Capacitance and Inductance Sensors for Location of Open and Short Circuited Wires

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Abstract

The location of an open or short circuited wire is linearly proportional to the capacitance or inductance of the wire, respectively. Several types of simple and inexpensive circuits to measure these values were tested and found to have highly variable performance. Open circuited (capacitance) measurements are very effective. Short circuited (inductance) measurements are more difficult, and not all of the circuits worked well for short circuits. A 555 timer circuit was found to have the best overall performance for locating both open and short circuited wires, although for specific cases, other circuits can be better. Also, capacitance and inductance values of various types of aircraft wires are measured and verified with analytical equations.

Key Words: Capacitance and Inductor Sensor, Aging Aircraft Wire Fault Detection, Wire Fault Detection.

I. INTRODUCTION:

Aging wiring has been identified as an area of critical national concern [1]. Miles of aging wires are buried inside virtually all of the major structures and systems with which we are familiar. Wiring is pervasive from private, commercial and military aircraft to the space shuttle, modest homes to massive skyscrapers, communication networks for business, entertainment, data collection, and control of critical systems, over land power lines to nuclear reactors and power plants, trains, warning systems, and switching stations to ships, dockyards, cranes, and autonomous loading systems, and even down to the "simple" family car. As these buried wires age they may begin to crack and fray, or their connectors may break, corrode, leak or be damaged in careless maintenance.

Detecting and locating these faults is extremely important, and there are several existing and emerging methods for doing this. The most common method of testing cables is to measure the resistance from end-to-end [2]. This method can be used to identify cold solder joints, bad crimps, carbonization of the cable or connectors, and foreign matter on or near the cables. This method can be used on a fueled airplane (unlike high voltage tests), but it is hard to pinpoint the fault locations. In addition, it is difficult to miniaturize and is expensive.

Time domain reflectometry (TDR) launches a short rectangular step of voltage down the cable. The wave travels to the far end of the cable, where it is reflected back at the end of the cable. TDR requires a fast-rise time pulse generator and fast voltage sampler to detect the reflected signal, and it is also costly and difficult to miniaturize. [2-8].

Frequency domain reflectometry (FDR, also called Swept Frequency Reflectometry sends a set of stepped-frequency sine waves down the wire. The waves travel to the end of the cable and are reflected back to the source. The reflected waves are analyzed. FDR systems include Standing Wave Reflectometry (SWR) systems [9, 10], and Phase Detection Frequency

Domain Reflectometry (PD-FDR) systems [2, 11-13]. Reflectometry methods are highly effective for locating faults, particularly open and short circuits, however they are more difficult to analyze than the capacitance methods described in this paper, are more expensive, require more power, and are bulkier.

Spread spectrum reflectometry [14-15] sends a pseudo-noise (PN) code down the wire and correlates with the returned reflection to determine the location of a fault. The digital PN code appears as random noise to the existing signal, therefore enabling the system to test the wires while they are live and potentially in flight [16].

Capacitance measurements have been used for locating open circuits on cables [17], however previous literature has not discussed how to locate short circuited wires. The capacitance of an open circuited wire and inductance of a short circuited wire are linearly proportional to their lengths. There are numerous methods of measuring capacitance, which are compared in this paper. A 555 timer circuit, for instance, has been utilized to detect the length of an open circuited wire [17].

Capacitance sensors are used for a variety of applications. They can be used to measure and detect the presence of a dielectric material or human [18, 19], humidity and water content [20, 21], micro imaging [22], position measurement, angular position and angular speed measurement [23-29], liquid level [30], pressure and temperature measurements [31, 32]. A capacitance sensor is a very simple and small device often built from one IC chip. Tests are made from one end of the wire.

Many different methods haven been introduced to convert the capacitance value into a voltage and use the capacitance sensor as motion, position or pressure sensor [33-36]. Most methods are not accurate enough to handle very small variations in capacitance that are required for location of wire faults to within a few inches. Reference [37] introduces an interface circuit to measure very small capacitance changes with a double difference principle using active rectifiers, a low pass filter and an analog-to-digital converter. Reference [38] shows a circuit of the differential capacitance to voltage converter using a current detector and AM demodulation circuit. It is accurate, albeit and complicated.

This paper shows the performance of three capacitance sensors that can be used to locate open and/or short circuits on wires. Two major capacitance sensors (Differential amplifier and 555 Timer) can locate both open and shorted circuits. Any conductor has a capacitance with respect to ground or another conductor. The capacitance will depend on the area and physical shape of the conductors and the permittivity of the dielectric separating the conductors from ground. A long wire can be thought of as a series of these localized capacitors, and the bulk capacitance of an open circuited wire is directly proportional to its length. Similarly short-circuited wires behave like a series of inductances at low frequencies, and the bulk inductance is directly proportional to the length.

Section II describes and summarizes the capacitance and inductance of thirteen different wire types, and the results of several different circuits (Two Inverter Oscillator, difference amplifier and 555 timer) for measuring the length of open and short circuited wires using capacitance and inductance. Section III summarizes the capabilities of these sensors and future work.

II. Capacitance and Inductance of Wire and Sensors

When designing sensors to measure the length of wire based on its capacitance or inductance, it is important to understand the range and variation of these values for realistic wire types. The section describes these values both analytically and experimentally.

The capacitance value ‘C’ of any two conductors is based on the distance between the conductor and ground (d), the area of the conductor (S), and the permittivity ε ($\varepsilon=\varepsilon_r\varepsilon_0$, ε_0 = 8.854E-12 F/m) of the dielectric separating the conductors. ε_r is the relative permittivity to the permittivity of air ε_0. For two parallel plates, the well-known equation for capacitance is given in equation (1).

$$C = \varepsilon \frac{S}{d} \tag{1}$$

The capacitance and inductance values of parallel insulated wires have been modeled and calculated [39-42]. For two circular parallel conductors (round wires) the capacitance and inductance are given by:

$$C = \frac{\pi\varepsilon}{\cosh^{-1}\left(\frac{D}{d}\right)} \text{ (Farads)} \tag{2}$$

$$\mathrm{L} = \frac{\mu}{\pi}\cosh^{-1}(D/d) \text{ for high frequency, (Henries)} \tag{3}$$

$$\mathrm{L} = \frac{\mu}{\pi}[1/4 + \cosh^{-1}(D/d)] \text{ for low frequency (Henries)} \tag{4}$$

where d is the diameter of the conductors, and D is the distance between the centers of the conductor and ε is the permittivity of the insulation. μ is magnetic permeability of the dielectric ($\mu=\mu_r\mu_0$, μ_0 = 4πE-7 H/m). μ_r is the relative permeability. μ_r and ε_r of polyethylene are about 0.994~1.0017 and 2.5~2.7, respectively.

