Preface to second edition

In this edition the changing emphases of modern Advanced level syllabuses have been met by the deletion of many experiments that used to feature strongly in pre-university practical physics courses and their replacement by others which more accurately reflect current syllabus requirements. The traditional Light and Sound sections have been regrouped into a considerably reduced Geometrical Optics section and an expanded Waves section which includes transverse and longitudinal waves on springs as well as 3 cm radio waves. Other additions include mechanical resonance, behaviour of a wire under gradually increasing tension, current balance, charge and discharge of a capacitor, a.c. search coil, Hall effect and use of Hall probe, fine beam tube method for e/m_e, back scattering of beta particles and inverse square law for gamma radiation.

Preface to first edition

Recent welcome changes in practical physics taught in the pre-University stage have been of two kinds:

(1) the incorporation of new experiments with modern apparatus,
and (2) the adoption of the SI system of units.

As a result pupils now need a less intricate practical acquaintance with such instruments of measurement as the tangent galvanometer and the vibration magnetometer and less experience of measuring the specific heat capacities and expansivities of solids and liquids. Instead they now need and expect to be introduced to working with alternating current, transistors and radioactivity through the aid of modern tools of measurement such as the cathode ray oscilloscope, the signal generator and the Geiger 'counter'.

Accordingly the new publishers decided that my two previous books—*Sixth Form Practical Physics* and *Modern Advanced Level Practical Physics*—should be combined in a single volume and brought up to date not only by the adoption of the SI system of units throughout, but also by the incorporation of many new experiments along with the retention of most of those that had proved valuable in more traditional practical physics. It is hoped that a correct balance has been struck between what is old and tried and what is new and exciting. If so, one of the two main aims of the book will have been accomplished.

The other aim has been to enable a number of students to begin different experiments without wasting time at the beginning of a session of practical work asking for apparatus and preliminary instructions in the carrying out of an experiment. It is hoped that this saving of time, both students' and instructor's, will result in more time being devoted to putting the apparatus to the best possible use and to a proper consideration of the errors in the experiment and the accuracy of any 'final' result. To further these ends, sections on 'Experimental details' and 'Errors and accuracy' are included where possible for all the experiments and in addition a separate chapter is devoted to errors at the beginning of the book.

I have pleasure in acknowledging my indebtedness and expressing my thanks to Mr C. B. Spurgin of Wolverhampton Grammar School and Mr T. B. Akrill of Clifton College, both of whom not only read the manuscript and made many valuable suggestions, but also advised on many points of presentation in SI units.

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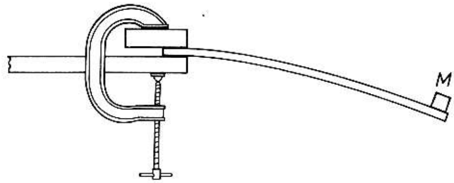
5 Experiments with a cantilever

Apparatus Boxwood metre scale, G-clamp or vice, stop-watch, set of masses, Sellotape.

Experiment 1 **To investigate how the time of vibration varies with the length vibrating**

Method Fix a 100 g mass M to one end of the metre scale firmly with Sellotape and then securely clamp the other end to the edge of the bench so that the scale can vibrate as a cantilever of length, say, 90 cm. Record this length and with the stop-watch take the time for 50 vibrations. Take two further observations of this time.



Reduce the length that is free to vibrate to 85 cm and repeat the timings.

Continue to reduce the length vibrating until the vibrations are too rapid to count.

Readings

Length vibrating L/m	Time for 50 vibrations				Time for 1 vibration (periodic time) T/s	$\log_{10}(T/\mathrm{s})$	$\log_{10}(L/\mathrm{m})$
	t_1/s	t_2/s	t_3/s	Mean t/s			

Plot a graph with values of $\log_{10}(T/\mathrm{s})$ as ordinates against the corresponding values of $\log_{10}(L/\mathrm{m})$ as abscissae. Measure the slope and interpret your result.

