchanged by the addition of the other PECS elements. Third, we assumed that any further mechanical losses arising in the PECS can be attributed to the silver epoxy. Thus, the resistive loss $R_{\text{epx}}$ in the transmission line elements representing the epoxy, was used as a tuning parameter for the resonant frequency since there was significant uncertainty about its true value. Thus, its thickness was adjusted between 50 and 100 $\mu$m in simulation to achieve matching between the simulated and measured frequency responses. The comparison between the modeled and measured impedance responses is presented in figure 6. The series and parallel resonances of the simulated PECS device are in strong agreement with their measured counterparts. The modeled response diverges most noticeably from the measured response far away from resonance.

5.3. Grounding rods ECM

The ECM for the grounding rods, as implemented in PSpice, is shown in figure 9. The ECM for the rods, and the ECM for the PECS, were connected in keeping with the experimental configuration shown in figure 1; however, the magnetic clamp was not included in the model. The grounding rods are modeled as a sequence of rod sections. The transmission line elements $Z_{\text{rod}}, Z_{\text{rod1}}$, and $Z_{\text{rod2}}$, represent rod-sections having lengths $L_{\text{rod}}, L_1$ and $L_2$, respectively, each with cross sectional area $A_{\text{rod}}$. The circuit model for Rod A is shown in figure 9(a), and the circuit model for both Rods B and C is shown in figure 9(b). The sections $Z_{\text{rod1}}$ and $Z_{\text{rod2}}$ were assigned $L_1$ and $L_2$ according to the geometry given in figure 10. The transmission line $Z_{\text{defect}}$ represents the defect in the rod with $L_{\text{defect}} = 1$ cm and $A_{\text{defect}} = A_{\text{rod}}/2$. The
characteristic impedance of an electrical transmission line is \( Z_L = \sqrt{L/C} \) [45]. Then, from equations (12) and (13) we see that the acoustic impedance \( Z_A \) of a rod section is directly proportional to its cross-sectional area according to equation (20). The phase velocity on a section of acoustic transmission line of length \( \ell \) is also a function of its material properties and is given by equation (21) [41].

\[
Z_A = A \sqrt{\rho E}, \\
v_{ph} = \sqrt{E/\rho}, \\
\Delta t = \frac{\ell}{v_{ph}}, \\
\Gamma = \frac{Z_{\text{defect}} - Z_{\text{rod}}}{Z_{\text{defect}} + Z_{\text{rod}}}. 
\]

From equation (23), the expected reflection coefficient \( \Gamma = -0.5 \). Thus, the reflected wave will have half the amplitude of the transmitted wave. Multiple reflections within the defect section are expected due to the impedance mismatch on either side of it. Based on an incident acoustic wave with \( f \approx 40 \text{ kHz} \) and \( v_\rho = 5103 \text{ m s}^{-1} \) [41], the acoustic wavelength is expected to be \( \lambda_\rho \approx 10 \text{ cm} \). Since \( \lambda_\rho \approx 10 L_{\text{defect}} \), the multiple reflections in the defect can thus be neglected.

5.3.1. Inclusion of losses in rod ECMs. In laboratory testing, non-zero signal attenuation was observed in the bare, defect-free rods. To account for this, the per unit length resistance \( R_{\text{rod}} \) of \( Z_{\text{rod}} \) (figure 9(a)) was adjusted iteratively until amplitude matching between measured and simulated echo signals was achieved. The same value of \( R_{\text{rod}} = 1 \text{ k}\Omega \) was then applied to sections \( Z_{\text{rod1}} \) and \( Z_{\text{rod2}} \) (figure 9(b)). The acoustic couplant was modeled as a lossless transmission line, as shown in figure 9, with electrical parameters \( Z_{cpl} \) and \( \tau_{cpl} \). The exact material parameters of the couplant are difficult to determine since this information is not readily available. Thus, typical values from datasheets were used to approximate \( Z_{cpl} \) and \( \tau_{cpl} \) using equations (20)–(22) [46]. The effect of the couplant on the simulation results was not closely investigated in this work.

6. Discussion and results

6.1. Simulation of pulse-echo system neglecting losses caused by soil

Simulations using the ECM were compared with laboratory measurements. A 5-cycle, 40 kHz, sinusoidal burst, with \( A = 2 V_{pp} \), was used to excite the PECS transmitter electrode in simulation and in experiment. The simulated and measured responses were normalized for the purposes of comparison. The results for Rod A, Rod B and Rod C (figure 10) are shown in figures 11(a)–(c), respectively. Reflections off of defects are marked with \( R_{n\text{defect}} \), where \( n \) indicates successive reflections off of the defect. Wave-groups resulting from mode conversion are labeled \( \kappa \), and are not captured by the model.

The main features of the simulated and measured results are strongly in agreement. For all three rods, the timestamp of the echo off the end of the rod is \( \Delta t_{\text{end}} = 1.2 \text{ ms} \). This is in agreement with the predicted value of \( \Delta t_{\text{end}} = 1.15 \text{ ms} \) using equations (21) and (22). In figure 11(b), the echo seen at 0.6 ms is the reflected signal from the machined corrosion pit at the center of the rod. As predicted from equation (1), the measured and simulated \( \Delta t_{\text{defect}} \) for Rod B is half \( \Delta t_{\text{end}} \). In figure 11(c), the echo signal seen at 0.3 ms is the reflected signal from the machined corrosion pit at the \( L/4 \) position. Multiple reflections by the defect are seen occurring between the first echo and the echo from the rod-end. While the major features are well matched, distinct differences between the simulation and the experiment were observed. In figures 11(b) and (c), two echoes (marked with \( \kappa \)) are observed that are not captured by the simulation. This discrepancy is the result of wave-mode conversion occurring at the defect [41]. Since the machined corrosion pit is not symmetric with respect to the center of the rod, when the wave reflects from the machined corrosion pit, a portion of the incident wave energy could be converted into torsional
or flexural modes [29, 47]. Complex mode conversion at the defect is also possible. However, since these evanescent modes do not propagate in the rod, they are observed indirectly as a loss in wave energy [47]. In this work, only the \( L(0, 1) \) is captured by the model, and the effects of mode conversion are neglected. Since the wave velocities of the different modes are different [15], the \( \Delta t \) of the converted modes will be different than the \( \Delta t \) of the \( L(0, 1) \) mode. The slight variation between the measured and simulated signal amplitudes observed in figure 11 is expected because of the various simplifying assumptions used in the modeling.