Twisted pair wire has about 20% greater capacitance than simple parallel wire due to extra length from the twists [40]. This capacitance is given by:

$$C_{\text{Total}} = \frac{\pi\varepsilon_0}{\cosh^{-1}\left(\frac{D}{d}\right)} + \int_a^b \frac{\varepsilon_0 dx}{D - \sqrt{d^2 - x^2}} + \int_a^b \frac{\varepsilon_0 dx}{D + (1.0/\varepsilon_r - 1.0)\sqrt{D^2 - x^2} - \frac{\sqrt{d^2 - x^2}}{\varepsilon_r}} \text{ (F)} \qquad (5)$$

Capacitance and inductance values of coaxial cable are

$$C = \frac{2\pi\varepsilon}{\ln(b/a)} \text{ (F)} \qquad (6)$$

$$L = \frac{\mu}{2\pi}\left[\ln\frac{b}{a} + \frac{1}{4} + \frac{1}{4\left(c^2 - b^2\right)}\left(b^2 - 3c^2 + \frac{4c^4}{c^2 - b^2}\ln\frac{c}{b}\right)\right] \text{ (H)} \qquad (7)$$

where a is the radius of inner conductor, and b and c are the inner and outer radii of the shield [41, 42]. ε is the permittivity of insulator between the inner conductor and the shield.

Figure 1 shows the capacitance values of thirteen different open circuited aircraft wires as a function of. length measured using an HP4262A LCR meter. Table 1 gives the specifics on the type of wires, military part numbers, and the measured capacitance and inductance per unit length for each wire. Figure 2 shows the inductance values of the same wires when short circuited. The coaxial cable is seen to have the largest capacitance per unit length followed by shielded twisted pair cable. Capacitance of parallel individual wire (single wire) is similar to twisted pair cable, but slightly lower. Among the same type of wire, the thicker wire (lower gauge) has larger capacitance per unit length. The lowest capacitance value is found from the single parallel wires in a bundle, since the distance between the wires is small. Within a bundle of wires (often 20-150 wires), the capacitance and inductance could vary due to the wire not staying in the same part of the bundle, and therefore varying the distance between two wires forming a test pair. This was found not to be large, however. Variations of about 4pF out of

350pF and 0.01uH out of 9.20uH for 392 inch (9.95 m) long M22759/16-22-90 in a bundle of 20 wires was measured.

Figure 2 shows the measured inductance value of these same wire types when they are short circuited. The coaxial cable has the least inductance per unit length. In Figures 1 and 2, it can be seen that a wire with higher capacitance value has lower inductance value. Three different types of shorts, a simple short at the end, a short in the middle of the length wire with the ends left open and shorts in both the middle and the ends, were measured. The inductance value with the short in the middle of the wire with the ends left open shows the same value as when there are no ends. This is good (and expected), because it means that the additional lengths of wire do not corrupt the measurement to the short.

Clearly the capacitance and inductance can be used to measure the length of wires and the distance to faults. There are numerous circuits for measuring these values [43], they are not all equally effective. The following section discusses the capabilities, advantages and disadvantages of several types of capacitance sensors.

III. Capacitance and Inductance Sensors

Sensors for measuring capacitance and inductance can be broadly divided into two categories. One type of sensor uses the wire as an inductive or capacitive element in a resonator circuit. The two inverter oscillator, difference amplifier and 555 timer sensors are only introduced here for brevity and page limit. Another set of sensors uses the capacitance or inductance of the wire as an impedance and measures the voltage drop between various impedances in the circuit. The voltage divider is an example of this class of sensor. Some circuits are more susceptible to stray capacitances or inductances, are more or less accurate, have ranges of measurement that are more or less effective, and in general work better for measuring wire length or distance to fault than other methods.

1. Two Inverter Oscillator Sensor

A two inverter oscillator is a stable multi-vibrator [44]. It consists of two inverters and an RC network, as shown in Figure 3. The output of each inverter is either logic 0 or logic 1, each corresponding to a fixed voltage. The input v1 can vary slowly between certain limits, because it is the voltage of the insulated gate. No current flows into the input. The only possible current path is between nodes *v2* and *v0*. When *v1* is logic 1, *v2* and *v0* will be logic 0 and logic 1, respectively. Then *v1* is greater than the inverter switching voltage. The voltage across R produces a current *i*, which charges the capacitor, in our case the wire, causing v_c to rise. Thus *v1* drops. When it is below the inverter switching voltage, the inverters switch states. The respective logic levels of *v2* and *v0* are now 1 and 0. The current *i* reverses, and v_c drops until *v1* rises above the inverter switching voltage. Then the inverters again switch states. Hence the circuit functions as an oscillator.

The frequency output of this oscillator can be estimated using the expression:

Open circuit:

Without C F (Hz) = 1 / (5* C_w *R) (8)

With C F (Hz = (C_w + C) / (5*C* C_w *R) (9)

Short circuit:

With C F (Hz) = (1+ L_w*C_w) / (5*R*C_w) (10)

where C is the reference capacitance, C_w is the capacitance due to the open circuited wire, and L_w is the inductance due to the shorted wire.

Without the capacitor 'C', the circuit can locate only open circuits. Short circuited wires would short out the oscillator. The "hot" wire lead should be connected in a feedback loop between one of the inverters and the resistor. The wire that acts as the return path for current is connected between the resistor and the input of the other inverter as shown. The frequency of the output voltage Vo is linear with the length of the wire, so the location of the open and short circuit can be estimated as shown in Figure 4. To locate a short-circuit, the inductance due of the wire is measured relative to the reference capacitance 'C', as shown in Figure 3.

Values chosen for the oscillator are R = 1 kΩ and V_{cc} above 3.2 V for the 74LS04 IC used. The capacitor 'C' (which is 50 pF in this case) limits the range of the sensor to 6 m for short circuits. As with the three-gate oscillator, changing C changes the minimum measurable length. The sensor output is very sensitive to the supply voltage, so a well-regulated voltage is required. To test a longer short circuited wire, a larger capacitance is required. Also the output frequency ranges of both the open and short overlap, so that another test or a priori knowledge about whether the load is an open or short is required.

2. Difference Amplifier for Open and Short Circuits

A non-inverting or inverting operational amplifier circuit has a gain defined by the feedback resistor (R_f). The relationship between input and output is:

$$V_o\,(V) = (1 + (R_f / R)) * V_{in}$$

For this circuit, the input voltage limits the circuit's performance. The change in output voltage due to change in capacitance is very small in certain cases, when compared to the input voltage. Also if the impedance is complex or purely imaginary, the calculations needed to estimate the unknown impedance become complicated. These limitations can be overcome, and the circuit can be made simpler and very sensitive to small changes in capacitance with the use of a voltage follower and a differential amplifier (subtractor) as shown in the Figure 5.

