13th Asian Physics Olympiad
New Delhi, India
Experimental Competition
Wednesday, 2nd May 2012

Please first read the following instructions carefully:

1. The time available is 2½ hours for each of the two experimental questions.
2. Use only the pen and equipment provided.
3. In the boxes at the top of each sheet of paper write down your **student code**.
4. There is a set of answersheets in which you have to enter your data and results. In addition blank sheets are provided which you can use.
5. Use only pencil to draw graphs on the graph sheets.
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8. Numerical results must be written with as many digits as appropriate; don't forget the units.
9. You should use mainly equations, numbers, symbols, graphs, figures and as little text as possible in your answers.
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    c. Used writing sheets
    d. The sheets which are marked with '**X**'
    e. Unused writing sheets and graph sheets
    f. The printed question paper
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12. **You are not allowed to take any sheet of paper or any material used in the experiment out of the room.**

FRICTION

If a cord is passed around a post or a beam and the tensions in the two segments are different, friction between the cord and the beam plays a role in controlling the motion of the cord (Fig.1). It is observed that to hold a body suspended at one end of the cord, the minimum force needed at other end of the cord is less than the weight of the body due to the presence of frictional forces. With the increase in the number of turns around the beam the decrease in force is spectacular. Sailors are known to use this idea for arresting the motion of ships by winding ropes tied to ships around posts at the docks.

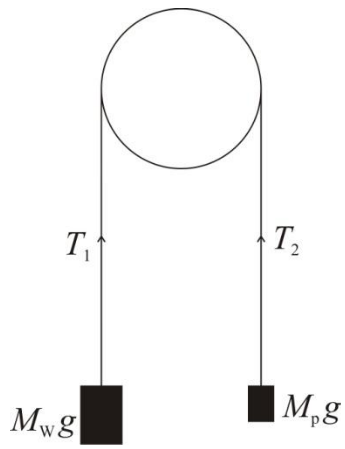

Fig.1

Objective:

To explore the relationship among the three quantities: the load W ($=M_w\,g$), the minimum effort P ($= M_p\,g$) needed to keep the system in equilibrium and the angle θ, subtended by the segment of the cord in contact with one or more beams, by systematically varying these quantities and to express it in the form of an equation.

Apparatus:

Sr. No.	Item	Quantity
1	An apparatus consisting of four pieces of steel pipe on four sides of an identical vertical piece at the centre, all fixed on a wooden platform	1
2	An acrylic sheet (with lines 1.5 mm apart) mounted in front of one of the horizontal pipes	1
3	A plastic pan (including supporting rods) with its mass (M_{pan}) written on its side	1
4	A magnifying glass with torch	1
5	White cord with blue markings (Dial cord)	2 pieces
6	Pink cord	1 piece
7	A weight box containing following weights	
	500.0 g	1
	200.0 g	2
	100.0 g	1
	50.0 g	1
	20.0 g	2
	10.0 g	1
	5.0 g	1
	2.0 g	2
	1.0 g	1
8	A body of unknown mass, M_u	1
9	A hanger of slotted weights with hook (each weight 100.0 g and total weight 800.0 g)	1
10	A piece of cleaning cloth	1

The blue switch can be moved to switch the torch ON/OFF. The acrylic plate with lines ruled on it is provided to detect the motion of the cord. The lines on the acrylic plate can be taken as reference against which the motion of the cord can be observed.

		
Fig.2(a) Steel pipes mounted on wooden platform	Fig.2(b) Set of weights	Fig.2(c) Plastic pan
		
Fig.2(d) Dial cord	Fig.2(e) Pink cord	Fig.2(f) Magnifying glass with torch
		
Fig.2(g) Body of unknown Mass, M_u	Fig.2(h) Slotted weights with hook	Fig.2(i) Complete set-up

Experimental Procedure:

Caution: Do not touch the surface of the pipes with which the cord would be in contact. Any greasy material can change the frictional properties of the surface (surface of the pipes as well as the cord). A cleaning cloth is provided if required.

