Exp 04 The d'Arsonval Galvanometer

To be Read: Note 06

In this experiment you will study the meter movement of a d'Arsonval galvanometer as a harmonic oscillator. The experiment has four parts. In Part A you will find the internal resistance and deflection sensitivity of the meter movement. In Part B you will investigate the steady state and transient responses of the meter movement. In Part C you will study how altering the resistance of the external circuit connected to the galvanometer affects the dynamic response of the meter movement. In Part D you will study the ballistic property of the galvanometer, that is, its response to a current impulse of duration short compared to the natural period of the meter movement. You will use the ballistic response of the galvanometer in two practical applications of your choosing.

Getting Started

In this experiment you will need the following apparatus:

- 1 galvanometer Walden Precision Apparatus WPA K120 series (K121, K122 or K123)
- 1 resistance box 1 kΩ maximum
- 1 resistance box 10 kΩ maximum
- 1 specially designed 3 MΩ resistance box
- 1 1.25V standard voltage source
- 1 plastic coil form (2-3 cm diam., 0.5 cm length)
- 3 metres enameled Cu wire 26 A.W.G.
- 1 stopwatch
- 1 specially designed capacitor box with single pole double throw switch (0.47μF or 0.5 μF)

You will also need access for a few minutes to a large magnet (either permanent or electromagnet).

In this experiment you will study the movement of the galvanometer as a mechanical torsional oscillator. It is therefore important for you to know the equation of motion of this oscillator. The theory below is expressly developed for the meter movement and is edited from the WPA manual. The basic mathematics is given in Note 06.

Preview of the d'Arsonval Galvanometer

You have already studied the DC characteristics of one example of a d'Arsonval meter movement in Experiment 01, "DC Circuits and Measurements". Currents required for full scale deflection (FSD) for that instrument were typically 50 μA. The galvanometer you will use in this experiment is much more sensitive, giving FSD for currents of the order of 1 μA. This kind of sensitivity makes the instrument useful in more demanding applications.

The meter movement of a d'Arsonval galvanometer is a rectangular coil of wire suspended in a horizontal radial magnetic field (Figure 4-1. The current to be measured flows through the coil via the suspension wire above and a light metal spiral below. When the coil rotates from its equilibrium position, the upper suspension exerts a restoring torque on the coil. The rotation is measured by means of an optical lever, which consists of a light source, a mirror attached to the coil, and a scale.

Rotation of the coil is induced by magnetic forces exerting a torque on the coil proportional to the current flowing through it. Under steady state conditions, the angular deflection of the coil and light spot is proportional to the DC current flowing in the instrument. The galvanometer is ingeniously made. For details on its construction see the appendix at the end of this note.

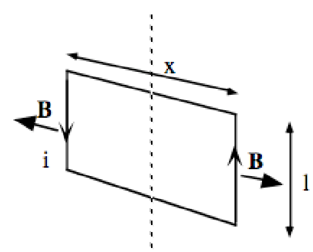

Figure 4-1. *Galvo coil in a radial magnetic field* ***B***.

Theory: Equation of Motion of the Galvanometer Coil

The coil (Figure 4-1) is a rectangular coil of N turns of wire with vertical sides of length l and horizontal sides of length x. The coil is immersed in a radial magnetic field **B** produced by an internal permanent magnet. This means that when a current i flows in the coil a torque τ_i is exerted on the coil given by [1]

$$\tau_i = NlxBi = NABi, \qquad \ldots[4\text{-}1]$$

[1] We use the symbol i here for current to avoid confusion with the symbol I that is reserved for the moment of inertia.

where A is the area of the coil. When the coil twists by an angle θ (radians) from equilibrium the suspension wire exerts a restoring torque on the coil given by the angular version of Hooke's law:

$$\tau_S = -k\theta, \qquad \ldots[4\text{-}2]$$

where k is the torsion constant of the elastic suspension. There is also a torque, proportional to the angular velocity of the coil, which is mainly due to air resistance when the coil is moving. This damping torque can be expressed as:

$$\tau_m = -\alpha\frac{d\theta}{dt}\ . \qquad \ldots[4\text{-}3]$$

If the coil has a moment of inertia I, then the coil's equation of motion is:

$$I\frac{d^2\theta}{dt^2} = NABi - k\theta - \alpha\frac{d\theta}{dt}\ . \qquad \ldots[4\text{-}4]$$

To eliminate i from eq[4-4] we must find a second equation linking the mechanical variable θ and the electric current i. The current i that flows is supplied by an external circuit, which can always be denoted by its Thevenin equivalent. Neglecting the normally tiny effects of the self inductance and capacitance of the coil, the equivalent circuit of the external circuit and coil can be indicated as shown in Figure 4-2. R_{eq} is the source resistance and R_I is the resistance of the coil.

