EXPERIMENTAL PHYSICS

A SELECTION OF EXPERIMENTS

BY

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CAMBRIDGE
AT THE UNIVERSITY PRESS
1934

EXPERIMENTAL PHYSICS

LONDON
Cambridge University Press
FETTER LANE

NEW YORK · TORONTO
BOMBAY · CALCUTTA · MADRAS
Macmillan

TOKYO
Maruzen Company Ltd

PRINTED IN GREAT BRITAIN

PREFACE

In the course of my work as a Demonstrator of Experimental Physics, which began in October 1888, many experiments have been devised for the instruction of my students at the Cavendish Laboratory. The three manuals on *Experimental Elasticity* (1908), on *Experimental Harmonic Motion* (1915) and on *Experimental Optics* (1925) describe courses of experiments in those subjects. Many experiments done in my Class had, by their nature, no place in these three volumes. Accounts of some have appeared in the *Proceedings of the Cambridge Philosophical Society* and elsewhere; others* have not, up to the present, been described by me, except in the manuscripts I have written for use in my Class.

The present volume contains accounts of experiments in Mechanics, Elasticity, Surface Tension, Viscosity, Heat and Sound. These experiments are not described in the three manuals already published. Prof. E. V. Appleton has called the new volume "The Odds and Ends Book"; I do not quarrel with his description.

My work as Demonstrator ceases on 30 September, 1935. It seemed right to prepare for that event by writing this book. I hope it may be of service to those who succeed me, and that it may be useful to students and teachers at the Cavendish Laboratory and elsewhere.

The book is, in one aspect, love's thank-offering for the many happy years spent in the service of students. The work has often been hard, sometimes very hard, but hard work need not be misery.

Mathematical discussions of some problems in Surface Tension, Conduction of Heat and Sound occupy Chapters V, VIII and X. The Chapter (X) on Sound may seem over-long for the small

* In his *Practical Physics* (1926) my colleague and former assistant demonstrator, Mr T. G. Bedford, gave, by my permission, brief accounts of a few of these experiments.

number of acoustical experiments described in Chapter XI, but I was anxious to bring out the character of the motion which the air has when a resonator is sounding.

The increase in the number of students led, some years ago, to the organisation of a new Practical Class in Electricity and Magnetism. The removal of these subjects from my Practical Course allowed them to be taught more fully than was previously possible, and compelled me to extend my course in Optics. The only, but very real, disadvantage is that students are now offered more than they can absorb in the time at their disposal.

I have abandoned a former project of writing a manual on *Experimental Electricity and Magnetism*.

To avoid the monotony of repetition, I record here my cordial thanks to each of the many friends who gave me help at any stage of the work.

Prof. Lord Rutherford, F.R.S., has seconded my endeavour to secure efficiency in my Class; he has been indulgent to me.

I have often sought the advice of Dr G. T. Bennett, F.R.S. By his help, many statements, particularly in the dynamical sections of the book, were put into precise forms.

The theory of the Sessile Drop in Chapter V was suggested by the interesting, but mathematically invalid, work of Mathieu. By using an elliptic integral method, to the same degree of approximation as I had adopted, Prof. R. H. Fowler, F.R.S., verified equation (25) of § 102 and equation (30) of § 104.

Several students gave their help during vacations. Messrs T. B. Rymer, C. L. Cook, J. G. P. Baker, R. Stone, K. G. Tupling, W. A. B. Carter, J. W. Jeffery and J. L. Roberts assisted in the preparation of the manuscript; Mr C. H. Garrett and Mr D. A. Crooks gave effective help in the correction of the proof sheets. My chief debt is to Miss F. W. Stubbins, of Girton College, who gave her help in the summers of 1929 and 1930. Besides transcribing for the press much of my rough manuscript, she made a large number of the drawings for the figures.

For some years I have had the help of Mr J. A. Ratcliffe, Fellow of Sidney Sussex College, and of Dr N. Feather, Fellow of Trinity College, as demonstrators. Their experience gave weight to their comments on the proofs of the first six chapters. It is

usually taught that the stable length of a cylindrical soap film, of radius a, is $2\pi a$, and this is true under suitable conditions. Dr Feather's criticism led me to the result that, if the pressure excess be maintained at the *constant* value $2T/a$, where T is the surface tension, the maximum stable length is only πa.