In this circuit if Z is complex, i.e. if the impedance is not real, the output signal V_o is also complex. Thus, both the magnitude and phase of the output signal have to be measured. The voltage output of the amplifier is given by equation (11). As the amplifier output is fed to the non-inverting terminal of the differential amplifier (subtractor) and the voltage follower output (which is the same as the input voltage) is fed to the inverting terminal of the differential amplifier, the final output (12) can be derived as shown below.

Open circuit:

Without Capacitor $V_o\,(V) = [\,(1 + (R_f/Z))*V_{in}\,] - V_{in}$

$$V_o\,(V) = (R_f/Z)*V_{in} \tag{11}$$

$$Z = (V_{in}/V_o) * R_f \tag{12}$$

With Capacitor

$$V_o\,(V) = (V_{in} * R_f * \omega * C * C_w) / (C_w + C) \tag{13}$$

Short circuit:

With Capacitor

$$V_o\,(V) = (V_{in} * R_f * \omega * C^2) / (L_w * \omega^2 * C - 1) \tag{14}$$

where R_f is the feedback resistance, C is the reference capacitance, C_w is the capacitance due to the open circuited wire, and L_w is the inductance due to the short circuited wire. Both C_w and L_w are directly proportional to the length of the wire. Both V_o and Z are complex, and the reactive part of Z (capacitance or inductance) can be found.

The circuit was tested for known capacitances ranging from 100 pF to 0.05 μF. The input voltage was 1 V at a frequency of 60 kHz. The frequency was chosen to be 60 kHz, because the output at this frequency was less distorted and easier to do phase measurements on. The voltage output was measured using an oscilloscope, and the capacitances were calculated using equation

(12). The close comparison of the actual capacitance and the measured capacitance is shown in Figure 6. The voltage output of the oscillator is plotted with respect to the length of the wire in Figure 7. It can be seen that the change in voltage is linear with the length of the open circuited wires without the reference capacitor (100 pF) over 4.5m, and the theoretical value matched very well for wires up to 450 cm long. The reference capacitor makes the response nonlinear as shown in Figure 7. For the circuit with the reference capacitor, there is overlap on the output voltage for open and short circuits for wires longer than 450 cm, which limits the range of this sensor. Changing the capacitor changes the range of the sensor. There is also an ambiguous region around 50cm for the open circuited wire with the reference capacitor. Therefore, it is nice to use the circuit without capacitor for the open circuited tests.

From Figure 7, it can be seen that output is not consistent for short circuited wires. The sensor is very stable for open circuited measurements for wires over 4.5m long. The maximum length of a short-circuited wire that can be measured is 425 cm. Beyond that the change in voltage is very small and cannot be measured accurately. Also the circuit is very sensitive to the position/posture of short circuited wires.

7. 555 Timer Circuit for Open and Short Circuit.

A 555 timer set up as an astable multi-vibrator is a well-known method for locating faults on open circuited wire. [17]. The frequency output for open circuited wires is

$$\text{frequency} = 1.443/[(R_A + 2R_B)C] \quad (15)$$

The circuit must be adapted to test short circuited wires as shown in Figure 8. The values used are Ra=1kΩ sign and Rb=10MΩ to obtain a 50% oscillation duty cycle. This circuit can distinguish between open and short circuits, because a short circuited wire produces DC output with the timer for open circuited wire in [17], and an open circuited wire produces DC output with the timer circuit in Figure 8 for short circuited wire. The period of the output is plotted in Figure 9, and both open and short circuited configurations are shown to be very linear. The maximum length that we have tested is 60 meters long. In theory this circuit can locate faults on wires up to about 1000m long wire with a little modification of the value of Ra and Rb in Figure 8.

III. Comparison of Methods and Conclusion

The different methods discussed in this paper are summarized in Table 2. All circuits were more accurate for open circuits (capacitance) than for short circuits (inductance), which is understandable since the parasitic inductance near the wire is strongly impacted by its surroundings. The 555 timer and differential amplifier can locate both open and short circuited wires with the least error. Maximum errors for the timer for open and shorts were 5.3cm and 20cm, and for the differential amplifier were 7.93cm and 28.43cm, respectively.

Calibration of these systems can be done by measuring wires of the type that will later be tested and storing the coefficients of a linear fit to that data. If no calibration is done, and the average values are used, errors on the order of 1~5% for open and 1~20% for short would be seen, so it is strongly recommended that the type of wire and its gauge be known and used for calibration.

Some of the important limitations of all of these methods is that if the capacitance or inductance of the wire changes along its path (such as from nearby metallic components on unshielded or untwisted wires, significant changes in the orientation or separation of the wire and its associated "ground" or paired wire, or from discrete components added to the system), the capacitance or inductance of these additional effects will also be measured and will create errors in the length measurements. Also, these methods are not suitable for location of faults on branched wires, as only the lumped capacitance or inductance is being measured. In spite of these limitations, these simple and inexpensive circuits can provide excellent location of open and short circuits on wires. They are ideally suited for integration in handheld test equipment (which has been done in our lab), and can provide an easy-to-use alternative to the manual search methods used today.

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References

1. NSTC, “Review of Federal Programs for Wire System Safety”, White House Report, Nov. 2000.
2. Cynthia Furse, You Chung Chung, Rakesh Dangol, Marc Nielsen, Glen Mabey, Raymond Woodward, “Frequency Domain Reflectometery for On Board Testing of Aging Aircraft Wiring,” *IEEE Trans. Electromagnetic Compatibility*, pp.306-315, May 2003.
3. N. A. Mackay and S. R. Penstone, “High-sensitivity narrow-band time-domain reflectometer,” *IEEE Trans. Instrumentation and Measurement*, vol. 23, no. 2, pp. 155-158, June 1974.
4. C. S. Chen, L. E. roemer and R. S. Grumbach, “Cable Diagnostics for power cables,” *IEEE Annual Conference of Electrical Eng. Problems in Rubber and Plastic Industries*, p. 20-22, Apr. 1978.
5. Brent Waddoups, “Analysis of reflectometry for detection of chafed aircraft wiring insulation,” *MS Thesis*, Utah State University, Logan, Utah, 2001
6. Mark Schmidt, “Use of TDR for Cable Testing “ *MS Thesis*, Utah State University, Logan,Utah, 2002.
7. Alok Jani, “Location of Small Frays using TDR,” *MS Thesis*, Utah State University, Logan,Utah, 2003
8. Campbell Scientific, “TDR100 Instruction Manual.” [ftp://ftp.campbellsci.com /pub/outgoing/manuals/tdr100.pdf]
9. P. J. Medelius, H. J. Simson, “Non-intrusive impedance-based cable tester,” US Patent 5977773, Nov, 1999.
10. Raymond J. Woodward, “Using frequency domain reflectometry for water level measurement“, *MS Thesis*, Utah State University, Logan, Utah, 2000
11. D. A. Noon and M. E. Bialkowski, “An inexpensive microwave distance measuring system,” *Microwave and Optical Technology Letters*, vol. 6, pp. 287-292, April 1993.
12. N. Kamdar, “Application of distance measuring system for location of robotic vehicles,” *MS Thesis*, Utah State University, Logan, Utah, 1998
13. Arvin Jayakar, “Use of FDR for analysis of cable trees,” *MS Thesis*, Utah State University, Logan, Utah, 2000.
14. K.Jones, et al., “Adapative apparatus for transmission line analysis,” US Patent App. 20020169585, Mar. 11, 2002
15. V.Taylor and M. Faulkner, “Line monitoring and fault location using spread spectrum on power line carrier,” *IEE Proc. Gener. Transm. Distrib.,* Sept. 1996, Vol. 143, pp. 427-434
16. P. Smith, Spread Spectrum Time Domain Reflectometry, PhD. Dissertation, Utah State University, Logan, Utah May 2003.
17. E. Edang, “Inexpensive "Reflectometer" Locates An Open Circuit Along A Cable,” *Electronic Design*, v 49, n 2, pp. 115, Jan.22, 2001.
18. T. A. York, I. G. Evans, Z. Pokusevski, and T. Source, “Particle detection using an integrated capacitance sensor”, *Sensors and Actuators, A: Physical*, v 92, n 1-3, pp 74-79, Aug. 2001.
19. N. L. Buck, and R. A. Aherin, “Human presence detection by a capacitive proximity sensor,” *Applied Engineering in Agriculture*, v 7, n 1, , pp 55-60, Jan. 1991.