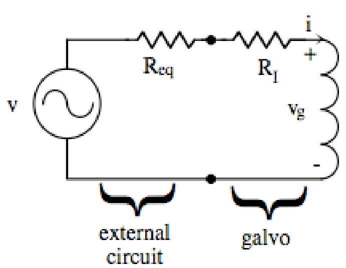

Figure 4-2. *Equivalent circuit of galvometer coil and external circuit.*

When the coil moves in a field **B** an emf v_g is induced in the coil given by

$$v_g = NAB\frac{d\theta}{dt}\ . \qquad \ldots[4\text{-}5]$$

(show this in your report). Writing $R_{eq} + R_I \equiv R$ the deflection θ is related to the current i by

$$v = Ri + v_g = Ri + NAB\frac{d\theta}{dt}\ . \qquad \ldots[4\text{-}6]$$

Substituting i from eq[4-6] into [4-4], eq[4-4] becomes

$$I\frac{d^2\theta}{dt^2} + \left(\alpha + \frac{(NAB)^2}{R}\right)\frac{d\theta}{dt} + k\theta = \frac{NABv}{R}. \qquad \ldots[4\text{-}7]$$

This is an equation in θ. It is somewhat more convenient to express it in terms of the scale deflection s, which for small deflections is related to θ by $s \approx 2L\theta$ (see note 3 in Part A below). The result is

$$I\frac{d^2s}{dt^2} + \left(\alpha + \frac{(NAB)^2}{R}\right)\frac{ds}{dt} + ks = \frac{2LNABv}{R} \qquad \ldots[4\text{-}8]$$

In what follows we shall solve this equation for a number of special conditions.

Static (Steady State) Response

When the galvanometer deflection is steady so that all the time derivatives in eq[4-8] are zero, $v = Ri$, and eq[4-8] has the solution

$$s = \frac{2LNAB}{k}\frac{v}{R} = \frac{2LNAB}{k}i. \qquad \ldots[4\text{-}9]$$

We define the *deflection sensitivity* of the galvanometer to be a constant K, where $s = Ki$. Substituting this definition into eq[4-9] we get an explicit expression for K:

$$K = \frac{2LNAB}{k}. \qquad \ldots[4\text{-}10]$$

Thus if K is known then the current i can be calculated from a measurement of s. This is arguably the most common use of the galvanometer.

Dynamic (Oscillatory) Response

For convenience we rewrite eq[4-8] in the standard form of a second order differential equation:

$$\frac{d^2s}{dt^2} + \eta\frac{ds}{dt} + \omega_0^2 s = \omega_0^2 K\frac{v}{R}, \qquad \ldots[4\text{-}11]$$

where $$\eta = \frac{\alpha + \dfrac{(NAB)^2}{R}}{I}, \qquad \text{...[4-12]}$$

and $$\omega_0^2 = \frac{k}{I}\,. \qquad \text{...[4-13]}$$

This is the well known equation of a damped harmonic oscillator. η is called the "damping constant" of the galvanometer coil, and ω_0 the natural frequency of free oscillations of the coil.

Suppose we start the coil moving, for example, with a step function or impulse, and then set $v = 0$ (or a constant—this would be equivalent to a shift of the origin for s). Eq[4-11] then reduces to the homogeneous equation:

$$\frac{d^2 s}{dt^2} + \eta\frac{ds}{dt} + \omega_0^2 s = 0. \qquad \text{...[4-14]}$$

Solutions of this equation take three different forms depending on the relative magnitudes of η and ω_0. We shall call these cases 1, 2 and 3.