Experimental details

1. Even when the length of the cantilever is large the vibrations are rapid and counting is difficult. For this reason at least three timings for each length are recommended.

2. The rate of vibration will of course depend on the material and dimensions of the metre scale and it may be desirable to change the size of mass attached accordingly.

3. As the vibrations get more rapid it may be necessary to take the time for 100 vibrations instead of 50 so that a large and more reliable reading on the stop-watch may be obtained, though, of course, the times recorded in the table should be those for 50 vibrations consistently.

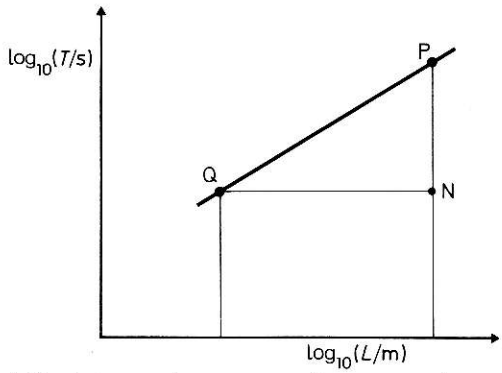
Theory and calculation Assuming that the relation between the time of vibration T and the length L vibrating is of the form $T \propto L^a$

then $\dfrac{T/\mathrm{s}}{(L/\mathrm{m})^a} = k$ where k is a constant.

Taking logs to the base 10 and rearranging,

$$\log_{10}(T/\mathrm{s}) = a \log_{10}(L/\mathrm{m}) + \log_{10} k$$

The graph of $\log_{10}(T/\mathrm{s})$ as ordinates against $\log_{10}(L/\mathrm{m})$ as abscissae is thus a straight line whose slope, $\dfrac{\mathrm{PN}}{\mathrm{QN}}$, obtained from two well-separated points on the line, is the value of a.



Errors and accuracy The errors in timing will be shown up by the variation existing between the separate values t_1, t_2 and t_3.

Estimate the difference between the slope of the chosen 'best' straight line and the slope of other possible straight lines and state your result for a accordingly. Compare it with the theoretical values in (1) on p. 27.

Experiment 2 **To investigate how the time of vibration of a cantilever of fixed length depends on the mass attached to its free end**

Method

As before fix a 100 g mass firmly to one end of the metre scale with Sellotape and securely clamp the other end to the edge of the bench so that the scale vibrates as a cantilever of length 90 cm.

Take three observations of the time for 50 vibrations.

Change the mass at the end to one of 50 g, 150 g, 200 g and suitable intermediate values in turn and repeat the timings.

Plot a graph with values of $\log_{10}(T/\text{s})$ as ordinates against the corresponding values of $\log_{10}(M/\text{kg})$ as abscissae. Measure the slope and interpret your result.

Addition **Determination of the Young modulus from Experiments 1 and 2**

Theory shows that the full relationship between the period time T, the length vibrating L and the mass M attached to the free end is

$$T = 2\pi\sqrt{\frac{4ML^3}{Ebd^3}} \tag{1}$$

where E is the Young modulus of the material of the cantilever and b and d the width and the thickness respectively.

Squaring we obtain
$$T^2 = \frac{16\pi^2 ML^3}{Ebd^3}$$

From this we see that if, from the results obtained from Experiment 1, values of T^2/s^2 are plotted as ordinates against the corresponding values of L^3/m^3 as abscissae, the slope is numerically equal to $\dfrac{16\pi^2 M}{Ebd^3}$ from which the values for the Young modulus for the material of the cantilever can be calculated when the values of M, b and d have been measured in the appropriate units (kg, m, m, respectively).

Similarly, from Experiment 2, if values of T^2/s^2 are plotted as ordinates against the corresponding values of M/kg as abscissae, the slope is numerically equal to $\dfrac{16\pi^2 L^3}{Ebd^3}$ from which, once again, E can be calculated.

Experiment 3 **To investigate how the sag of the free end of a weighted cantilever varies with the mass suspended from the free end**

Method

Clamp the metre scale to the edge of the bench. Place a vertical scale at the free end and note the reading. Obtain values for the further depression s of this free end produced by masses M suspended by cotton from the free end. By a graphical method determine the relation between s and M assuming it to be of the form $s \propto M^n$.