Part 1:

(Note: Use the dial cord in this part.)

Use the hanger with slotted weights as load M_w. Attach the load at one end of the given piece of dial cord (whose mass is negligible) and a pan (with known mass) at the other. A weight box with weights is also provided. The angle θ subtended by the cord can be changed by passing it over/around two or more of the given pipes. (Refer Fig.3).

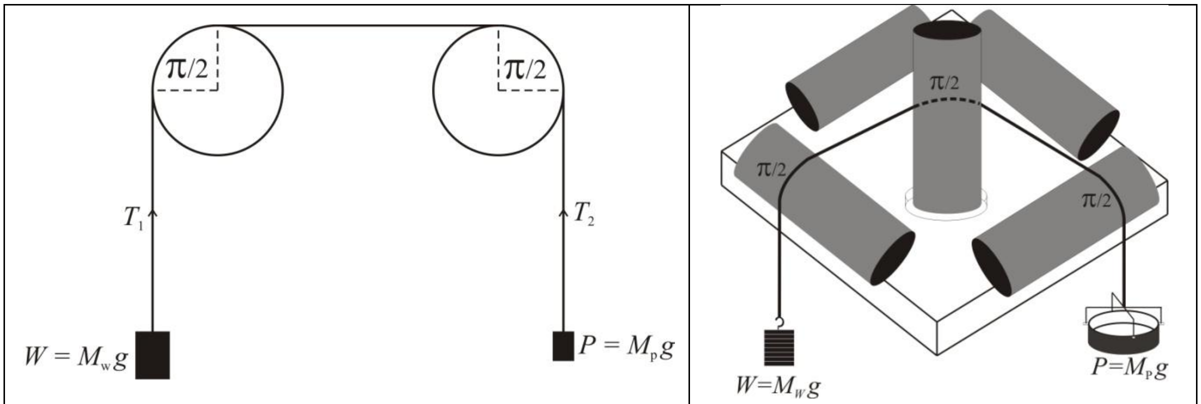

Fig.3 Schematic arrangements of the assembly for angles π and 3π/2 respectively

The minimum value of angle θ is obtained when the cord passes over two parallel rods without making any contact with the central post (Fig.3). By winding the cord around the vertical post and shifting the position of the effort the angle θ can be changed by steps of $\pi/2$. The load M_w should be suspended from the pipe to which the ruled acrylic plate is mounted.

For increasing the angle θ the cord is to be turned around the central vertical post. To observe whether the cord suspending the load is slipping over the pipe, the transparent acrylic plate is provided. You can use the magnifying glass with torch to view whether the cord is slipping over the pipe. Ideally one should note the effort M_p when the load M_w is on the verge of moving down (overcoming static friction). But that is not possible. However, it is possible to determine the interval $[M_{p-}, M_{p+}]$ within which this value lies. Since this interval is a measure of the uncertainty in the magnitude of M_p, it should be made as small as possible.

For $\theta = \pi$, take observations over as wide range as possible with the weights provided. Make estimate of the uncertainties in the observations. Plot the necessary graphs and combine the results from the graphs to get the desired equation. On the basis of the analysis of your data write down the quantitative relation giving value of P in terms of W and θ. The value of P is also dependent on friction between the cord and the pipe. Identify the term in your equation which accounts for friction and equate it to the coefficient of friction μ for the given system. Estimate the expanded uncertainty in its value.

Part 2:

(Note: Use the pink cord in this part.)

A body of unknown mass M_u and a pink cord is provided. Suspend the unknown mass from one end of the cord and the pan from the other end. Write down the relevant equations to determine M_u and μ_u. With $\theta = \pi$, take necessary observations to determine its mass and the coefficient of friction between the pink cord and the pipes using the relationship obtained in the experiment. Estimate the expanded uncertainty in your results.