Case1: Underdamping

If the damping is small, that is, if $\eta^2 < 4\omega_0^2$, then the solution of eq[4-14] is

$$s = s_0 e^{-\eta t/2}\sin(\omega t + \phi), \qquad \text{...[4-15]}$$

where s_0 and ϕ are determined by the initial conditions, and

$$\omega^2 = \omega_0^2 - \frac{\eta^2}{4}. \qquad \text{...[4-16]}$$

Eq[4-15] is plotted in Figure 4-3. This is the classical representation of the displacement of an underdamped harmonic oscillator as a function of time. You will be observing this kind of motion in Parts B and C.

When a working galvanometer is used in a practical non-ballistic application, underdamping is usually of only academic interest (as here). It is more important that the galvanometer be critically damped so that it takes up a new equilibrium position as quickly as possible to enable the deflection to be read.

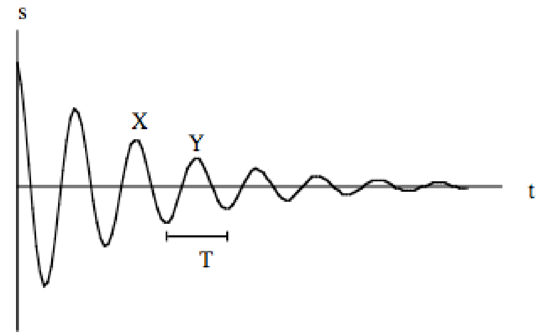

Figure 4-3. *Typical displacement or deflection of an underdamped oscillator as a function of time. X and Y mark successive maxima in the coil's displacement.*

Case 2: Critical Damping

In the case of a special amount of damping, that is, if $\eta^2 = 4\omega_0^2$, the solution of eq[4-14] is

$$s = (A + Bt)e^{-\eta t/2}, \qquad \text{...[4-17]}$$

where A and B are determined by initial conditions. This is the most desireable motion for a meter movement as we have stated, since the movement, once changed, takes a minimum time to come to a new steady state.

Finally, it is possible for the amount of damping to be greater than that necessary for critical damping. This leads to what is known as an overdamped condition.

Case 3: Overdamping

If the damping is large, that is, if $\eta^2 > 4\omega_0^2$, then the solution of eq[4-14] is:

$$s = A_1 e^{-\gamma_1 t} + A_2 e^{-\gamma_2 t}, \qquad \text{...[4-18]}$$

where $$\gamma_1 = \frac{\eta}{2} + \frac{1}{2}\sqrt{\eta^2 - 4\omega_0^2}$$

$$\text{...[4-19]}$$

and $$\gamma_2 = \frac{\eta}{2} - \frac{1}{2}\sqrt{\eta^2 - 4\omega_0^2}\,.$$

Note that one of the time constants (γ_1 here) is always larger than $\eta/2$, and the other is smaller. This case is seldom of practical interest in the context of galvanometers, and you will not be concerned with this kind of motion in this experiment.

Now that we have completed the theory of motion of the galvanometer meter movement we can move on to the first activity.

Part A
Measuring Internal Resistance and Deflection Sensitivity

Before you do anything read the caution and the notes following.

*** **CAUTION** ***

A d'Arsonval galvanometer is an extremely delicate instrument. It must be moved gently, always upright and level, and **ALWAYS** with the switch turned to "SHORT". (As you will see in part B, this gives the maximum damping to the movement). **NEVER** pass steady currents greater than about 1μA directly through the galvo coil; in particular, never connect a battery directly to the galvo terminals! If you damage an instrument through lack of attention to these precautions, you will be held responsible for the cost of repair or replacement (approximately $200).

NOTES:

1 The galvanometers have a switch with several positions, including "SHORT", "DIRECT" and "×1, ×10, etc.". The SHORT position is used for protection. Do all of your final measuring at the DIRECT position, where the terminals on the front of the instrument are connected directly to the galvanometer coil. All the other positions connect damping and current dividing resistors into the circuit. You can use these other positions to help "settle down" your galvo before you make a measurement, but make your final measurements on the DIRECT position.

