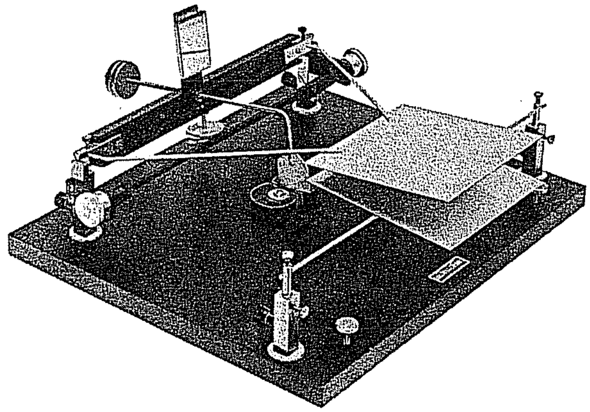
Instructions for Use of

Cat. No. 2353A Coulomb Balance Attachment



Attachment shown mounted on Current Balance.

Description. No. 2353A Coulomb Balance Attachment is designed for use with Cat. No. 2353 Current Balance to determine the electrostatic constant (permittivity in free space, $\varepsilon_0$ ) by measuring the electrostatic attractive force between two oppositely charged plates.

The Coulomb Balance Attachment consists of two flat aluminum plates with attached aluminum mounting rods. Two short rods are also supplied for attaching the fixed lower plate to the balance assembly.

The plates replace the conductor rods on the Current Balance and are used in measuring electrostatic forces in a manner similar to the use of the conductors in measuring electromagnetic forces.

Theory. Maxwell predicted that electromagnetic fields should travel with the speed $\sqrt{1/\varepsilon_0 \mu_0}$ in which $\varepsilon_0$ is the electrostatic constant called permittivity in free space, and $\mu_0$ is the electromagnetic constant called permeability in free space (rationalized MKS system). This value has proved to be identical to the value obtained by Michelson for the speed of light, thereby supporting the theory that light is an electromagnetic radiation and suggesting that measuring $\varepsilon_0$ and $\mu_0$ is an indirect way of determining c the speed of light.

The electrostatic constant is the constant of proportionality in the relationship for expressing the force between electrostatic charges just as the gravitational constant is the constant of proportionality in the similar relationship for expressing the force between masses. Thus the Coulomb Balance experiment is the electrical analog of the Cavendish gravitational experiment.

The force of attraction between two oppositely charged, parallel plates of equal area is given by

$$F = \frac{\varepsilon_0 A V^2}{2 d^2} \qquad (1)$$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in which

$F$ is the force of attraction in newtons, when
$\varepsilon_0$ is the electrostatic constant (permittivity in free space) in farads/meter,
$A$ is the area of plates in meters$^2$,
$V$ is the potential difference between the plates in volts, and
$d$ is the distance between plates in meters.

The value of $d$ should be small. If $d$ becomes large relative to the area of the plates, edge effects become significant, lack of parallelism between the plates increases, and equation (1) is no longer valid.

Equation (1) can be written

$$\varepsilon_0 = \frac{2Fd^2}{AV^2} \tag{2}$$

Hence, with $d$ and $A$ remaining unchanged, by measuring $V$ for various values of $F$ an average value of $\varepsilon_0$ can be determined.

In the experiment with the Current Balance (see attached instructions for same) the data was used to compute an arbitrary constant, $k_c$, which can be shown to be related to the electromagnetic constant, $k_m$ (MKS system) by

$$k_m \doteq \frac{d}{2L} k_c \tag{3}$$

since $k_m$ is $10^{-7}$. The terms are defined in the Current Balance experiment. Then from equation (3) $\mu_0$ (rationalized MKS system) is seen to be

$$\mu_0 = \frac{2\pi d}{L} k_c \tag{4}$$

since $\mu_0$ is $4\pi k_m$.

With the data from the two experiments the two constants, $\varepsilon_0$ and $\mu_0$ can be computed and from their values the speed of light can be determined.

