

EXPERIMENTAL PHYSICS

A SELECTION OF EXPERIMENTS

BY

G. F. C. SEARLE, Sc.D., F.R.S.

UNIVERSITY LECTURER IN EXPERIMENTAL PHYSICS

AND

DEMONSTRATOR OF EXPERIMENTAL PHYSICS

AT THE CAVENDISH LABORATORY

SOMETIME FELLOW OF PETERHOUSE

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

All rights reserved

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.

G. F. C. SEARLE

Cavendish Laboratory
Cambridge

17 September 1934

CONTENTS

CHAPTER I

EXPERIMENTS IN DYNAMICS

Experiment 1. An example of conservation of angular momentum.

§ 1. Angular momentum of a particle about an axis. 2. Angular momentum of a system about an axis. 3. Method. 4. Experimental details. 5. Practical example [Pages 1 to 7]

Experiment 2. Kater's pendulum.

§ 6. Introduction. 7. Periodic time of a rigid pendulum. 8. Pendulum with two parallel knife edges. 9. Buoyancy and inertia of air. 10. The pendulum. 11. Observation of periodic time. 12. Practical example. 13. Theory of adjustment by sliding masses . . . [Pages 7 to 16]

Experiment 3. Moment of inertia of a body about a non-principal axis.

§ 14. Introduction. 15. The momental ellipsoid. 16. Apparatus. 17. Method. 18. Practical example [Pages 16 to 22]

Experiment 4. Recording gyroscope.

§ 19. Introduction. 20. Relation between couple and precession in simplest case. 21. General case of motion with constant slope of axle. 22. Apparatus. 23. Experimental details. 24. The moments of inertia. 25. Relation of average to actual angular velocity. 26. Practical example. 27. Effect of the earth's rotation . . . [Pages 22 to 42]

CHAPTER II

THE STROBOSCOPE

Experiment 5. Determination of frequency of alternating current.

§ 28. Introduction. 29. Method. 30. Accuracy of standard frequency. 31. Practical example [Pages 43 to 51]

CHAPTER III

EXPERIMENTS IN ELASTICITY

§ 32. Transverse vibrations of a thin rod. 33. Mathematical theory of vibrations of rod. 34. Roots of $\cosh m \cos m = -1$. [Pages 52 to 58]

Experiment 6. Determination of Young's modulus by vibrations of a rod.

§ 35. Introduction. 36. Calibration by tuning forks. 37. Determination of Young's modulus. 38. Ratio of m_1 to m_0 . 39. Practical example. [Pages 58 to 63]

Experiment 7. Determination of frequency of alternating current by vibrations of a rod.

§ 40. Introduction. 41. Method. 42. Determination of frequency of current. 43. Practical example. 44. Experiment with several nodes. 45. Practical example [Pages 63 to 69]

Experiment 8. A bifilar method of measuring the rigidity of wires. § 46. Introduction. 47. Bifilar couple. 48. Apparatus. 49. Theory of method. 50. Experimental details. 51. Conversion table. 52. Practical example [Pages 69 to 79]

CHAPTER IV

OPTICAL METHODS OF DETERMINING ELASTIC CONSTANTS

§ 53. Introduction. 54. Thermal effects due to strain. 55. Mechanical work spent in stretching. 56. Application to bending of bar. 57. Mechanical work spent in shearing. 58. Geometry of helicoid. 59. Application to torsion of blade [Pages 80 to 88]

Experiment 9. Determination of elastic constants of glass by Cornu's method.

§ 60. Introduction. 61. Optical arrangements. 62. Method for measurement of Young's modulus and Poisson's ratio. 63. Theory of fringes for case of bending. 64. Method for measurement of rigidity. 65. Theory of fringes for case of twisting. 66. Comparison of results. 67. Practical example. [Pages 89 to 101]

Experiment 10. Determination of elastic constants of glass by focal line method.

§ 68. Introduction. 69. Focal lines due to reflexion at curved surface. 70. Optical method of measuring curvatures of reflecting surface. 71. Determination of Young's modulus and Poisson's ratio. 72. Determination of rigidity. 73. Practical example . . . [Pages 101 to 113]

Experiment 11. Measurement of Young's modulus by method of optical interference.