2 Check the zero of the galvanometer before each measurement, and adjust it if necessary.

3 The galvanometer scale is graduated in millimeters. As a convenience, the position s of the light spot on the scale is taken to be proportional to the deflection angle θ, and is taken as a measure of θ. As you can see from Figure 4-4, $s = L\tan 2\theta \approx 2L\theta$ if $\theta \ll 1$ (radian), or if $s/L \ll 1$. The error is about 1% if $s = L/4$. From the value of L given on the case of your instrument, estimate at what scale reading you would expect significant departure from linearity. (You cannot measure L yourself, since to do so you would have to open up the case of the instrument and we cannot allow you to do that.)

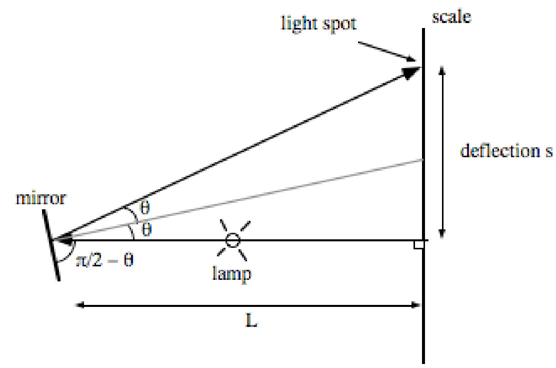

Figure 4-4. *Geometry of the moving mirror deflection system showing the meanings of L, s and θ.*

Measuring Internal Resistance

Measure the internal resistance of the galvanometer in a manner similar to that employed in Experiment 01, "DC Circuits and Measurements". As shown in Figure 4-5a, connect the 1.25V standard voltage source in *series* with the 3 MΩ resistance box and select a resistance value to give a reasonable deflection.

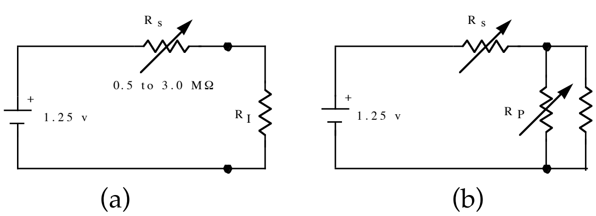

Figure 4-5. *Circuits used in measuring a deflection (a) and a half-deflection (b).*

Note the deflection θ and the resistance R_S. Now connect a 1000 Ω resistance box across the galvo terminals, as shown in Figure 4-5b and find the value of this parallel resistance R_p which reduces the deflection to "half" of the former value. "Half" is to be interpreted as half the *angular* deflection, so you must correct for the difference between 2θ and $\tan 2\theta$ as described in note 3 above. Having done this you can calculate the internal resistance R_I from the expression

$$R_I = \frac{R_p R_S}{R_S - R_p} \qquad \text{...[4-20]}$$

Measuring Deflection Sensitivity

Now remove R_p and measure the deflection θ for a series of values of R_S. Plot deflection θ versus current *i*. Is there evidence of non-linearity associated with the difference between 2θ and $tan2\theta$? If so, correct for it, and determine the deflection sensitivity (for small deflections) in mm/μA. Do this in a professional manner with a program like *pro Fit* as described in Experiment 01. Before proceeding, verify that your value is in reasonable agreement with the manufacturer's specification given in Table A-1 in the appendix to this guidesheet.

Part B
Dynamic Response
with No External Damping

In this part you will embark on the study of the galvanometer coil as a torsional oscillator. Connect the 1.25V standard voltage source in series with the 3 MΩ resistor box as shown in Figure 4-6 and set R_S to give a reasonable deflection. Open the series switch and verify that the subsequent motion is oscillatory. (Opening the series switch drops the driving current to zero in a step function with the initial condition shown in Figure 4-3.) Time the oscillations; repeat several times to estimate the statistical uncertainty of your measurement of the period. Calculate ω.