20. Ralston, R. K. Andrew, and etc., “Capacitance humidity sensor,” *Materials Research Society Symposium - Proceedings*, v 382, *Structure and Properties of Multilayered Thin Films*, pp 469-475, 1995.
21. B. Ruth, “Capacitance sensor with planar sensitivity for monitoring soil water content,” *Soil Science Society of America Journal*, v 63, n 1, pp 48-54, 1999.
22. T. A. York, I. G. Evans, Z. Pokusevski, and T. Dyakowski, “Capacitance sensor for micro imaging,” *Proceedings of SPIE - The International Society for Optical Engineering*, v 4188, pp 251-260, 2001.
23. L. Xiujun, C. M. Gerard, and Meijer, “Novel smart resistive-capacitive position sensor,” *IEEE Trans. Instrum. Meas*, v 44, n 3, pp 768-770, Jun. 1995.
24. L. Xiujun, Meijer C. M. Gerard, de Jong, and W. Gerben, “Microcontroller-based self-calibration technique for a smart capacitive angular-position sensor,” *IEEE Trans. Instrum. Meas*, v 46, n 4, pp 888-892, Aug. 1997.
25. S. Lanyi, “Analysis of linearity errors of inverse capacitance position sensors,” Measurement Science & *Technology*, v 9, n 10, pp 1757-1764, Oct. 1998.
26. T. Fabian, and G. Brasseur, “Robust capacitive angular speed sensor,” *IEEE Trans. Instrum. Meas*, v 47, n 1, pp 280-284, Feb. 1998.
27. de Jong, W. Gerben, C. M. Meijer, and etc., “Smart capacitive absolute angular-position sensor,” *Sensors and Actuators, A: Physical*, v 41, n 1-3 pt 3, pp 212-216, Apr. 1994.
28. H. Kobayashi, Hosokawa, and Yasuhiko, “Study of a capacitance-type position sensor for automotive use,” *Sensors and Actuators, A: Physical*, v 24, n 1, p 27-33, May 1990.
29. S. Lanyi and Stefan, “Analysis of linearity errors of inverse capacitance position sensors,” *Measurement Science & Technology*, v 9, n 10, pp 1757-1764, Oct. 1998.
30. F. N. Toth, C. M. Meijer, and M. van der Lee, “A planar capacitive precision gauge for liquide-level and leakage detection,” *IEEE Trans. Instrum. Meas*., vol. 46, pp. 644-646, Apr. 1997.
31. S. Guo, J. Guo, W. H. Wen, “Monolithically integrated surface micromachined touch mode capacitive pressure sensor,” *Sensors and Actuators, A: Physical*, v 80, n 3, pp 224-232, Mar. 2000.
32. L. Jansak, “A capacitance temperature sensor for the liquid nitrogen region,” *Cryogenics*, v 41, n 8, pp 607-608, 2001.
33. R. Pallas-Areny and J. G. Webster, *Sensor and Signal Conditioning*. New York: Wiley, 1992.
34. D. Mariolo, E. Sardini, and A. Taroni, “Measurement of small capacitance variation,” *IEEE Trans. Instrum. Meas*., vol. 40, pp. 426-428, Apr. 1991.
35. F. N. Toth, Gerard, C. M. Meijer, “A low-cost, smart capacitive position sensor,” *IEEE Trans. Instrum. Meas*., vol. 41, no. 6, pp. 1041-1044, Dec. 1992.
36. M. Yamada, T. Takebayashi, S. Notoyama, and K. Watanabe**,** “A switched-capacitor interface for capacitive pressure sensors,” *IEEE Trans. Instrum. Meas*., vol. 41, no. 1, pp. 81-86, Feb. 1992.
37. D. M. G. Preethichandra and K. Shida, “A simple interface circuit to measure very small capacitance changes in capacitive sensors,” *IEEE Trans. Instrum. Meas*., vol. 50, no. 6, pp. 1583-1586, Dec. 2001.
38. J. C. Lotters, W. Olthuis, and P. Bergveld, “A Sensitive differential capacitance to voltage converter for sensor applications,” *IEEE Trans. Instrum. Meas.*, v 48, n 1, p 89-96, Feb, 1999.

39. H. E. Green, "A Simplified derivation of the capacitance of a two-wire transmission line," *IEEE Transactions on Microwave Theory and Techniques*, v 47, n 3, pp 365-366, Mar. 1999.
40. B. B. Wadell, Transmission Line Design handbook, Artech House, Norwood, MA, 1991.
41. W. H. Hayt, Engineering Electromagnetics, 5th edition, McGraw-Hill Book Co. 1989.
42. B. N. Das, S. B. Chakrabarty, K. Rao and R. Siva, "Capacitance of transmission line of parallel cylinders in the presence of dielectric coating," *IEEE Transactions on Electromagnetic Compatibility*, v 37, n 1, p 94-96, Feb. 1995.
43. Larry K. Baxter "*Capacitive Sensors – Design and Applications*", IEEE Press Series on Electronic Technology, c1997.
44. Theodore F. Bogart, Jr. "*Linear integrated circuits: applications and experiments*" New York: J. Wiley, c1983.