Note on uncertainty evaluation

1) If it is observed that the magnitude X of a quantity to be measured lies somewhere in an interval $[X_1, X_2]$, and there is equal probability that it can have any value in this interval, then the probability distribution is said to be uniform or rectangular. The standard uncertainty for such distribution is given by $\frac{|X_1 - X_2|}{2\sqrt{3}}$.
2) After evaluating the combined standard uncertainty in a measured quantity, the result is stated with an expanded uncertainty. If the expanded uncertainty is taken equal to twice the combined standard uncertainty, the confidence level is approximately 95 %. The number giving expanded uncertainty is rounded upwards to retain a single digit (generally) and the number giving the magnitude of the measured quantity is rounded to keep appropriate number of digits such that the last digit has the same decimal place as that of the expanded uncertainty.

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ELECTROMAGNETIC INDUCTION

The modern technique of eddy current testing employed for detecting defects under the surfaces of metallic objects is based on the principles of electromagnetic induction. The circulating currents induced in conducting bodies due to changing magnetic flux in the region where they are located are called eddy currents. The defects are detected by observing the changes in the resistance and inductance of a coil carrying alternating current when held near the surface of the object.

Unless the core of the solenoid has some ferromagnetic material the magnetic flux ϕ is proportional to the current i .The constant of proportionality is called self inductance of the coil and is represented by letter L. The self-induced emf in a coil with inductance L is, therefore, given by - $L\frac{di}{dt}$.

In a coupled system of circuits with current i_1 in one circuit the magnetic flux linked with it is given by

$$\phi = L_1 i_1 + M_{21} i_2$$

Where L_1 is the self inductance of that circuit and M_{21} is the mutual inductance of the coupled system.

Similar equation holds for the reverse, with $M_{12}=M_{21}$

L-R Circuit

A sinusoidal alternating current with angular frequency ω flowing through a series combination of resistance R and inductance L produces a voltage drop across the combination.

If we represent current by $i = I_0 \sin \omega t$, the voltage drop across the resistance is equal to $I_0 R \sin \omega t$ and that across the inductance it is $I_0 \omega L \cos \omega t$. We can combine these to get the voltage across the R-L combination. The quantity ωL is called inductive reactance and is represented by symbol X. One can readily show that the voltage across the coil is equal to $I_0 Z \sin(\omega t+\theta)$, where

$$Z = \sqrt{R^2 + X^2} \qquad (1)$$

and

$$\theta = \tan^{-1}\left(\frac{X}{R}\right) \qquad (2)$$

Alternating voltage as well as current vary continuously in both magnitude and polarity during the course of time but the rms values of these quantities calculated over a cycle are independent of time and the relation $V = IZ$ where both V and I represent the rms values, is analogous to Ohm's law. From this we see that

$$V^2 = (IR)^2 + (IX)^2 \qquad (3)$$

(Note:- The concept of resistance is basically related to dissipation of electrical energy and the value of resistance of a coil in ac circuit can be different from its value determined by applying Ohm's law with dc currents.)

When there are additional resistances and/or inductances in series with the coil, we can still consider the voltage drop across the combination as equal to the square root of the sum of the squares of voltage drops across the total resistance and across the total inductance.

Measurement of Inductance and Resistance of a Coil

For measuring alternating current and voltage, generally the rms values are noted. From Equations (2) & (3) we get

$$V\cos\theta = IR \qquad (4)$$

and

$$V\sin\theta = IX \qquad (5)$$

To obtain the values of R and L of the coil we can use the above equations. Voltage V and current I can be measured. But there being three unknown quantities θ, R and X we need one more equation.

