MECHANICS OF FLIGHT AS PART OF AN INTRODUCTORY PHYSICS COURSE

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Introduction

The study of mechanics is a basic part of nearly all first year physics courses at University level, and in elementary mechanics, more than in most other branches of physics, the presentation usually consists of a large selection of carefully chosen examples illustrating the application of the relatively small number of physical principles involved.

To many students the mechanics part of the course is dull. We do our best with the examples, and linear and rotational air-tracks have revolutionized the laboratory part of the course, but still much of the exposition fails to excite the interest of students.

In an attempt to improve this situation we have developed a presentation of related applications of physical principles based upon the theory of flight (or elementary aerodynamics). This is a subject involving a large range of mechanical principles which can be fairly easily dissected out, it is of considerable interest to young people, it is of obvious practical relevance, and useful laboratory experiments can be devised. Even biologists appreciate its application to the flight of birds and the structure of their wings.

This article describes briefly the way in which we are using this subject, not to be taught in its own right but as an illustrative vehicle for a mechanics course. It also describes the fundamental laboratory experiment which we have developed and our plans for further variety.

Theory of Flight

Because all our first year students have had a reasonable prior exposure to elementary physics, it is possible to introduce a discussion of Bernoulli's theorem for fluid flow before the course is too far advanced and to introduce the concept of dynamic pressure, $\frac{1}{2}\rho v^2$. The usual discussion of the Venturi and the Pitot tube then leads naturally to consideration of the force acting on a moving aerofoil. As shown in figure 1, this force **F** can be resolved into two components: the lift L acting perpendicularly to the airstream velocity v and the drag D acting parallel to it. From quite general considerations we can then define coefficients of lift and drag, C_L and C_D, by

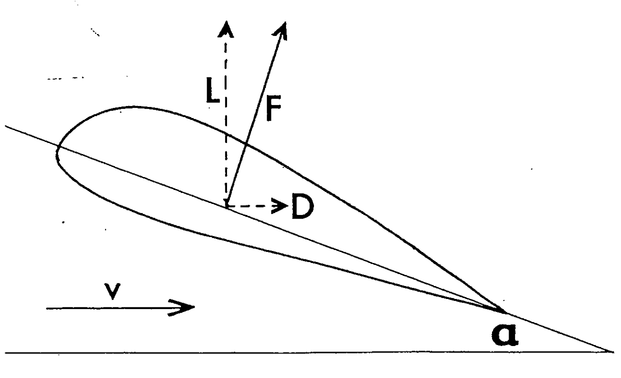

Figure 1

The resultant force **F** *acting on an aerofoil in motion resolved into a lift component L perpendicular to the airstream velocity v and a drag component D parallel to it. α is the angle of attack.*

$$L = \tfrac{1}{2}\rho v^2 C_L A \qquad (1)$$

$$D = \tfrac{1}{2}\rho v^2 C_D A \qquad (2)$$

where A is the area of the aerofoil.

It is clear that both lift and drag depend upon the angle of attack α, shown in the figure, and the experiment to be described later allows this dependence to be examined, in addition to verification of the form of equations (1) and (2). In particular the most efficient attack angle (that giving maximum lift-to-drag ratio) can be found and the phenomenon of stall, when lift decreases sharply with increasing attack angle, can be demonstrated.

A simple discussion of the propeller—a twisted aerofoil—and the jet as thrust producers is useful at this stage as it allows illustration of the relation between force and momentum change, as well as setting the stage for the next part of the development.

An aircraft can now be considered as a simple body acted on by thrust and drag (both parallel to the direction of motion but in opposite senses), by lift produced by the wings acting perpendicularly to the direction of motion, and by weight acting vertically downwards. This is an excellent system for illustrating a variety of mechanical problems and is far more interesting than blocks of wood sliding on rough planes or cyclists racing around banked tracks.

Simple level flight, climbing and diving situations provide useful examples and, of particular interest, we find that, if the thrust is set equal to zero, the angle of descent θ is given simply by

$$\tan\theta = C_L/C_D \qquad (3)$$

This leads to useful discussion of aircraft behaviour and of relative design features of heavy aircraft and of sailplanes, particularly if the original discussion of drag includes the notion of induced drag and its dependence on the aspect ratio of the wing.