Experiment 4 **To investigate how the sag of the free end of a weighted cantilever varies with the length of the cantilever**

Method

Clamp the metre scale to the edge of the bench with a measured length L projecting. Place a vertical scale at the free end and note the reading. Suspend a given mass from the free end and note the further depression s thus caused. Alter the length of the cantilever but keep the mass suspended constant and note the new value of s. Determine graphically the relation between s and L assuming it to be of the form $s \propto L^n$.

Addition

Theory shows that the full relationship between the sag s of the free end of a cantilever produced by the suspension of a mass M from its free end is

$$s = \frac{4MgL^3}{Ebd^3}$$

where L, b and d are the length, width and thickness respectively, and E the Young modulus of the material.

Thus, graphs of s/m against M/kg (Experiment 3) and of s/m against L^3/m^3 (Experiment 4) could enable E to be deduced from the respective slopes.

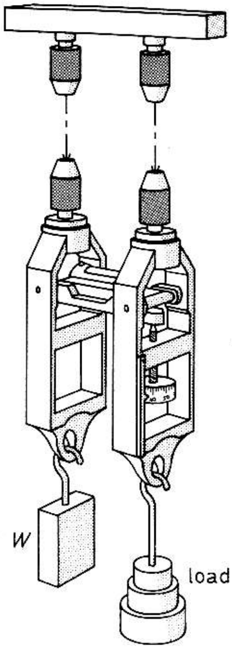
8 Measurement of the Young modulus for a wire

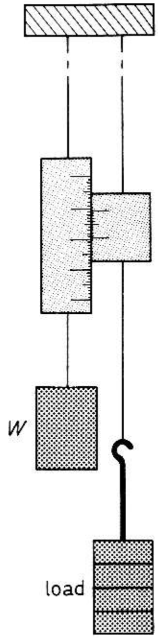
Apparatus

A simple form of apparatus for examining the behaviour of a wire under gradually increasing tension, from which the Young modulus can be obtained, is described in Experiment 9.

For the more accurate determination of the Young modulus for a wire the apparatus is probably a permanent fitting in the laboratory. It consists of two long vertical wires of the same material suspended from the same support. One of these carries a scale and a large mass W sufficient to keep the wire taut. The other wire is the wire under test and it carries a vernier which moves against the fixed scale. This wire is loaded with $\frac{1}{2}$ kg masses.

A more sensitive form of this apparatus is also shown. It consists of a frame carrying a spirit level which bears against a micrometer screw. When a load on the wire has tilted the spirit level out of the horizontal the micrometer screw enables it to be restored to the horizontal, the movement of the load being measured by the movement of the micrometer screw.





Method

Load the wire under test so that it is just taut and read the vernier. Increase the load by successive additions of $\frac{1}{2}$ kg and read the vernier after each addition. When the load has reached about 12 kg, unload the wire by $\frac{1}{2}$ kg at a time and again read the vernier.

Readings

Additional load M/kg	Initial reading of vernier V_0/mm =			Mean extension e/mm from $e = V - V_0$
	Readings of vernier/mm			
	Load increasing/mm	Load decreasing/mm	Mean reading V/mm	

Measure the length l of the test-wire with a metre scale from the point of support to the beginning of the vernier scale.

With a micrometer gauge take several readings of the diameter d of the wire, taking two readings at right angles at several points along the wire.

Plot a graph with values of the mean extension e/mm as ordinates against the corresponding values of the additional load M/kg as abscissae.

Experimental details

1. Before starting the experiment, see that both wires are free from kinks and that the original loads render the wires quite taut.

2. Before starting to take the readings, it is advisable to load and unload the wire several times to straighten it and to accustom it to extending and contracting which it often resists after a long rest.