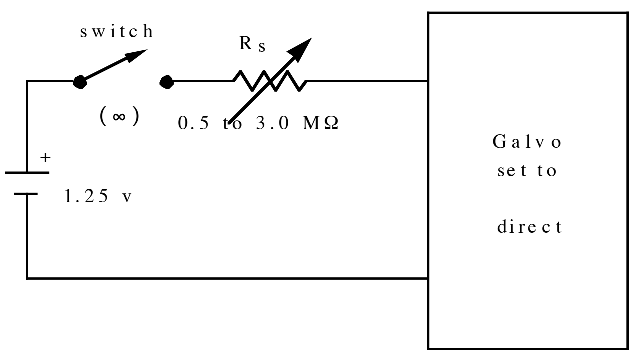

Figure 4-6. *Circuit to measure underdamped response (external damping is zero).*

If the damping is not too large (a reasonable criterion, corresponding to uncertainties of order 1%, is $\eta/2\omega_0 < 1/7$, i.e., 1/7 of critical damping), the deflection maxima can be considered to occur at the maxima of $\sin(\omega t+\phi)$, and from eq[4-15], the ratio of amplitudes at successive maxima (points X and Y on Figure 4-3) is

$$\frac{S_Y}{S_X} = e^{-\eta T/2} = e^{-\lambda}. \qquad \ldots[4\text{-}21]$$

The constant $\lambda = \eta T/2$ is called the *logarithmic decrement*. Record the amplitudes of as many successive oscillations as you can measure with reasonable accuracy. Repeat several times. Determine the amplitude ratio of all pairs of successive oscillations, and calculate the logarithmic decrement λ for free oscillations of the galvanometer.

In this part of the experiment, the external resistance *R* which enters in eq[4-12] is infinite. Hence, from eq[4-12], η is given by:

$$\eta = \eta_0 \equiv \frac{\alpha}{I}. \qquad \ldots[4\text{-}22]$$

We introduce the notation η_0 for this special value of η. Calculate ω_0 and η_0 for the galvanometer from your experimental results.

Part C
Dynamic Response
with External Damping

It should be evident from eq[4-12] that an external resistance *R* can provide additional damping of the oscillatory motion, because of the coupling between the electrical and mechanical systems. Connect a 10 kΩ resistance box across the galvanometer, and measure the logarithmic decrement in the same way as in Part B, for a number (about 6 or 8) resistance values (choose values approximately equally spaced in $1/R$). Start by determining the resistance required to give an amplitude ratio for successive oscillations of about 3; you would find it hard to study more heavily damped oscillations by eye. Determine the damping constant η and period *T* self-consistently from eq[4-16] and [4-21]; note that it is more accurate to use eq[4-16] than to measure ω in a heavily damped situation.

To calculate η self-consistently, calculate the first estimate $\eta_0 = 2\lambda/T_0$ where $T_0 = 2\pi/\omega_0$. Then use this first estimate η_0 to find a corrected ω_1 using $\omega_1^2 = \omega_0^2 - (\eta_0/2)^2$. From ω_1 calculate a corrected T_1 $(=2\pi/\omega_1)$, calculate a new estimate of η ($\eta_1 = 2\lambda/T_1$) and repeat the iteration until the desired precision is achieved. One or two iterations should suffice.

Plot η vs. $1/R$; don't forget to include the point η_0 at $1/R = 0$. According to eq[4-12], your plot should be linear. Fit a straight line by least squares (using *pro*

Fit). From the slope you can determine $(NAB)^2/I$. Since you know $\omega_0^2 = k/I$ (eq[4-13]), $K = 2L(NAB)/k$ (eq[4-10]) and L (given on the instrument), you can calculate the spring constant k, the moment of inertia I, and the product NAB for your galvanometer. Extrapolate your plot to estimate the critical damping resistance R_0, i.e., the external resistance for which $\eta = 2\omega_0$.

No doubt you have noticed that an undamped galvanometer is awkward to use for measurement, since it overshoots and takes a long time to settle. Critical damping gives the fastest settling (recall that in overdamped motion one exponential is always slower than the critical exponential). Hence the critical damping resistance is normally connected across the galvanometer coil. Since R_0 is typically 10 or more times larger than the coil resistance R_I, the overall sensitivity is reduced only by 10% or less. Such a resistance is, in fact, connected when you turn the selector switch to " ×1, ×10, etc.".

Part D
The Galvanometer as a Ballistic Instrument

In this part of the experiment you will use the galvanometer as a *ballistic* instrument, that is, as an instrument that responds to an impulse (short burst) of charge. It is in this kind of application that the galvanometer is superior to digital instruments. You are expected to complete two of the three activities below.