Enlarging the glide problem to include the effects of a wind upon glide path relative to the ground is now simple and a wide selection of problems including wind-shear is possible.

Finally a discussion of an aircraft in a banked turn illustrates the essential features of circular motion and the 'g' forces produced by acceleration. It is not generally realised that the rudder is of very little effect in making a turn and that its real purpose is to compensate for minor unbalances in other forces. Almost the entire turning force comes from the centrally directed component of the lift produced by banked wings. Discussion of the problem is therefore simple and we find, for a turn of radius R,

$$\tan \theta = v^2/Rg \qquad (4)$$

where θ is the bank angle. Useful examples can be devised about optimum speeds for race circuits around pylons and similar problems.

The discussion can now easily be extended to calculate the load supported by the wings

$$L = W \sec \theta \qquad (5)$$

where W is the aircraft weight, and the g loading on the pilot,

$$g' = g \sec \theta \qquad (6)$$

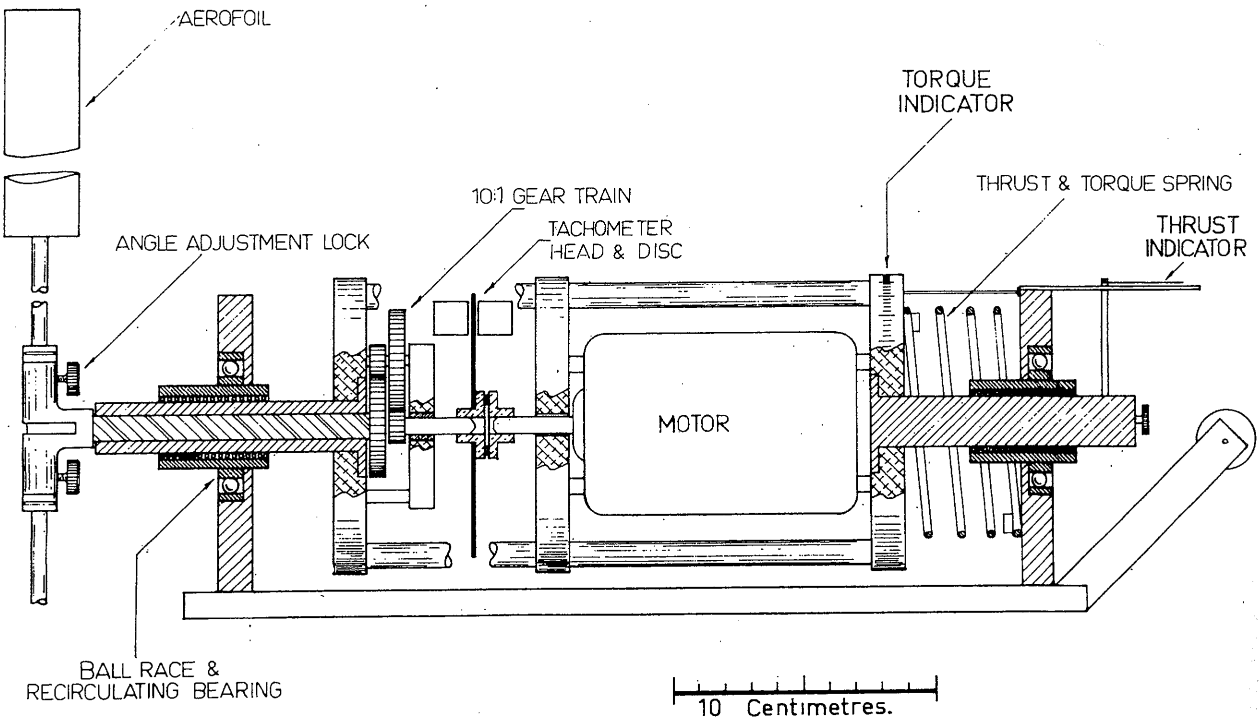

Figure 2

Construction of the experimental equipment. Calibrated scales read the forces exerted by the reaction spring.