List of Figures and Tables

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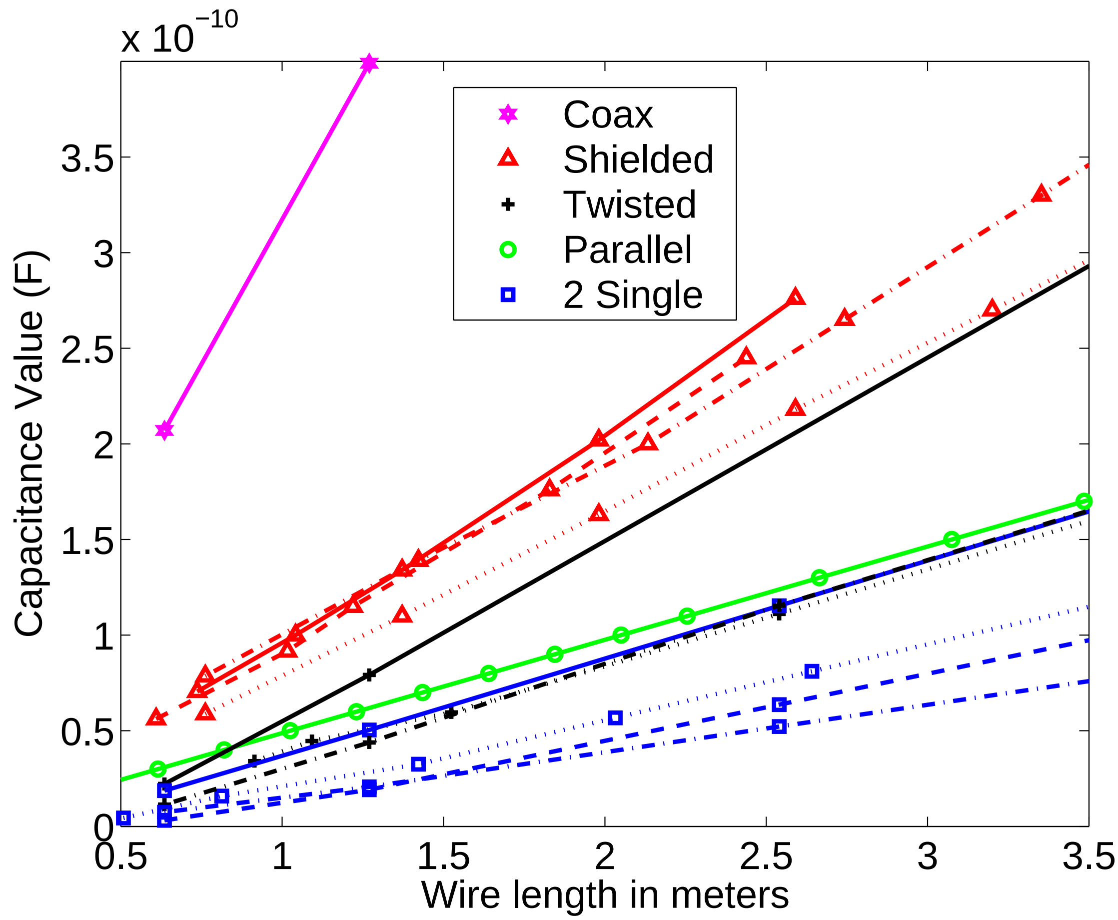
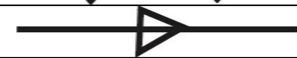
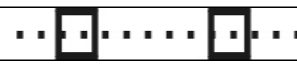


Figure 1. Wire length vs. measured capacitance of 13 different open circuited air craft wires using HP4262A LCR meter. The specifics of each wire are given in Table 1.

Table 1. Measurement results of capacitance and inductance of wires

Wire Type	Part Number	Line Type for Figures	pF/m	uH/m
Coax	C4931-22L		339	0.161
Twisted shielded quadruple	M27500-22SC4S23		106.5	0.517
Twisted shielded triple	M27500-24SC3S23		100.5	0.55
Twisted pair shielded	M27500-2408T23		102.4	0.544
Twisted pair shielded	M27500-24SE2S23		84.7	0.614
Thick twisted triple	M81381-11-12		90.29	0.467
twisted pair	C4932-26L2		49.61	0.659
twisted pair	M27500-24SC2U00		47.28	0.587
parallel pair speaker wire	20 gage		49.27	0.785
thick single pair in a bundle	M81381-11-12 (C4932-12N3)		49.34	0.651
single pair in a bundle	M81381/7-20-2 (C4928-20)		31.76	0.976
single pair in a bundle	M22759/16-22-90		35.15	0.924
single pair in a big bundle	M22759-43-22-9		23.36	1.08

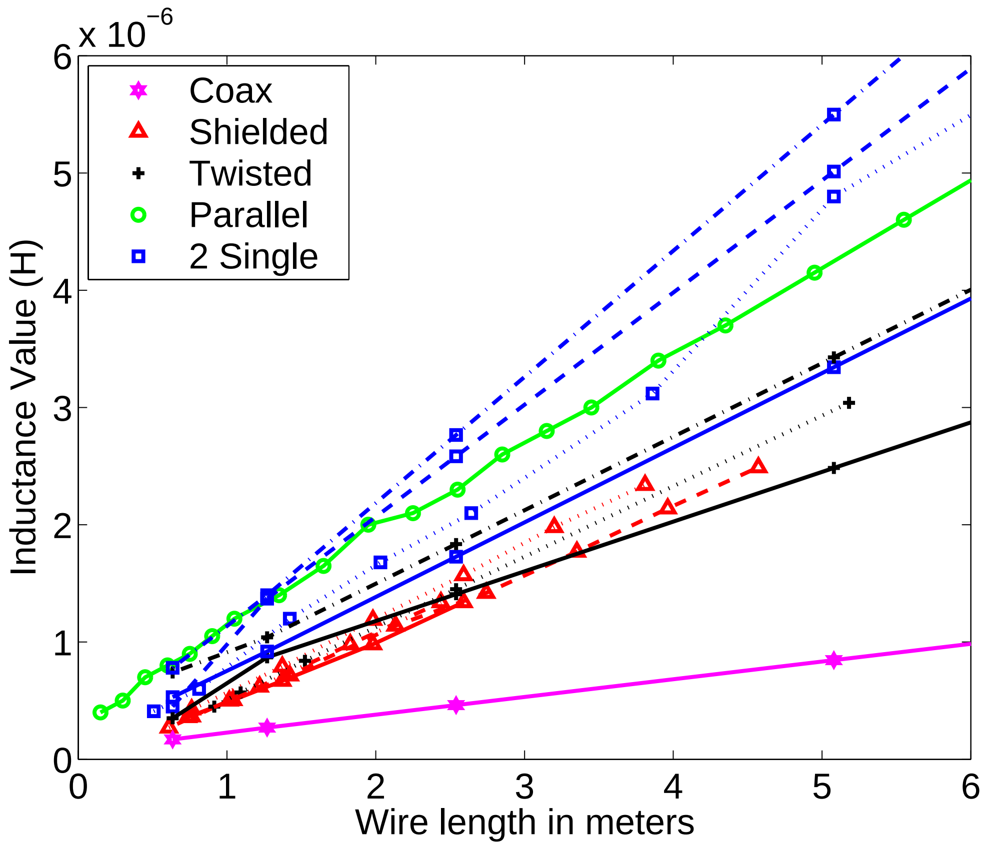


Figure 2. Wire length vs. measured inductance of 13 different short-circuited air craft wires using HP4262A LCR meter. The specifics of each wire are given in Table 1.

