ITY 1.2.6 for Windows (http://audacity.sourceforge.net/).

[13] The speed of sound in a solid depends on several factors such as its composition and the method of production. Thus, one can find in the literature different values for the speed of sound in steel. For example, one finds a value of 5130 m/s in R. A. Serway, *Physics for Scientists and Engineers with Modern Physics*, 3rd ed. (Saunders, Philadelphia, 1990), Table 17.1, or values in the range of 5000–5200 m/s in the *Handbook of Chemistry and Physics*, 56th ed. (CRC, Cleveland, 1976), edited by R. C. Weats, p. E-41.

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[15] H. M. Ledbetter, N. V. Frederick, and M. W. Austin, "Elastic-constant variability in stainless-steel 304," J. Appl. Phys. **51**, 305–309 (1980).

[16] R. A. Serway, *Physics for Scientists and Engineers with Modern Physics*, 3rd ed. (Saunders, Philadelphia, 1990), Table 12.1.

[17] By applying the hit with the hammer perpendicularly to the axis of the bar, at a point on the lateral surface close to one end (lateral hit), one can measure 21 flexural frequencies.

[18] Reference 6, p. 526.

New experimental method of visualizing the electric field due to surface charges on circuit elements

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Although static surface charges on circuit elements are of enormous interest, recent papers and textbooks have only discussed the problem theoretically using analytical or numerical approaches. The only well-known experimental method to visualize the structure of electric fields around circuit elements was reported by Jefimenko almost half a century ago. In our paper, we report on a simple method to visualize the electric field produced by static surface charges on current-carrying circuit elements. Our method uses a mixture of PTFE (Teflon) sealant and mineral oil, a copper wire placed in the mixture's container, and two 6 kV power supplies. We believe that our new method can be used directly in the classroom.
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I. INTRODUCTION

Introductory Physics courses traditionally treat electrostatics and circuits as two completely separate, disjoint topics. The stationary electric field, produced by static charges on the surface of current-carrying wires, is an important subject neglected in most textbooks. Circuits are only discussed in terms of electromotive forces and Kirchhoff's rules, suggesting that Coulomb's law is of little importance for electric circuits. As a result, the electric forces and fields that move the charges to produce the currents in the circuit elements are not discussed in any detail. The roles of the static surface charges are to maintain the potential around the circuit, to provide the electric field in the space around the circuit, and to assure the confined flow of current.[1]

Several recent publications focus on static surface charges in circuits.[1–6] However, these papers and textbooks only discuss the problem theoretically using analytical and/or numerical approaches. The only well-known experimental method of visualizing the structure of electric fields around circuit elements was reported by Jefimenko[7] almost half a century ago. Jefimenko's method is complicated to reproduce.

In this work, we present a new, simple experimental method to visualize the structure of the electric field produced by static surface charges on current-carrying wires. Our method does not use any of Jefimenko's printed-circuits, rapidograph, India inks, glass plates, and Redtop grass seeds. Instead, our method uses materials readily available in any high-school and college laboratory, such as copper wires, solutions of PTFE sealant in mineral oil, and Petri dishes. We believe that our method is simpler than Jefimenko's and can be used directly in the classroom.

II. JEFIMENKO'S METHOD

Jefimenko's method of visualizing the electric field due to static charges on the surface of high-voltage current-carrying conductors can be accomplished by drawing circuit-type models on glass plates using transparent conducting ink and grass seeds strewed upon them.[7] In order to test Jefimenko's method, we used two 6 kV Pasco power supplies, red and blue rapidograph ink, India ink, five glass plates, Redtop grass seed, and mineral oil. The power supplies and ink were used to construct the circuits. Red ink, diluted 1:1 with water, was used for wires, and the better conducting India ink was used for battery terminals. We found that the red ink did not sufficiently conduct, and India ink was used also for the wires. Several methods of aligning grass seed to the electric field were tried, including simply spreading the grass seed on the glass plate, using PTFE on the glass plate to reduce friction, and immersing the seeds in mineral oil in a tray underneath the glass plate. In each of these methods, the grass seeds would move only when the electrodes of the power

Fig. 1. The picture shows a PTFE sealant mixed with mineral oil in an 88 mm diameter × 12 mm high plastic Petri dish. An S-shaped 1 mm diameter (18 gauge), 13 cm long copper wire is placed in the Petri dish and connected in series with an 8 MΩ resistor to the power supply (not shown in the picture). The PTFE groups into strands and clumps, which visibly align perpendicular to the wire.

Fig. 2. This is a 400%-magnified version of Fig. 1. It shows the copper wire and the electric field lines close to the wire.

supplies were placed less than 1 cm away; they would not easily align to the electric field produced by a current running through the ink, or else no field was readily produced by the ink.

III. NEW METHOD AND RESULTS

Our new experimental method uses two 6 kV Pasco power supplies, PTFE (Teflon) sealant, mineral oil, a 1 mm diameter (18 gauge) copper wire, and an 88 mm diameter × 12 mm high plastic Petri dish. The PTFE sealant is mixed with mineral oil in the Petri dish. An S-shaped 13 cm long copper wire is placed in the Petri dish. One end of the wire is soldered to an 8 MΩ resistor, and the system is connected to two 6 kV power supplies installed in series to create a 12 kV supply. The high voltage is limited to 7 kV to avoid burning out the resistor. After a few minutes, one can see the PTFE grouping into strands or clumps, which visibly align along the electric field lines, perpendicularly to the wire, as can be seen in Figs. 1 and 2. This new method provides visual evidence of the electric field due to static surface charges on the wire.

We have determined that the optimum mixture of PTFE and mineral oil requires 1 cm^2 of PTFE paste with a thickness of about 2 mm and 7 cc of mineral oil. We have compared three brands of PTFE paste and found them all to have equal or near equal visibility. This suggests that the movement and clumping observed are due to the PTFE rather than the other chemicals present in the paste since these would likely differ from brand to brand. We have found that the minimum voltage at which movement is clearly visible is 5 kV.

IV. CONCLUSION

We have reported a new, simple experimental method to visualize the structure of the electric field produced by static surface charges on current-carrying wires. This method uses a mixture of PTFE (Teflon) sealant and mineral oil, a copper wire, and two 6 kV power supplies. The PTFE groups into strands or clumps, which visibly align themselves along the electric field close to the wire. Unlike Jefimenko's method, we use actual wires, and the direction of the electric field lines close to the copper wire are clearly visible and the effect is readily reproduced. We believe that our new method is of great interest to instructors for in-class demonstrations.

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