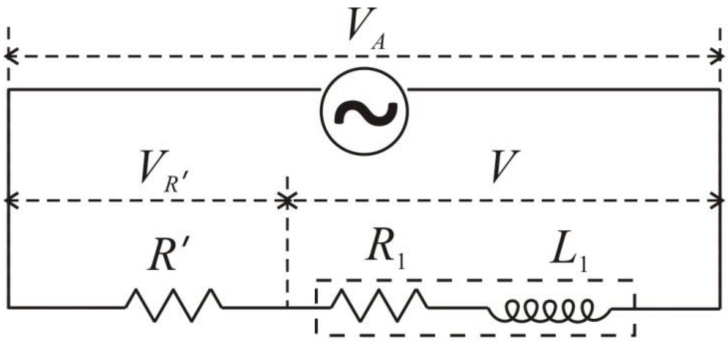

Fig.1

If the applied voltage across the series combination consisting of a known resistor R' with the coil is V_A, then an expression relating applied voltage V_A to the voltage drops $V_{R'}$ across R', V across the coil and the angle θ is

$$V_A^2 = V_{R'}^2 + V^2 + 2V_{R'}V\cos\theta \qquad (6)$$

All quantities except θ in Equation (6) are measurable.

Hence measuring the three voltages V_A, V_{R}' and V, and using Equations (4), (5) and (6), θ, R and X can be determined. Knowing the frequency of the alternating current the value of L can be calculated.

Alternatively, from Equations (4) and (6) we can express the value of R in terms of the three measured voltages as

$$R = \left(\frac{R'}{2}\right)\left[\frac{V_A^2 - V^2}{V_{R'}^2} - 1\right] \tag{7}$$

The impedance Z of the coil can be calculated using the formula $Z = \frac{V}{V_{R'}}R'$ and the value of X could be obtained from

$$X = \sqrt{Z^2 - R^2} \tag{1A}$$

Coupled Circuits

The energy supplied by the power source to the primary can be dissipated partially in the primary and the remainder in other mutually coupled secondaries. When no mechanical work is done, the energy dissipation is only in resistances. The inductances store energy in the magnetic field associated with them. With current I (rms value) the average stored energy in inductance L is equal to $\frac{1}{2}LI^2$.

When a current flows in the secondary the emf induced due to it in the primary brings about change in the primary current. Seen from the primary side the effect is a consequence of change in the effective resistance and reactance of the primary coil and there is no need to know the parameters in the secondary circuit. The total energy dissipated in primary as well as secondary circuits appears as if it is dissipated in the effective primary resistance when seen from the primary side.

The effective values of resistance R_{PE} and inductance L_{PE} of primary can be related to a 'reflected' resistance R_R and a 'reflected' inductance L_R from the secondary side. The (average) power dissipated in the reflected resistance R_R in the primary has to be equal to that in resistance R_S in the secondary circuit. This gives

$$I_P^2 R_R = I_S^2 (R_S + R_L) \tag{8}$$

Similarly, we can relate the reflected inductance L_R to the secondary inductance L_S from

$$\frac{1}{2}L_R I_P^2 = \frac{1}{2}L_S I_S^2 \tag{9}$$

Considering the fact that the induced emf in the secondary due to an alternating primary current I_P has magnitude equal to $\omega M I_P$ we can write the equation corresponding to Kirchhoff's loop rule for the secondary in terms of rms values of primary and secondary currents as

$$\omega M I_P = I_S Z_S \tag{10}$$

where Z_S is the impedance of the secondary circuit. When the secondary impedance is infinite the mutually induced emf appears as the voltage across the open ends of the secondary.

APPARATUS:

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<tr>
<td>Resistance Board</td>
<td>Connecting Wires</td>
<td>Digital Multimeter</td>
<td>Coils wound one over the other</td>
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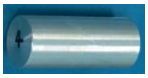
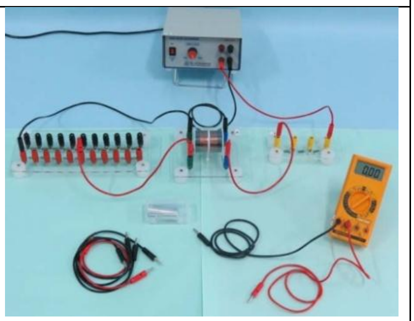
<td></td>
<td></td>
</tr>
<tr>
<td>Sine wave Generator</td>
<td>Resistance Board</td>
<td>Aluminium Rod</td>
<td>Complete experimental set up</td>
</tr>
</table>

The apparatus provided for the experiment consists of the following.