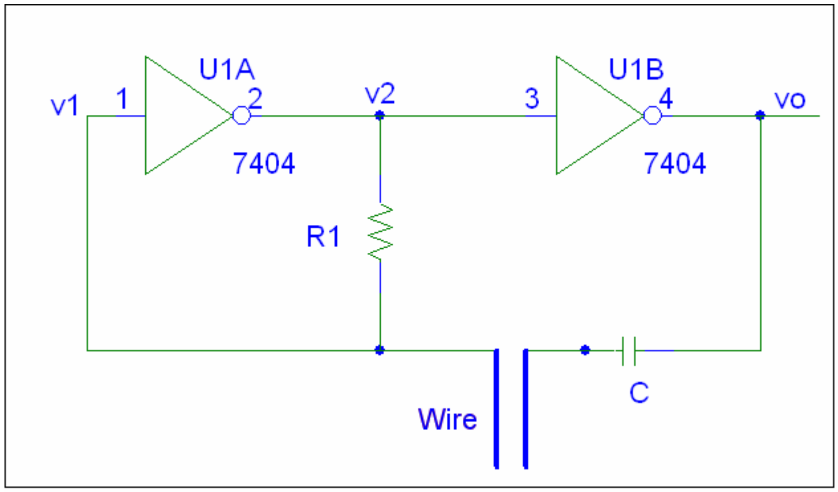


Figure 3. Two inverter oscillator for open and short circuit wire measurements.

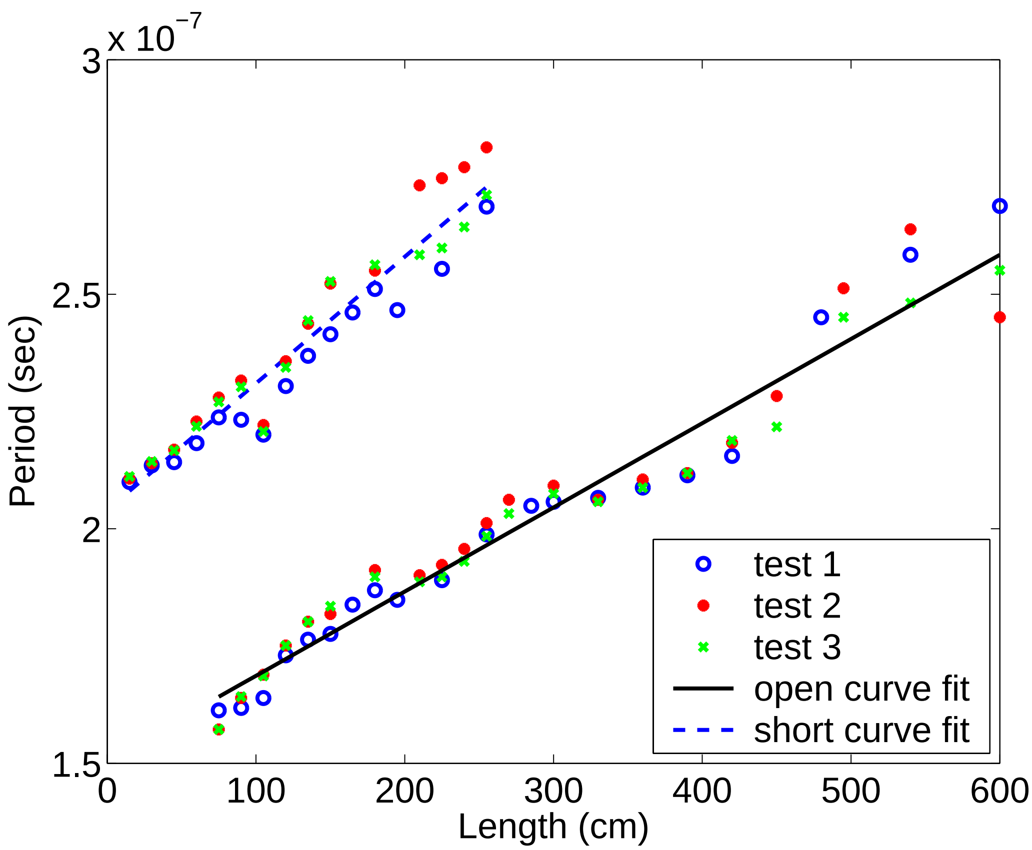


Figure 4. Length versus period of output for open and short circuited wires.