§ 74. Introduction. 75. Method. 76. Optical adjustments. 77. Experimental details. 78. Mechanical theory. 79. Theory and practice of optical measurements. 80. Practical example . . . [Pages 113 to 127]

CHAPTER V

MATHEMATICAL DISCUSSIONS OF PROBLEMS IN SURFACE TENSION

§ 81. The nature of surface tension. 82. Surface energy. 83. Application of thermodynamics. 84. Surface energy and surface tension. 85. Geometry of spherical film. 86. Stability of spherical film. 87. General theory of stability of spherical film. 88. Relation between

curvature of surface and normal force per unit area due to surface tension. 89. Principal curvatures of surface of revolution. 90. Form of meniscus in capillary tube [Pages 128 to 142]

THEORY OF CATENOID FILM

§ 91. Catenoid film. 92. Maximum length of catenoid. 93. Surface of catenoid. 94. Solution of equation $\coth n = n$ [Pages 143 to 148]

THEORY OF CYLINDRICAL FILM

§ 95. Unduloid film. 95A. Cylindrical film with constant internal pressure. 96. Theory of stability of cylindrical film. [Pages 148 to 153]

THEORY OF SESSILE DROP

§ 97. Sessile drops. 98. Introduction to theory. 99. Large finite drop. 100. Curvature at vertex. 101. Circle of contact. 102. Form of drop where x is comparable with c . 103. Determination of surface tension. 104. Determination of angle of contact [Pages 153 to 163]

CHAPTER VI

EXPERIMENTS ON SURFACE TENSION

§ 105. Soap solution. 105A. Cleaning of glass surfaces. [Pages 164 to 165]

Experiment 12. Measurement of surface tension of liquid by capillary tube.

§ 106. Method. 107. Preparation of the tube. 108. Measurements. 109. Practical example [Pages 165 to 171]

Experiment 13. Measurement of surface tension of soap solution by torsion balance.

§ 110. Method. 111. Practical example [Pages 171 to 174]

Experiment 14. Measurement of surface tension of liquid by torsion balance.

§ 112. Introduction. 113. Method. 114. Practical example
[Pages 174 to 177]

Experiment 15. Measurement of surface tension of soap solution by thread method.

§ 115. Method. 116. Practical example [Pages 177 to 180]

Experiment 16. Measurement of surface tension of soap film by viscosity potentiometer.

§ 117. Method. 118. The bubble holder. 119. Note on design of apparatus. 120. Practical example [Pages 180 to 185]

Experiment 17. Measurement of surface tension of soap film by buoyancy method.

§ 121. Method. 122. Practical details. 123. Practical example
[Pages 185 to 188]

- Experiment 18.** Study of catenoid film.
 § 124. Introduction. 125. Apparatus. 126. Method. 127. Practical example [Pages 188 to 190]
- Experiment 19.** Study of cylindrical film.
 § 128. Method. 129. Spherical caps left by collapsing cylindrical film. 129A. Cylindrical film with constant internal pressure. 129B. Unduloid film. 130. Practical example [Pages 190 to 196]
- Experiment 20.** Measurement of surface tension of mercury by Quincke's sessile drop method.
 § 131. Introduction. 132. Method. 133. Optical discussion. 134. Practical example [Pages 196 to 202]
- Experiment 21.** Surface tension of interface between two liquids.
 § 135. Introduction. 136. Methods for pair of solutions of first class. 137. Methods for pair of solutions of second class. 138. Liquids. 139. Torsion balance. 140. Experimental details. 140A. Effect of change of surface of plate. 141. Surface tension of solutions in contact with air. 142. Practical example. 143. Form of interface [Pages 203 to 215]

CHAPTER VII

EXPERIMENTS ON VISCOSITY

- § 144. Introduction. 145. Stresses in a viscous fluid due to shearing. 146. Heat produced by shearing. 147. Turbulent motion. 148. Distribution of velocity in a tube deduced from minimum heat production. 148A. Flow through tube of elliptic section. 149. Angular velocity of liquid between a fixed and a rotating cylinder found by minimum heat method [Pages 216 to 225]
- Experiment 22.** Determination of viscosity of a liquid.
 § 150. Introduction. 151. Method. 152. Calibration correction. 153. Practical example. 154. Notes on the method [Pages 225 to 235]
- Experiment 23.** Determination of viscosity of air.
 § 155. Introduction. 156. Calculation of velocity. 157. Calculation of pressure. 158. Correction for gravity. 159. Formula for viscosity. 160. Conditions for stream-line motion. 161. Experimental details. 162. Calibration correction. 163. Practical example [Pages 235 to 246]
- Experiment 24.** Determination of viscosity of very viscous liquid by viscometer.
 § 164. Introduction. 165. Elementary theory. 166. Stability of stream-line motion. 167. The viscometer. 168. Experimental method. 169. Practical example [Pages 246 to 254]

CHAPTER VIII

MATHEMATICAL DISCUSSIONS OF PROBLEMS
IN CONDUCTION OF HEAT

§ 170. Introduction. 171. Non-isotropic substances. 172. Difficulties of experimental work. 173. Steady radial flow from axis. 174. Non-uniform flow in a rod. 175. A simple conduction problem
[Pages 255 to 264]

CHAPTER IX

EXPERIMENTS IN HEAT

§ 176. Temperature. 177. Centigrade scales of temperature. 178. Mercury in glass thermometers. 179. International temperature scale
[Pages 265 to 269]

Experiment 25. Correction for the emergent column of a thermometer.