1 Measuring a Charge Pulse

Suppose we pass an impulse of current through the galvanometer coil over an elapsed time much less than the natural period of the coil's motion $T_0 = 2\pi/\omega_0$. The coil will start to move. If the galvanometer coil starts from rest and is fairly well underdamped, (again $\eta < \eta_c/7$ is the criterion for 1% accuracy) then the subsequent motion will be a damped sinusoid:

$$s = s_0 e^{-\eta t/2}\sin(\omega t). \qquad \text{...[4-23]}$$

The initial velocity resulting from the impulsive torque produced by the impulsive current will be:

$$\left.\frac{ds}{dt}\right]_{t\,=\,0+} = \omega_0^2 KQ, \qquad \text{...[4-24]}$$

where $$Q = \int i\,dt,$$

is the total charge which flows through the galvanometer coil. (Prove this for yourself, and include the proof in your report). From eq[4-23]

$$\left.\frac{ds}{dt}\right]_{t\,=\,0+} = \omega_0 s_0 = \omega_0^2 KQ. \qquad \text{...[4-24]}$$

Therefore $$s_0 = \omega_0 KQ. \qquad \text{...[4-25]}$$

You can use the approximation $\omega \approx \omega_0$ which is valid for low damping. The first maximum of oscillation is reached at $t \approx T/4$ and the peak deflection is

$$s_{\max} = \omega_0 KQ e^{-(\eta/2)(T/4)} = \omega_0 KQ e^{-\lambda/4}. \qquad \text{...[4-26]}$$

So, by (quickly) measuring the peak deflection $s_{\max}$, and knowing the numerical values of ω_0, K and λ, you can calculate the total charge flowing in the current pulse through the galvanometer. The ballistic galvanometer enables you to measure charge in a way that is not possible with a conventional digital multimeter.

2 Measuring Charge on a Capacitor

To measure the charge on a capacitor, connect a 1.25V standard voltage source to the capacitor box which contains an SPDT switch, 1 MΩ resistor, and 0.5 μF capacitor as shown in Figure 4-7. Charge the capacitor by switching to the battery side for a few seconds. With the galvanometer coil initially at rest at zero, discharge the capacitor through the galvanometer. Quickly record the amplitudes of successive maxima, determine λ, and calculate the charge Q which passed through the coil. How does Q compare with the product CV?

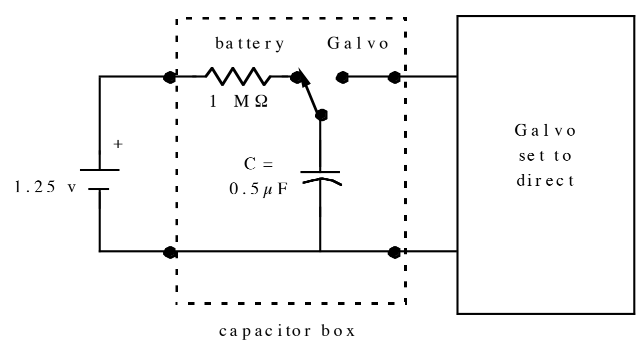

Figure 4-7. *Circuit to measure the charge on a capacitor.*

Verify, by switching out the capacitor after it has discharged, that its presence has a negligible effect on the motion of the galvanometer.

3 Measuring the Field of a Magnet

To use the galvanometer to measure the magnetic field of a magnet you need a search coil. To make one wind 10 turns of 26 AWG enamelled Cu wire onto the coil form provided. Leave about 1/2 meter extra wire at each end. Tape the coil so it won't unravel, cut the ends to equal length, and twist them uniformly. (Ask your demonstrator to help you do this with an electric drill.) Bare the metal at the free ends.

Connect this coil in series with a resistance $R_s > 7R_0$ to the galvanometer as shown in Figure 4-8. Note that in this case a series resistor must be provided; otherwise the total resistance would be effectively the galvo coil resistance and the galvo would be heavily overdamped. Move the coil swiftly by hand into (or out of) a magnetic field; for accurate measurements, hold the axis of the coil in your fingers parallel to the direction of the field.