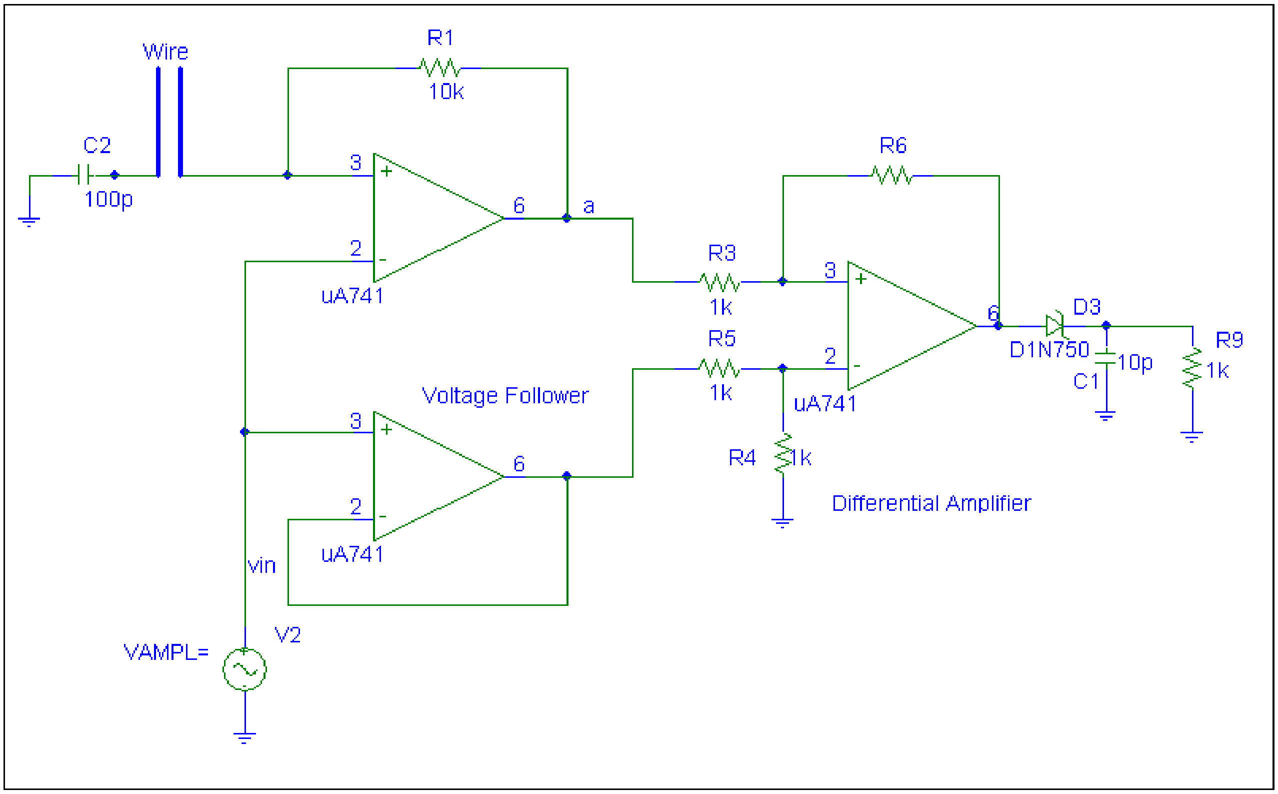


Figure 5. Difference amplifier sensor for open and short circuit wire fault detector.

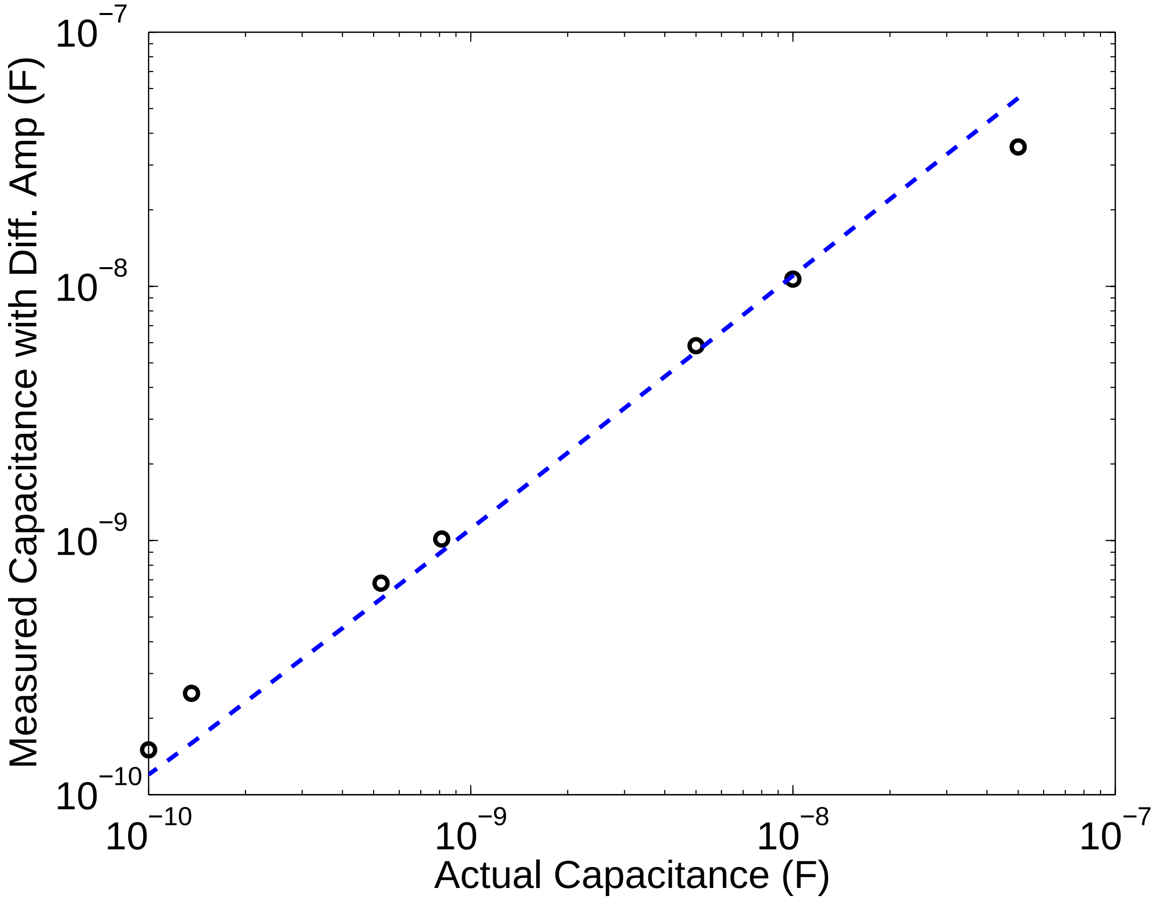


Figure 6. Actual vs. measured capacitance with the differential amplifier using LM741CN.