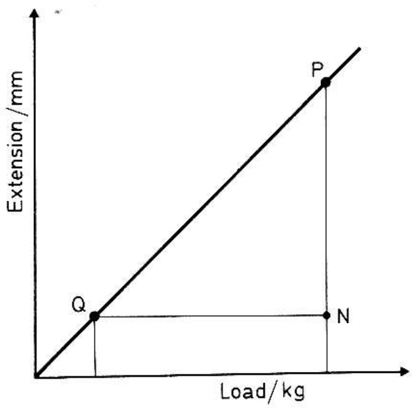
3. If the vernier readings for an increasing load are not repeated approximately when the load is decreasing, the elastic limit of the wire has been passed, and the readings for a decreasing load will have to be scrapped.

4. Since both the wire carrying the vernier and the wire carrying the scale are suspended from the same support, errors due to the yielding of this support are avoided.

5. Since the wires are of the same material, errors due to the change in the length of the test-wire caused by a slight change in temperature are also avoided.

Theory and calculation

The graph will be found to be a straight line which should go through the origin if the original load put on to keep the wire taut was large enough. In any case, from the straight portion of the graph it is seen that any increase QN in the load is proportional to the extension PN it produces, i.e. Hooke's law is obeyed.



If a mass M produces an extension e in a wire of length l and diameter d then the Young modulus E is given by

$$E = \frac{\text{elongational stress}}{\text{elongational strain}} = \frac{Mg}{\frac{1}{4}\pi d^2} \div \frac{e}{l} = \frac{4gl}{\pi d^2} \cdot \frac{M}{e} \qquad (1)$$

The mean value of $\frac{M}{e}$ is obtained from the graph and is equal to $\frac{\text{QN kg}}{\text{PN} \times 10^{-3}\,\text{m}}$. Insert in (1) also the values of l and d (both in m) and the value of g ($9{\cdot}81\ \text{m s}^{-2}$).

Hence $$E = \ldots\ldots\ \text{N m}^{-2}$$

Errors and accuracy

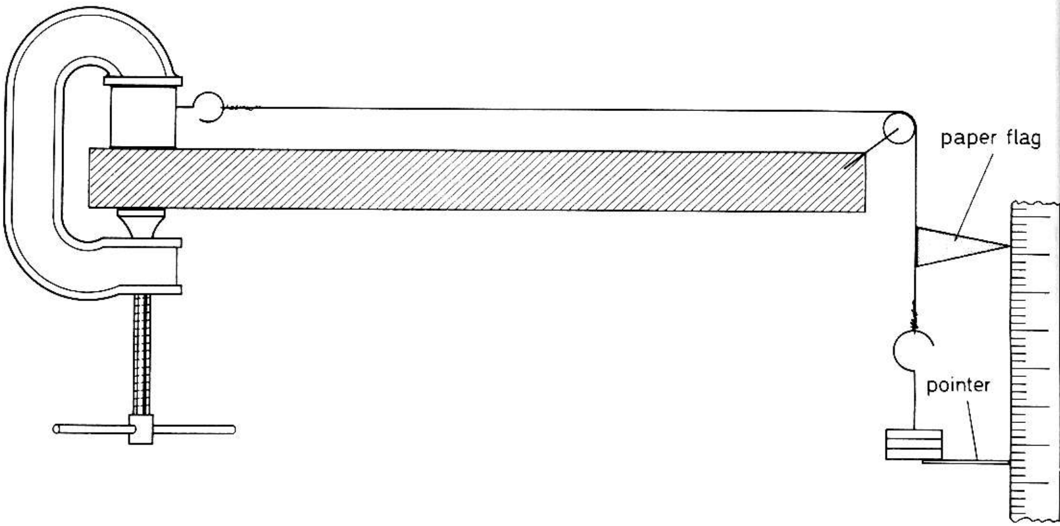
Rearranging equation (1) from which E is calculated

$$E = \frac{4g}{\pi} \times \frac{l}{d^2} \times \frac{1}{\text{slope of graph}}$$

Hence % error in E = % error in $l + 2 \times$ % error in $d +$ % error in slope of graph

From a consideration of the markings on the scales involved estimate the errors and hence the % errors in l and d. Estimate the % error in the slope from the difference between the slopes of the chosen 'best' straight line and of other possible straight lines drawn through the points. Evaluate the total % error and state your result accordingly.