§ 180. Introduction. 181. Method. 182. Practical example
[Pages 269 to 273]

Experiment 26. Determination of thermal conductivity of copper.

§ 183. Introduction. 184. Apparatus. 185. Method. 186. Practical example. 186A. Correction for emergent columns [Pages 273 to 280]

Experiment 27. Determination of thermal conductivity of rubber.

§ 187. Introduction. 188. Theory of method. 189. Practical example
[Pages 280 to 284]

Experiment 28. Distribution of temperature along a bar heated at one end.

§ 190. Introduction. 191. Measurement of temperature by thermocouple. 192. Method. 193. Practical example. [Pages 284 to 294]

Experiment 29. Determination of mechanical equivalent of heat.

§ 194. Introduction. 195. Apparatus. 196. Method. 197. Calculation of correction for cooling. 198. Heat produced. 199. Work done. 200. Calculation of mechanical equivalent of heat. 201. Practical example. 202. Further discussion of correction for cooling [Pages 294 to 305]

CHAPTER X

MATHEMATICAL DISCUSSIONS OF
PROBLEMS IN SOUND

§ 203. Introduction. 204. Calculation of velocity of plane waves of sound [Pages 306 to 310]

SPHERICAL WAVES AND RADIATION OF ENERGY

§ 205. Spherical waves. 206. Radiation of energy. 207. Radiation from a pulsating sphere. 208. Radiation in a conical space
[Pages 310 to 319]

THEORY OF RESONATORS

§ 209. Kinetic energy of radial stream of liquid. 210. Resonators. 211. Frequency of resonator. 212. Criticisms of theory of resonator. 213. Correction of volume due to potential energy of air in neck of resonator. 214. Resonator with multiple and equal openings. 215. General case of multiple openings. 216. "Conductivity" of opening of resonator. 217. Opening in a thin plane plate. 218. Circular opening. 219. Elliptical opening. 220. Opening of any form. 221. Resonator with thin-plate opening. 222. Correction for thickness of plate. 223. Decay by radiation of vibrations in a resonator. 224. Application to Helmholtz resonator. 225. Radiation from resonator with tubular neck. 226. Effect of viscosity. 227. Distribution of velocity in circular opening in thin plate. 228. Dissipation of energy in resonator with tubular neck. 229. Comparison of Helmholtz with tube-neck resonator. 230. Selectivity of a resonator [Pages 319 to 344]

CHAPTER XI

EXPERIMENTS IN SOUND

Experiment 30. Effect of temperature upon velocity of sound.

§ 231. Method. 232. Practical example . . . [Pages 345 to 349]

Experiment 31. Resonance with a bottle.

§ 233. Introduction. 234. Method. 235. Practical example
[Pages 349 to 351]

Experiment 32. Resonator with multiple openings.

§ 236. Method. 237. Practical example . . . [Pages 351 to 352]

Experiment 33. Resonator with variable cylindrical neck.

§ 238. Introduction. 239. Estimation of F and H . 240. Correction for open ends. 241. Experimental details. 242. Practical example
[Pages 352 to 356]

Experiment 34. Resonator with thin-plate opening.

§ 243. Method. 244. Correction for edge effect. 245. Practical example
[Pages 356 to 359]

Note I. Awbery's method for combination of observations

[Pages 360 to 362]

Note II. Exact equation for spherical waves .

[Pages 362 to 363]

CHAPTER I

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 $ON \cdot P \sin \theta$. The momentum P has the component $P \cos \theta$ parallel to A , but this has no moment about A . Hence $ON \cdot P \sin \theta$ 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

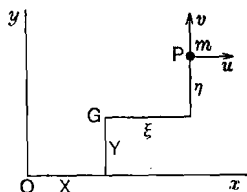


Fig. 1

* "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,

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

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,

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

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),

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

$$\text{and hence} \quad \Sigma m\alpha = 0, \quad \Sigma m\beta = 0. \dots\dots\dots(3)$$

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

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

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

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

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

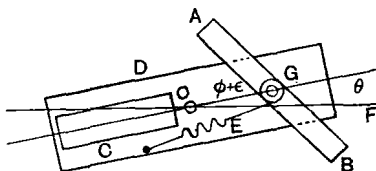


Fig. 2

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 .

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 $ad\theta/dt$, the momentum of M at G is $Mad\theta/dt$, 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