1. A sine wave generator with output of about 10 V (rms) at 1000 Hz frequency
2. A digital multimeter (DMM) to be used as a voltmeter
3. A pair of coaxial coils wound one around the other on a cylindrical hollow piece of non magnetic non conducting bobbin
4. A piece of aluminum rod capable of fitting inside the bobbin
5. Two series of ten resistors mounted on an acrylic board: one consisting of 100 ohms resistors and the other of 10 ohm resistors with banana pin sockets
6. The required resistance for load R_L or sampling resistance R' can be selected using this resistance board and connecting wire pieces. A separate acrylic board with

resistance of 300 ohms is provided which can be used for sampling resistor when the other board is used for load resistance.

7. A set of five red and five black wires with banana pins at their ends (the pair of longer red and black wires is meant for use as DMM probes).

The output of the sine wave generator of frequency 1000 Hz is to be used as the alternating source voltage. Use the 20 V range of the DMM to measure rms ac voltages.

The magnitudes of currents I_P and I_S when needed are to be calculated from the measured voltages across known values of R' in primary and R_L in secondary respectively.

EXPERIMENT

PART 1: Determining Resistance and Inductance of a Coil with Air-core and Aluminium Core [3.4]

Connect coil 1 (with blue terminals) in series with a resistor R' (to be selected from the resistance board) across the output terminals of the sine wave generator. The sine wave generator will be on before you start your experiment for stabilization of its output. Do not turn it off. Keep the output voltage amplitude maximum. (The DMM should show the output about 10 V).

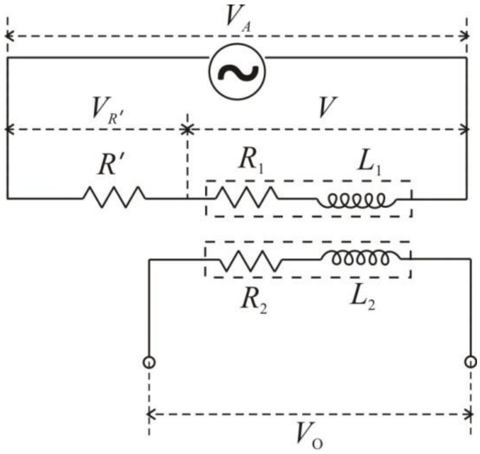


Fig.2

The ac output of the generator may have some asymmetry. In that case, the readings of the DMM will show slightly different readings, when the input polarities of the DMM are interchanged between 'V/Ω' to 'com'. To correct for the error due to asymmetry repeat each reading by interchanging the polarity of the probes of the DMM and take the mean of the two readings.

Choose the value of R´ to obtain $V_{R'}$ and V approximately equal so that the systematic error in Z becomes negligible.

a) Measure the voltages V_A, $V_{R'}$ and V as well as V_O across the terminals of the other coil. Determine the resistance R_1 and inductance L_1 of coil 1 (with blue terminals) and estimate the uncertainties in the values determined. (0.9)

b) Connect the other coil (coil 2 with green terminals), make the necessary measurements and determine R_2 and L_2. Evaluate the uncertainties in the values obtained. (0.9)

c) Now insert the piece of aluminium rod at the core of the coils and repeat the procedure to obtain the values of inductances L_1* and resistance R_1* and the uncertainties in them for coil1. (0.8)

d) Make necessary measurements and determine inductance L_2* and resistances, R_2* of coil 2 when it has an aluminium core. Estimate the uncertainties in the values. (0.8)

Note: Uncertainty calculations need not be done for parts 2, 3 and 4.