Behaviour of a wire under gradually increasing tension



Apparatus A 2 m length of copper wire s.w.g. 32, 100 g slotted masses and hanger, stands and clamps, metre scale, micrometer gauge. Goggles (see safety note in italics below).

Method Arrange for the wire to be stretched horizontally by the apparatus shown in the diagram. One end of the wire is twisted round a hook in a wooden block which is firmly secured to the bench by means of a G-clamp. (Alternatively, a loop at the end of the wire may be folded inside a folded-over piece of PVC insulating tape and then clamped between two wooden blocks.) The other end of the wire is twisted round the hanger which acts as a holder for the slotted masses. Improvise a pointer against a vertical metre scale by folding a shaped piece of gummed paper round the vertical straight portion of the wire. (Alternatively by sticking a needle, by means of Plasticine, to the underside of the hanger.)

Measure and record both the initial length l of the wire and also its mean diameter d from readings taken at right angles at several points along the wire.

Note the pointer reading on the scale (p_0).

Add a 100 g mass to the hanger and record the new reading of the pointer. Remove the 100 g mass and observe whether the pointer reading reverts to its initial reading (p_0).

Continue to add successive masses of 100 g to the hanger, reading the pointer each time and then observing the reading after the total load has been removed. Note the load at which *permanent* extension of the wire is observed. *At this point put on the goggles.*

Continue to increase the load by 100 g increments, standing well back after each addition to the hanger, until the wire eventually breaks. *The need for caution as breaking approaches is real, as fast-moving ends of snapping wire can cut flesh or, worse, damage an eye. For this reason it is advisable to wear goggles.*

eadings

Load/g	Initial pointer reading p_0/mm =		Extension/mm
	Pointer reading/mm		
	Under load	Load removed	

Plot a graph with values of extension/mm as ordinates against corresponding values of load/g as abscissae.

heory and alculation

1. Deduction of the *Young modulus* for the wire.

Over the straight portion of the graph it is seen that an increase in the load is proportional to the extension it produces, i.e. Hooke's law is obeyed.

If a mass M produces an extension e in a wire of original length l and diameter d then the Young modulus E is given by

$$E = \frac{\text{elongational stress}}{\text{elongational strain}} = \frac{Mg}{\frac{1}{4}\pi d^2} \div \frac{e}{l} = \frac{4gl}{\pi d^2} \cdot \frac{M}{e}$$

The mean value of $\dfrac{M(\text{in kg})}{e\ (\text{in m})}$ is obtained from the slope of the straight portion of the graph and hence the Young modulus can be deduced.

2 From the graph estimate also

the *breaking stress* = force per unit area at breaking

and the *breaking strain* $= \dfrac{\text{extension at fracture}}{\text{original length}}$

dditional xperiments

1. If copper wire of a different thickness is available (say s.w.g. 26) measure its breaking stress and note whether the breaking stress of copper wire depends upon its thickness.

2. By replacing the copper wire by steel wire (s.w.g. 44) the Young modulus, the breaking stress and the breaking strain for steel may be determined and compared with the corresponding values for copper.

3. The very different behaviour of rubber may be investigated by suspending a small piece of rubber (e.g. a severed rubber band) vertically from a clamp and then loading and unloading it with successive loads of 100 g until it breaks.

A LABORATORY MANUAL OF PHYSICS FOURTH EDITION

SI VERSION

for Advanced Level, Scholarship, and Ordinary National Certificate

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Experiment 12

Determination of Young's modulus for a wire

APPARATUS Two long wires of the same material are suspended side by side from the same support. The extension of the wire under test AB is taken by a vernier scale V against the main scale S supported by the wire CD, which is kept under constant load by a heavy weight L'. This arrangement obviates any errors due to temperature changes during the experiment, or yielding of the support, from affecting the observed extensions. The heavy weight L and the original load on AB should both be sufficient to keep the wires taut and free from kinks. The extending load on AB is increased by the addition of slotted half-kilogramme weights at W.