Dr Guy Barr, of the Department of Metallurgy and Metallurgical Chemistry, National Physical Laboratory, read the proofs of the Chapter (VII) on Viscosity. His expert knowledge of Viscometry made his help of great value.

Dr Barr, and Dr Allan Ferguson, East London College, made some useful remarks on the Chapters (V and VI) on Surface Tension.

Dr J. K. Roberts, sometime Assistant in the Heat Department of the National Physical Laboratory, made a careful revision of the Chapters on Heat. The Chapters on Sound were read by Dr J. E. R. Constable, of the Physics Department of the National Physical Laboratory, and also by Mr W. R. Dean, Fellow of Trinity College. Mr Dean's detection of a mathematical error led me to set out in full the *exact* equation for spherical waves of sound.

The Cambridge Philosophical Society and Messrs W. G. Pye & Co. have lent blocks for several figures.

The work of the Staff of the Cambridge University Press has won my admiration and my gratitude.

I owe very much to my assistant, Mr C. G. Tilley, for his faithful help for over fifteen years, and for his unfailing kindness and thought for me. If the apparatus described in this book be efficient for its purpose, it is, in many cases, due to Mr Tilley's resourcefulness, to his knowledge of workshop methods, and to his skilled craftsmanship. In former years, I received much help from Mr F. Lincoln and Mr H. D. Roff, instrument makers at the Laboratory.

I have authorised Messrs W. G. Pye & Co., of Cambridge, to supply apparatus made to my designs.

I dare not conclude without a word of grateful testimony. For about seven years, I went through a dark time of nervous and physical weakness, with a complete breakdown in 1910. At the end of 1914, there came into my hands Miss Dorothy Kerin's little book, *The Living Touch*, a record of her miraculous healing. It opened my eyes, as they had never been opened before, to the present-day Power of the Living God, the Creator of the universe. As an immediate result, all the old weakness left me, and I was well. In recent years, at Miss Kerin's hostel, Chapel House, Mattock Lane, Ealing, London, many have realised the greatness of the Lord's Power and Love, and have learned to trust Him.

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Cavendish Laboratory
Cambridge
17 *September* 1934

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CHAPTER 1

EXPERIMENTS IN DYNAMICS

EXPERIMENT 1. **An example of conservation of angular momentum.***

1. Angular momentum of a particle about an axis. If at any instant a particle of mass m be moving with velocity v, it has momentum mv. The momentum is a vector lying along the tangent to the path of the particle at the point where the particle is at the instant considered.

Just as a force has a moment about any straight line or axis A unless its line of action either intersect A or be parallel to it, so momentum P along a given straight line has a moment about an axis A unless the straight line either intersect A or be parallel to it. To find the value of the moment of P about A we take a plane cutting A at right angles at O and project P upon this plane. If the perpendicular from O upon the projection of P be ON, and if the angle between P and the axis be θ, the moment of the projection about OA is $ON \, . \, P \sin\theta$. The momentum P has the component $P\cos\theta$ parallel to A, but this has no moment about A. Hence $ON \, . \, P\sin\theta$ is the moment of the momentum P about A.

The moment about A of the momentum mv of the particle m is often called the angular momentum of m about A.

2. Angular momentum of a system about an axis. For the purpose of the experiment we may confine ourselves to the simple case in which every particle of the system moves parallel to a fixed plane, which we take as the plane of Oxy (Fig. 1). The axis of z is perpendicular to Oxy and its positive direction is towards the reader. The three axes then form a right-handed system. In the experiment the plane Oxy is horizontal. Let P be the projection on Oxy of a particle of mass m. Let the coordinates of P relative to the fixed

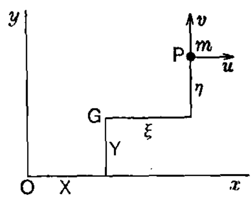

Fig. 1

* "An experiment illustrating the conservation of angular momentum," *Proc. Camb. Phil. Soc.* Vol. XXI, p. 75 (1922).