PART 2: Mutual Inductance and Coupling Constant **[3.0]**

f) Mutual inductance M can be obtained from the readings of $V_{R'}$ and V_O (recorded in **Part 1).** Find the average values for air core as well as aluminium core coils. The relation between the mutual inductance and the self inductances of the coupled coils is given by $M = k\,(L_1L_2)^{1/2}$. Determine the value of k, the coupling coefficient in the two cases. (0.4)

g) Select coil 1 (with blue terminals) as primary and coil 2 (with green terminals) as secondary. Connect the primary in series with the sampling resistor $R' = 300$ ohm across the output terminals of the generator. Connect across the secondary the variable load R_L. The output voltage V_O is to be measured across R_L. Change R_L and measure the voltages V_A, $V_{R'}$, V and V_O corresponding to each value of R_L. (0.8)

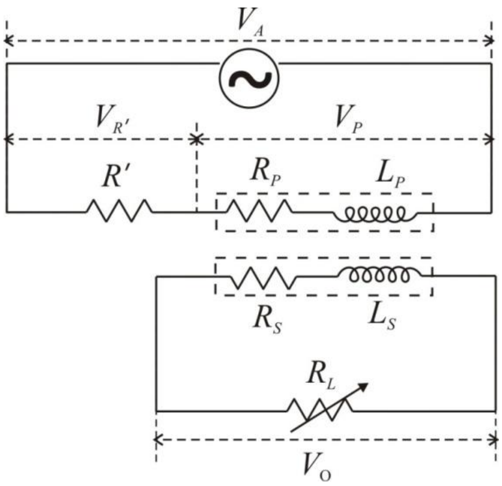


Fig.3

h) A linear graph can be plotted combining various terms appearing in Equation (10) written in expanded form. Write the linear expression for plotting a graph whose slope can be used to obtain the value of M and intercept to obtain the value of secondary reactance X_S. (0.2)

i) Calculate the necessary quantities using data from (**g**) to plot the graph corresponding to the expression obtained in the step (**h**) above. (0.9)

j) Plot the graph and obtain the values of M and X_S. (0.7)

PART 3: Relations between Effective Primary Impedance and the Reflected Quantities from Secondary [2.4]

k) Use the data collected in Part 2 to determine the effective resistance R_{PE} and the effective reactance X_{PE} of the primary corresponding to each value of R_L in secondary. (0.6)

l) Use the data of **Part 2** to calculate the values of reflected resistance R_R as defined in Equation (8) and of reflected reactance X_R referring Equation (9) corresponding to the values of R_L. (0.6)

m) Plot graph of X_{PE} against X_R. Taking into consideration the likely uncertainties of the quantities plotted write down the equation giving the relationship between the effective primary reactance and the reflected reactance. (0.6)

n) Represent graphically the relation between R_R and R_L over the range of study and find the value of R_L for which the reflected resistance attains a maximum. *If needed, take some more observations to supplement the observations in Part 2 for locating the point with greater precision.* (0.6)

PART 4: Eddy Current Effects [1.2]

o) A model based on the analysis of the data in **Part 3** suggests how to estimate the ratio of inductance and resistance seen by the eddy currents set up in the core of a coil connected to a power source.

The analysis of the data of **Part 2(i) and (j)** should show that $R_{PE} = R_P + R_R$. The relation between X_{PE} and X_R is obtained from **Part 3(m)**.

Refer to the data collected in **Part 1(c)** and estimate the ratio of inductance and resistance as seen by eddy currents in the aluminium core when the power supply is connected to coil 1 and coil 2 respectively. (0.8)

p) Connect the coils as in **Part 2 Fig.3** and insert the piece of aluminium rod at the core of the coils. Write down the expression giving the power loss ΔP in the aluminium core.

Set R' = 300 ohms and R_L = 1000 ohms. Adjust the magnitude of V_A equal to 9.0 V. Make the necessary measurements and calculate the power dissipation due to the eddy currents in the aluminium core. (0.4)