A metre rule and a screw gauge will also be required.

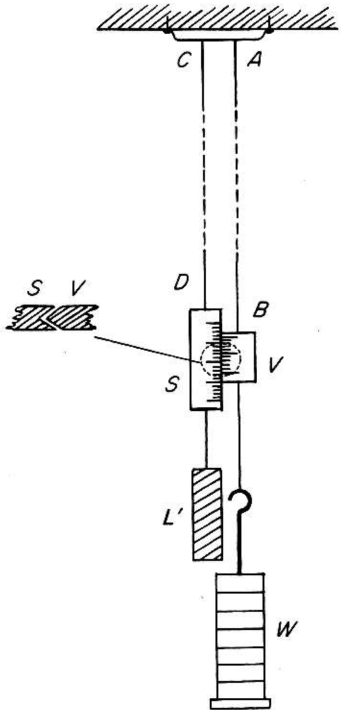

FIG. 12.1

METHOD When the wire AB is taut the vernier is read to give the zero position. The load is progressively increased by the addition of $\frac{1}{2}$-kg weights at W and the vernier is read on each occasion. When about 5 kg have been added, the weights are removed in successive stages, and vernier readings are again taken. The length of AB—from the support to the point of attachment to the vernier scale—is measured by a metre rule. The diameter is also measured (for cross-sectional area) by the screw gauge, at least six readings being taken.

NOTE If loaded within the limits of perfect elasticity the graph of extension against load will be a straight line, thus verifying **Hooke's law**. On unloading the wire will recover its original length.

Further loading beyond the elastic limit will result in much larger relative extensions, and on removing the weights the wire will be found to have acquired a 'permanent set'.

THEORY

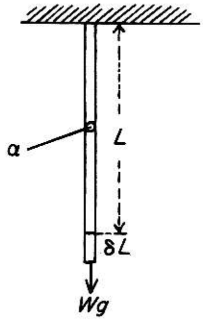

FIG. 12.2

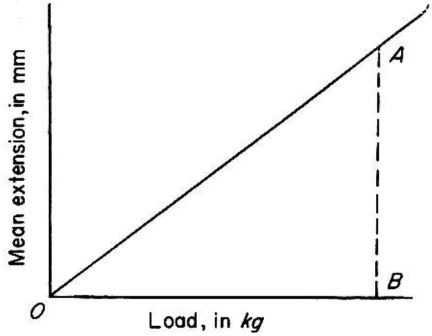

FIG. 12.3

$$\text{Young's modulus } (E) = \frac{\text{elongatory stress}}{\text{elongatory strain}}$$

$$= \frac{Wg}{\alpha} \div \frac{\delta L}{L} = \frac{WgL}{\pi r^2 . \delta L}$$

RESULTS

$L =$ m

Screw-gauge readings: , , , , , , mean value = m

Zero error = ± m

∴ true mean diameter = m

i.e. $r =$ m

Load in kg	Extension in mm		
	Load increasing	Load decreasing	Mean

From graph

$$\frac{Wg}{\delta L} = \frac{OB \times 9{\cdot}81}{AB \times 10^{-3}}$$

$$\therefore \quad E = \frac{L}{\pi r^2} \times \frac{OB}{AB} \times 9{\cdot}81 \times 10^3$$

$$= \underline{\qquad\qquad} \text{N m}^{-2}$$

Experiment 15

Determination of Young's modulus by bending a beam

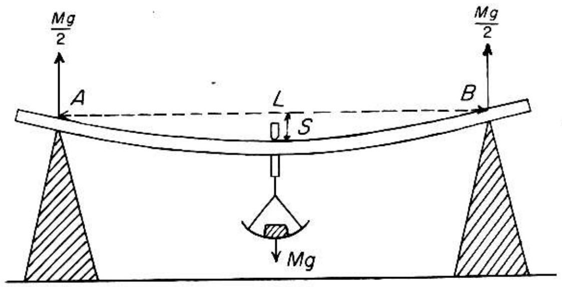

FIG. 15.1

APPARATUS A beam, of suitable material, about 1 m long, 2 or 3 cm wide, and about 5 mm thick. Two rigid supports with sharp edges clamped firmly to the bench. Scale-pan supported by a knife edge resting on the middle of the beam. Set of weights, travelling miscroscope, screw gauge.