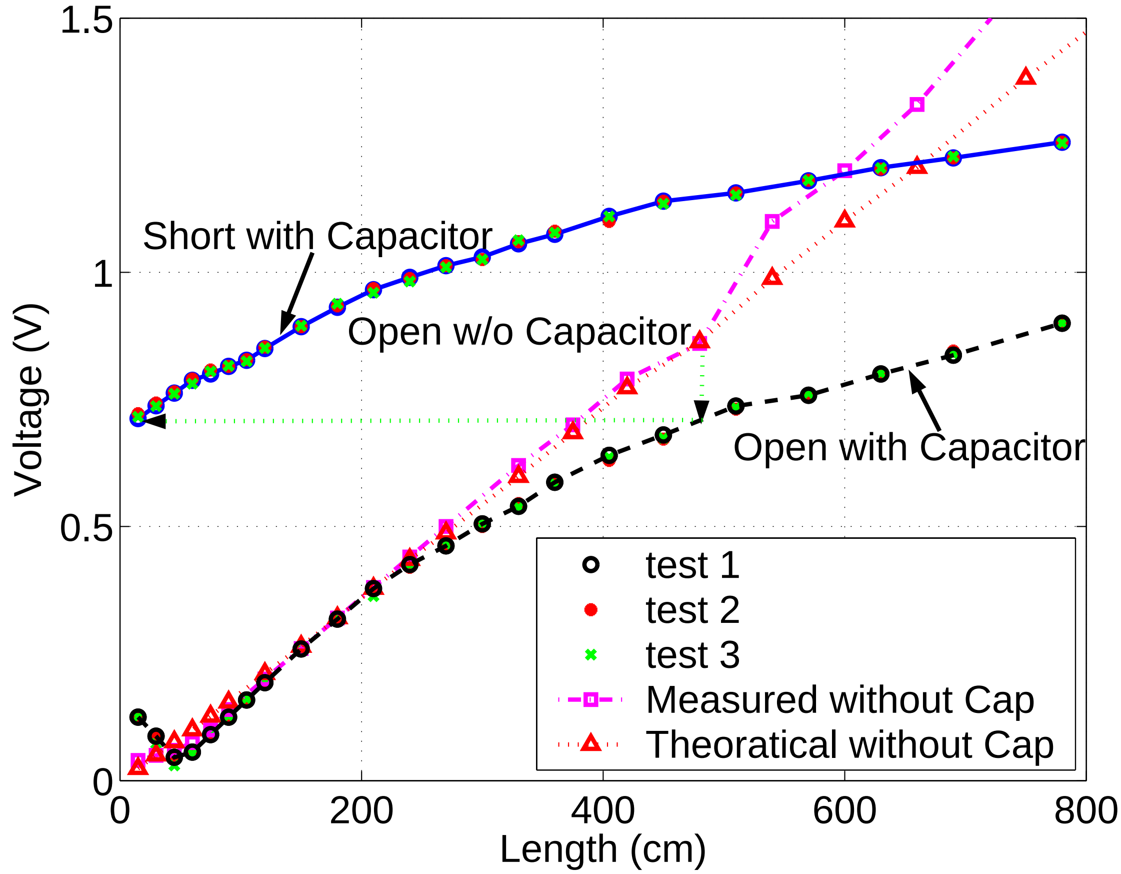


Figure 7. Length vs. voltage for open and short circuited wire with the differential amplifier.

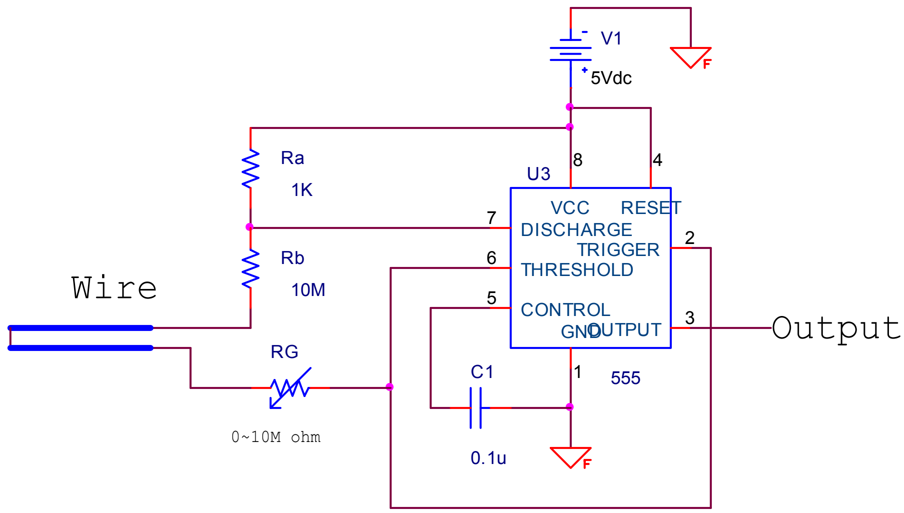


Figure 8. Timer sensor for short circuit fault detection.

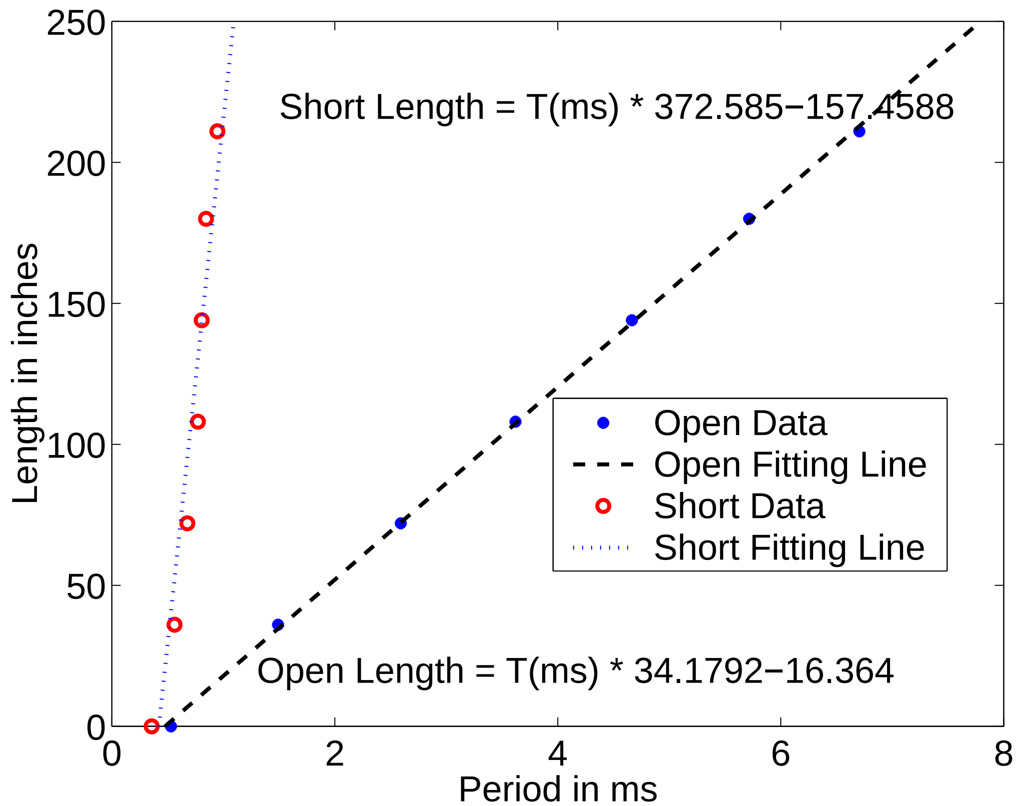


Figure 9. Timer output period vs. length of the twisted pair shielded wire M27500-24SE2S23.

Table 2. Comparison of methods for detecting both open and short circuits.

Sensors	Open (Cm)			Short (Cm)		
	Max. Length	Max. Error	Min Error	Max Length	Max. Error	Min Error
Two Inverter Oscillator	600	63.19	1.9117	255 (C=50 pF)	46.62	0.8414
Difference Amplifier	225	7.93	0.0984	225 (C=100 pF)	28.43	0.0134
555 Timer	Less than infinity	5.3	0.01	Less than infinity	20	0.5