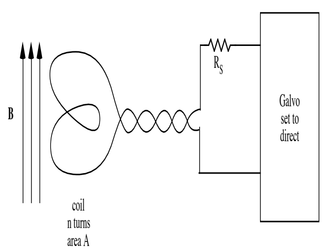

Figure 4-8. *Measuring the field of a magnet with a search coil.*

The emf generated in a coil of n turns of area A by a changing magnetic field is given by Faraday and Lenz's laws:

$$v = -n\frac{d\Phi}{dt} = -nA\frac{dB}{dt}. \qquad \ldots[4\text{-}27]$$

If the coil is moved from a region of field B to one of zero field, then

$$\int v dt = -nA\int\frac{dB}{dt}dt = nAB. \qquad \ldots[4\text{-}28]$$

But this emf produces an impulsive current i in the coil and galvanometer given by

$$i = \frac{v}{R}, \qquad \ldots[4\text{-}29]$$

where R is the total series resistance $R_s + R_I$. Hence the impulsive charge which flows is

$$Q = \int i dt = \frac{\int v dt}{R} = \frac{nAB}{R}. \qquad \ldots[4\text{-}30]$$

Note the response of the galvo. If it goes off scale, then increase R_s. From the amplitudes of successive oscillations, calculate the decrement λ and then calculate the charge Q which flowed through the coil. Measure the diameter of the search coil, calculate the area A, and finally calculate the strength of the magnetic field B from your measured Q.

CHALLENGE: Do an internet search for a similar experiment done at another university, and from which this experiment might be improved upon.

Tidying Up

Before leaving your station in the lab, turn off all the powered equipment. Put away all connecting wires so your work station looks the same as when you found it. Thank you.

Appendix
The Walden Precision Apparatus
WPA K120 Series Galvanometer

The following description is extracted and modified from the WPA manual.

Optics

The sensitivity of a galvanometer can be improved in two ways: either by decreasing the strength of the suspension or increasing the scale-to-movement distance. The optical system of the K120 series galvanometer (Figure A-1) is double reflecting, a return mirror gives an effective pointer length of almost twice that of the instrument case.

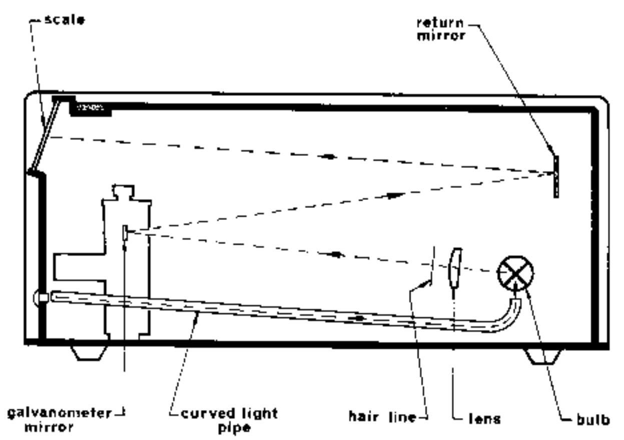

Figure A-1. *Optical arrangement of the K120 series galvanometer. For more details of the suspension positioned in the lower left of the instrument case see Figure A-2.*

The light Source is a Krypton-filled low Volt, 1 Amp bulb—produced according to Ministry Specification. A spare bulb is fitted in the case and a further supply can be obtained on request. Instructions for changing the bulb are printed on the inside of the lid. The lamp indicator shows the bulb to be alight and is a highly refractive plastic light pipe which carries the light through a 90° bend to the front panel. Illumination of the light spot is outstandingly high, giving a comfortable view even in a sunlit laboratory.

The galvanometer mirror is spherical of 11 cm focal length.

Mains feed is to a built-in double wound transformer with tapped primary 115, 200 and 240 Volts, AC., 50-60 cps.

Movement

The delicate parts of the movement are protected by a metal outer case, the sectional drawing in Figure A-2 illustrates the arrangement.