METHOD The beam is placed on the supports which are about 80 cm apart. The cross-wires of the microscope are focused on the knife edge supporting the scale-pan, and the reading of the verniers taken. Weights are now placed in the scale-pan and the corresponding depressions are obtained from the microscope readings. After loading to a maximum a further set of readings is taken as the weights are removed from the pan. A graph of mean depression against load is plotted from which is obtained the load required for unit depression. The length AB of the beam between the supports, and also the width of the beam, are now measured. The depth of the beam must be obtained very carefully (since it appears to the 3rd power in the expression for E), and this is done by taking at least six readings by a screw gauge at various points along the beam.

RESULTS

Load	*Values of s*		*Mean sag*
	Load increasing	*Load decreasing*	

Screw-gauge readings: , , , , , , mean = m

zero error = ± m

$b =$ m $L =$ m $\therefore\ d =$ m

$E =$ ______ N m^{-2}

THEORY Figure 15.2 represents a cantilever subject to flexure by a load W attached at B. Elements above the middle line (or neutral axis) are in extension, and those below it are in compression. Ignoring the weight of the beam beyond P, the bending moment at $P = W(L - x)$. Let the curvature of the beam at P be $\frac{1}{R}$, and consider the extension of a filament of length dx at P of depth dz and distant z

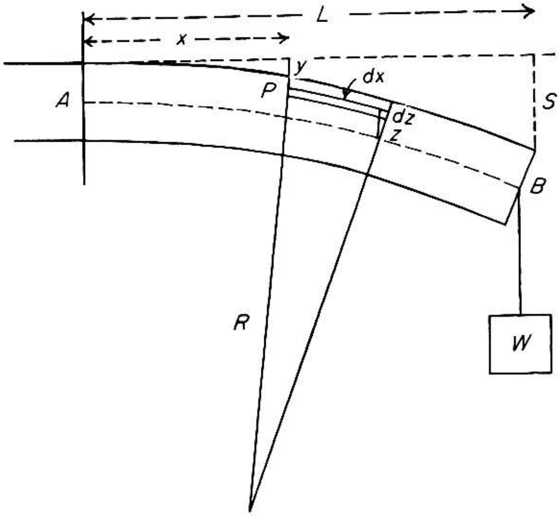

FIG. 15.2

from the neutral axis. Let the width of the beam at this point be b. Then by similar triangles:

$$\frac{\text{elongation of } dx}{z} = \frac{dx}{R}$$

i.e. strain in filament $= \dfrac{\text{elongation of } dx}{dx} = \dfrac{z}{R}$

Now since stress $= E \times$ strain (where $E =$ Young's modulus), then stress $= Ez/R$. Thus the tension in the filament $=$ stress $\times$ area of cross-section $= \dfrac{Ez}{R}\, b\, dz$; the moment of this tension about the neutral axis $= \dfrac{Eb}{R} \cdot z^2\, dz$.

$\therefore$ total moment of these tensions at

$$P = \frac{E}{R}\int bz^2\, dz$$

$= \dfrac{R}{E} \cdot I$ (where $I = \int bz^2\, dz =$ moment of inertia of cross-section of beam about the neutral axis)

$=$ external moment $W(L - x)$

Now for slight bending $\dfrac{1}{R} = \dfrac{d^2y}{dx^2}$, since $\dfrac{1}{R} = \dfrac{\dfrac{d^2y}{dx^2}}{\left\{1 + \left(\dfrac{dy}{dx}\right)^2\right\}^{3/2}}$ and $\dfrac{dy}{dx}$ is small.

$$\therefore \quad EI\frac{d^2y}{dx^2} = W(L - x).$$

Integrating $EI\dfrac{dy}{dx} = WLx - W\dfrac{x^2}{2}$, the constant of integration $= 0$, since $\dfrac{dy}{dx} = 0$ when $x = 0$.