axes Ox, Oy be x, y, and let the components of the velocity of P be u, v. Then the components of the momentum of the particle are mu, mv. Hence, when counter-clockwise rotation about Oz is counted as positive, the sum of the moments about Oz of the momenta mu, mv, or the angular momentum of the particle about Oz, is $m(vx-uy)$. If H be the angular momentum about Oz of the whole system of particles,

$$H=\Sigma m(vx-uy). \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Let G be the projection on Oxy of the centre of gravity of the system. Let its coordinates relative to the fixed axes Ox, Oy be X, Y, and let the components of its velocity be U, V. Let $x=X+\xi$, $y=Y+\eta$, so that ξ, η are the coordinates of P relative to axes through G parallel to the fixed axes Ox, Oy. Then, since G is the centre of gravity,

$$\Sigma m\xi=0, \qquad \Sigma m\eta=0. \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Let $u=U+\alpha$, $v=V+\beta$, so that α, β are the components of the velocity of P relative to G. Then, since $u=dx/dt$, $v=dy/dt$, $U=dX/dt$, $V=dY/dt$, we have $\alpha=d\xi/dt$, $\beta=d\eta/dt$. But, by (2),

$$\Sigma m\, d\xi/dt=0, \qquad \Sigma m\, d\eta/dt=0,$$

and hence

$$\Sigma m\alpha=0, \qquad \Sigma m\beta=0. \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Now, by (1),

$$\begin{aligned} H&=\Sigma m\{(V+\beta)(X+\xi)-(U+\alpha)(Y+\eta)\} \\ &=\Sigma m\{VX-UY+V\xi-U\eta+\beta X-\alpha Y+\beta\xi-\alpha\eta\}. \end{aligned}$$

Since U, V and X, Y do not change from particle to particle, we may bring them outside the sign of summation. Thus

$$\begin{aligned} H=(VX-UY)\Sigma m&+V\Sigma m\xi-U\Sigma m\eta \\ &+X\Sigma m\beta-Y\Sigma m\alpha+\Sigma m(\beta\xi-\alpha\eta). \end{aligned}$$

Denoting Σm, the mass of the whole system, by M and using (2) and (3), we have

$$H=M(VX-UY)+\Sigma m(\beta\xi-\alpha\eta). \quad \ldots\ldots\ldots\ldots(4)$$

The first term in (4) is the angular momentum about Oz of a particle of mass M placed at G and moving with G. The second term is the angular momentum of the system, for the motion relative to G, about an axis through G parallel to Oz.

3. Method. A board D (Fig. 2) is suspended by a thread which we suppose to exert no torsional control. The thread is attached to a torsion head, which is carried by a fixed support. The plane of the board is horizontal and the axis of suspension cuts the board in O. The vertical through O is the axis Oz of § 2. The inertia bar AB turns about a vertical shaft fixed to the board, the axis of the shaft passing through G, the centre of gravity of AB. A second bar C, suitably fixed to the board, acts as a counterpoise to AB. By adjusting C, the plane of D is made horizontal. By a light spring E attached to the board and operating by a string wound round a drum carried by AB, this bar can be set in motion about G relative to the board, when a thread attached to the board and holding AB in its initial position is burned. Before the thread is burned, the system is at rest. At any later time let the axis OG of the board make an angle θ with OF, its initial direction, and let the axis GA of the bar make an angle $\phi+\epsilon$ with GO, where ϵ is the angle between GA and GO before the thread is burned. Let ϕ be measured in the opposite direction to θ.

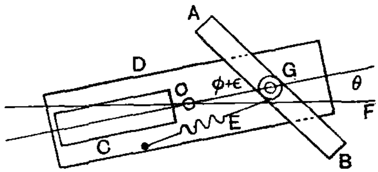

Fig. 2

With the exception of gravity and the tension of the suspension, no external forces act on the system at any time. Before the thread is burned, the system has no angular momentum about Oz. The burning of the thread does not call any external force into action and hence the angular momentum of the system about the vertical axis Oz remains zero. If the moment of inertia about Oz of the board, the counterpoise and all the other fittings *except* the bar AB be K_1, the angular momentum about Oz of this part of the system is $K_1 d\theta/dt$.

Let M be the mass of AB and let $OG=a$. Since the linear velocity of G is $a d\theta/dt$, the momentum of M at G is $Ma d\theta/dt$, and the moment of this momentum about Oz is $Ma^2 d\theta/dt$. This angular momentum is in the same direction as that of the board.

The angular velocity of AB, in the same direction as that of the board, is $d\theta/dt - d\phi/dt$, and hence, if the moment of inertia of AB about a vertical axis through G be K_2, its angular momentum