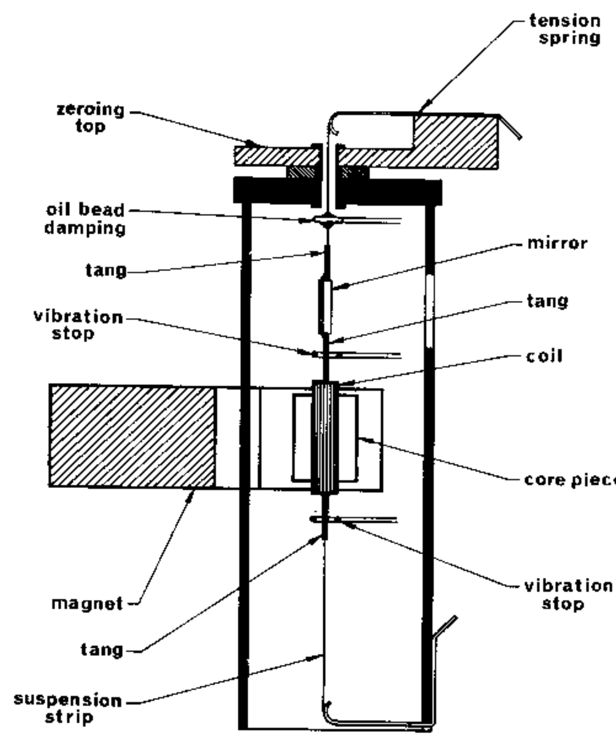

Figure A-2. *The galvanometer suspension.*

Coil. The coil is wound with non-magnetic or spectrographically pure copper wire, where the ferrous impurities are controlled down to two parts per million, and the basic material is more precious than gold. The coil is bonded in epoxy resin for maximum strength and stability.

Tangs. Tangs are carefully proportioned to ensure a firm grip on the coil. The material is as critical as the coil wire.

Suspension. The suspension is made from non-corroding noble metal alloy supplied to our specification and rolled to a strip by a specially designed mill. The breaking strength of this alloy is 73 tons per sq. inch, so that a wire as thick as an average human hair will safely hold half-a-pound.

Pre-Twist of suspension. A plainly rolled and anchored suspension strip causes perceptible hysteresis and thus "zero" error. The WPA pre-twisted suspension is unique and provides outstanding zero stability.

Anti-Vibration stops. Anti-Vibration stops limit the sideways movement of the coil. With the well designed vibration stops a K120-type galvanometer can be dropped from 1 ft., on to a wooden bench, or in the delivery packing 14 drops from 4 ft. on to concrete, without ill effects.

Oil-Bead Damping. Oil-bead damping smooths out any unwanted vibration of the coil so that our galvanometers can even be used under slightly vibrating conditions.

Slow motion zero setting. Several turns of the zero knob move the light spot from one end of the scale to the other. The hair line can, of course, be set to any point of the scale.

Circuit

The sensitivity is controlled by a 2-pole 6-way switch with silver contacts. The resistors are of 1% accuracy.

The switch positions are:

Shorted position. The input circuit is broken and the movement is shorted for its protection in transit.

×1 position. The galvanometer movement is shunted by an internal damping resistor as shown in Figure A-3. This setting provides the maximum sensitivity with near critical damping.

×.03 and ×.001 positions. The current sensitivity is reduced by an Ayrton-Mather shunt by .03 and .001 with respect to the ×1 range. In addition, series resistors are introduced to keep the same input resistance as on the ×1 range. Figure A-4 shows the circuits.

Series position. To be used if the exterior circuit resistance is so low that the light spot would creep. At this switch settting a series resistance is introduced to improve the speed of response.

Direct position. The movement is connected straight to the terminals without any shunts, giving the highest sensitivity with no interior damping.

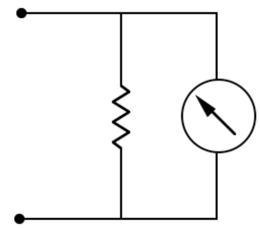

Figure A-3. *Circuit for x1 position.*

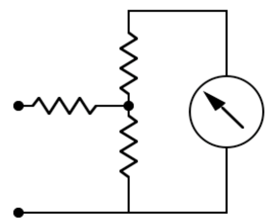

Figure A-4. *Circuit for x.03 and .001 positions.*

As can be seen in Table A-1, WPA K120-type galvanometers differ as to sensitivity, internal resistance and critical damping resistance.

Table A-1. *Manufacturer's Data on WPA K120-type Galvanometers. The value of L is given on the case of the instrument.*

Type	Sensitivity (mm/μA)	Internal Resistance R_I (Ω)	Critical Damping Resistance (Ω)	Period (s)
K121	25	12	30	2
K122	60	25	300	2
K123	120	52	1000	2