Integrating again $EIy = WL\dfrac{x^2}{2} - W\dfrac{x^3}{6}$, the constant of integration $= 0$ since $y = 0$ when $x = 0$.

At B where $x = L$, $y = S$, i.e. $EIS = \dfrac{WL^3}{3}$ or $E = \dfrac{WL^3}{3IS}$.

For a beam supported by two knife edges and loaded at the centre the force W acting on *one half* of the beam is $\dfrac{Mg}{2}$ (see Fig. 15.1), and therefore $E = \dfrac{MgL^3}{48IS}$.

For a beam of rectangular cross-section $I = \dfrac{bd^3}{12}$, and from the graph $\dfrac{M}{S} = \dfrac{OB}{AB}$.

$$\therefore \quad E = \frac{L^3 g}{4bd^3} \cdot \frac{OB}{AB}$$

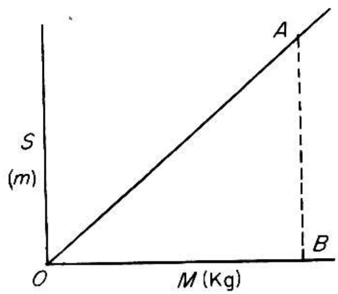

FIG. 15.3

Experiment 17

Determination of Young's modulus from the period of vibration of a loaded cantilever

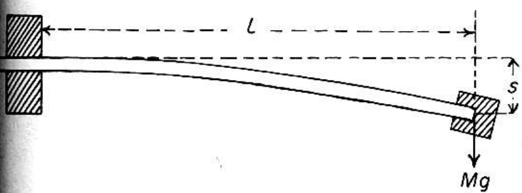

FIG. 17.1

APPARATUS

Boxwood metre rule with weight rigidly attached to one end. G clamp, screw gauge, stop-watch.

METHOD The loaded beam is clamped firmly to the edge of the bench by the G clamp with a definite length l projecting from it. The load affixed to the beam should be such as to cause but a small depression. The beam is now caused to vibrate, and the periodic time T is obtained by timing 20 vibrations. The experiment is repeated to find T for various values of l. A graph of T^2 against l^3 is plotted from which to obtain a mean value of $\frac{l^3}{T^2}$. The width and depth of the beam are measured. This latter measurement should be taken carefully from an average of at least six screw-gauge readings taken at different points along the beam.

THEORY The depression s due to a load $W\,(= Mg)$ at the end of a cantilever of length l is

$$s = \frac{Wl^3}{3IE}$$ (see p. 33).

This strain brings into play internal stresses which produce a restoring force equal to W, i.e. equal to $\frac{3IEs}{l^3}$.

If the acceleration of the load is $\ddot{s}$ when the cantilever is displaced to produce vertical oscillations, then

$$M\ddot{s} = -\frac{3IE}{l^3}\cdot s$$

or

$$\ddot{s} + \frac{3IE}{Ml^3}\cdot s = 0$$

Hence the motion is simple harmonic and the periodic time T is

$$T = 2\pi\sqrt{\frac{Ml^3}{3IE}}$$

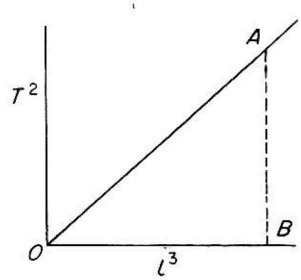

FIG. 17.2

from which $$E = \frac{4\pi^2 Ml^3}{3IT^2}$$

For a beam of rectangular section $$I = \frac{bd^3}{12}$$

from graph $$\frac{l^3}{T^2} = \frac{OB}{AB}$$

$$\therefore\quad E = \frac{16\pi^2 M}{bd^3}\cdot\frac{OB}{AB}$$