### 6.2. Simulation of loss using wet-clay wrapped rods

The damping effects of the surrounding soil on acoustic wave propagation within the rod was investigated. To mimic the effects of soil in lab testing, a wrapping of wet potters clay (Plainsman M340) with thickness \( \approx 3 \) cm was applied to the test rods. The thickness and relative humidity of the clay were adjusted to match the properties of soil seen in field testing and those reported in literature [22, 23, 27]. The attenuation observed during lab testing was then used as a basis for modeling soil-induced loss in PSpice. The measured and simulated results for Rod A, Rod B, and Rod C, are shown in figures 12(a)-(c), respectively.

Comparing figures 12 with 11, it is seen that the amplitude of the echo signals are greatly reduced due to the loss of wave-energy into the potters clay. Comparing figures 12(b) to 11(b), we see that the signals arising from mode conversion at the defect have vanished. Since these converted modes readily attenuate in the presence of clay, their echoes are not directly observable in figure 12. The loss coefficient \( \alpha \) in Np/m and the loss coefficient \( \mathcal{L} \) in dB/m can be determined using equations (24) and (25) [17], respectively,

\[
\alpha = \frac{1}{2L_{\text{clay}}} \ln \left( \frac{A_0}{A_{\text{clay}}} \right),
\]

\[
\mathcal{L} = \alpha 20 \log_{10} e, \tag{25}
\]

where \( A_0 \) and \( A_{\text{clay}} \) are the respective amplitudes of the unattenuated and clay-attenuated echo signals, and \( L_{\text{clay}} \) is the length of rod covered by clay. In laboratory testing, we observed that signal attenuation depends on the level of humidity in the clay, such that dry clay attenuated the signals much more than wet clay. Since the soil conditions relevant to this study are relatively humid, the results shown in figure 12 were taken within 30 minutes of wrapping the rod in clay so that the effects of clay-drying could be neglected.

The simulated and experimental results are well matched in amplitude and time. The lossy transmission lines are a good model for lossy, acoustic-wave transmission into steel grounding rods. The difference in amplitude for the signals arising from the defect in figures 11(b), (c), 12(b) and (c), are attributed to energy loss at the defect which is not captured by the model.

### 6.3. Preliminary field tests

The defect detection system has been used in preliminary field tests. Figure 13 shows field testing results using the PECS transducer. The testing was carried out at a local substation which had some grounding rods exposed above ground. The PECS is shown attached to one of these rods in figure 13(a). Before applying the PECS, the tops of the rods were made smooth and flat, and acoustic couplant was applied. The field results show similar echo signals as those observed in simulation and laboratory experiments. The plot shown in figure 13(d) is consistent with a defect-free ground rod since only one echo is observed, and its size and time signature are consistent with a rod-end reflection. In figure 13(c), two echoes are observed, one echo from the rod-end, and a second echo at 0.9 ms. Thus, from equation (1), given \( v_p = 5100 \text{ m s}^{-1} \) (figure 2(c)), the second echo was predicted to have come from a small defect at \( L_{\text{defect}} = 2.3 \) m. After testing, the field rods were extracted to validate our predictions. The field rod associated with figure 13(d) was found to be defect free, consistent with our prediction. In the field rod associated with figure 13(c), a small defect was observed at \( L_{\text{defect}} = 2.2 \) m, and is shown in figure 13(b). Thus, the condition of the second field rod proved to be in agreement with our prediction. Signals arising from converted modes are not directly observed in figure 13 since these signals are highly suppressed due to energy dissipation into the surrounding soil. The preliminary field-test results demonstrate that our pulse-echo system and ECM are promising tools for detecting corrosion damage in individual grounding rods.
also be characterized. We have demonstrated that our model and experimental setup can give useful insight into the corrosion status of individual grounding rods before they are excavated for direct inspection. The model will also be useful for further sensor development and simulation, and possibly for tomographic analysis using the acquired signals.

Acknowledgments

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada, Canada Foundation of Innovation, Research Manitoba and Manitoba Hydro.

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Figure 13. (a) Exposed field rod with PECS held in place at rod end with magnetic clamp. (b) Photo of defect in extracted field rod. (c) signal profile of rod with defect, (d) a defect-free extracted rod.

7. Conclusions

A resonant transmission line sensor that selectively generates the L(0, 1) wave mode into cylindrical grounding rods was presented. A circuit model capable of reproducing most major features of measured echo signals was developed. PSpice models were developed for the PZT disk, PECS transducer, and the complete pulse-echo defect detection system. Simulated and experimental results were observed to be in strong agreement with each other. Both the simulated and experimental results reproduced features observed in preliminary field tests. Future work with the model, combined with lab experiments, will be helpful for analyzing field-collected data. Topics of future work should include: an improved model for the acoustic coupling between the PECS and the rod, the modeling of mode conversion at the defects, and the investigation of different wave-shapes for transmission into the rods. The effect of temperature on the PECS behavior should...