Accessory Apparatus. The following accessories, or the equivalent, will be needed:

Cat. No. 2606V Variable Power Supply (to provide about 200 volts D.C.)
Cat. No. 3035E D.C. Voltmeter, 15/30/300
Cat. No. 4186 Fractional Weights
Cat. No. 2738 Reading Telescope with Scale
One megohm resistor.

Setting up the Apparatus. Remove the movable and fixed conductors from the Current Balance assembly. Examine the knife-edges and bearing surfaces and, if necessary, use fine emery cloth or a fine stone to put them in good condition. Thoroughly clean the capacitor plates with fine steel wool to avoid sticky operation when in use. Carefully determine and mark the center of the upper plate. Measure the dimensions of the plate and compute the area. Attach the two plates to the balance exactly as the conductors were attached, using the short rods with knurled setscrews to support the lower, or fixed, plate. The plates must be so attached that the horizontal supporting rods are on the outside surfaces of the plates and not between them.

With the upper and lower plates approximately aligned and with the knife-edges properly positioned on the bearing surfaces, adjust the couterpoise behind the mirror until the frame with upper plate oscillates freely and comes to rest with the upper plate a few millimeters above the lower one. Adjust the sensitivity by means of the counterpoise below the mirror until the period of oscillation is a convenient value.

Place the balance on a solid table in a draft-free location. Connect the high voltage D.C. terminals of the power supply to the terminals on the balance which connect to the plates. Connect the megohm resistor in one branch of this circuit to limit the current to prevent possible damage to the power supply in case the two plates accidentally touch. Connect the voltmeter to the terminals on the balance and leave it connected during the experimental procedure.

Precise aligning of the plates and making them parallel is accomplished in a manner similar to that used for aligning and adjusting the conductors, as described in the attached copy of instructions for the Current Balance.

The setup and use of the telescope and scale to determine the separation of the plates is also described in those instructions. For convenience the formula is repeated here. The separation of the plates $d$ is given by

$$d = \frac{Da}{2b} \qquad (5)$$

where $D$ is the difference in readings of the scale for the contact and equilibrium position of the plates, $a$ is the perpendicular distance from the line of the knife-edges to the center of the plates, and $b$ is the distance from mirror to scale.

Procedure.

1. Measure and record the values of $a$ and $b$ of equation (5).

2. Place sufficient weight (a small coin) anywhere on the upper plate to bring it into contact with the lower one. Record the reading of the scale.

3. Place a 50-mg weight on the upper plate at the exact center (which was determined and marked earlier) and record the scale reading.

4. Remove the 50-mg weight and let the plate come to rest. Turn on the power supply and gradually increase the voltage until the plate separation is reduced to the same value (determined by watching scale reading in telescope) as it was with 50 mg on the upper plate.

5. The electrostatic force of attraction between the plates is (50 mg) x g = $4.9 \times 10^{-4}$ newton.

6. From the scale readings obtained in steps 2 and 3 compute $d$ the separation of the plates.

7. Compute the electrostatic constant $\varepsilon_0$ using equation (2).

8. Make several trials using the same or slightly different masses. Compute the average value of $\varepsilon_0$ and compare with the accepted value. Discuss the possible reasons for a lack of agreement.

9. Use this value of $\varepsilon_0$ and the value of $\mu_0$ obtained from the data of the Current Balance experiment to compute the speed of light.

Value of Constants.

1. $\varepsilon_0 = \dfrac{1}{4\pi \times 8.98776 \times 10^9} \quad \dfrac{\text{coulomb}^2}{\text{newton m}^2}$ or $\dfrac{\text{farad}}{\text{meter}}$

2. $\mu_0 = 4\pi \times 10^{-7} \quad \dfrac{\text{weber}}{\text{amp meter}}$ or $\dfrac{\text{henry}}{\text{meter}}$

3. $c = 2.9979 \times 10^8$ m/sec

Instructions supplied with Welch apparatus are intended primarily as an aid to the teacher in preparing the apparatus for use and in becoming acquainted with its operation. The experimental procedure suggested is not necessarily the most appropriate for all students. It is assumed that each teacher will develop a procedure best suited to his students. Information regarding any applications of the apparatus which have proven especially interesting and instructive will be gratefully received by the Sargent-Welch Scientific Company.

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