A Laboratory Experiment

A small wind-tunnel for a laboratory experiment is clearly out of the question if hundreds of students working in groups of two must be accommodated. We have therefore devised an experiment in which two matched aerofoils are mounted on the ends of light rods and rotated about an axle. The airspeed varies about 30 per cent from the inner to the outer end of the aerofoil but this is not of any importance. The slight fan-effect can also be neglected and the aerofoils treated as though moving through still air.

The aerofoils are rotated by a variable-speed electric motor, freely mounted so that the thrust produced by the lift force and the torque produced by the drag are both taken up in a helical spring as shown in figure 2. The motor speed is measured by means of a simple electric tachometer.

After calibration of the reaction spring by means of a spring balance attached to the aerofoils, the apparatus is used to verify equations (1) and (2) and to determine C_L and C_D as functions of angle of attack. A more advanced experiment, carried out only by those interested, allows similar measurements to be made on wings of different aspect ratio and on wings fitted with flaps, slats and slots.

As examples of the sort of results obtainable with the equipment, figure 3 shows the measured dependence of L and D on v^2, of C_L and C_D on α and of C_L/C_D on α for an aerofoil with an aspect ratio (span/chord) of 3 and a fineness ratio (chord/thickness) of 6. Part of the scatter of points in the curve for C_L seems to represent a real departure from the simple curve drawn but this is best ignored and treated as the normal student error involved in a rather complex experiment. The measured lift coefficient is a little large and the stall behaviour is not very clearly apparent, probably because of the rather low Reynold's number achieved ($R \sim 3000$), but the measurements demonstrate the general behaviour quite convincingly.

The actual equipment was designed around an ordinary sewing-machine motor and more details of the

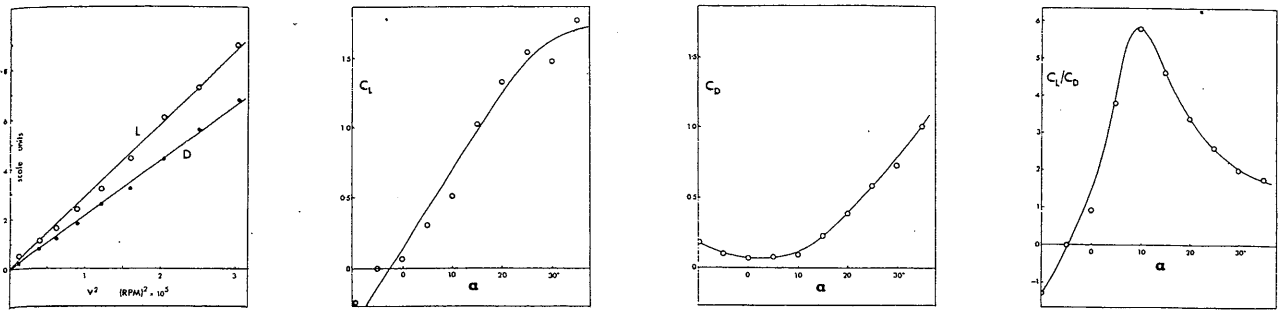

Figure 3

Experimental results for the dependence of lift L and drag D on airspeed v and for the dependence of the coefficients C_L, C_D and C_L/C_D on angle of attack α.

construction are shown in figure 2. The speed control supplied with the motor can be used, with the help of a screw clamp, but a small variable transformer is more convenient. Two-stage gearing provides a 10:1 speed reduction to the drive shaft. Simple mechanical indicators are used for the two reaction forces and the only really critical point in the whole assembly is the quality of the bearings supporting the motor. Combined bearings each consisting of a $\frac{3}{4}$-inch (2 cm) shaft of hardened steel (with a clearance hole for the motor drive shaft) supported by a recirculating-ball bearing inset into a ball race have been found to give adequately smooth motion in both directions.

To add further interest to the presentation, we are producing a short 16 mm film giving a pilot's-eye view of a banked turn, a stall and several other manoeuvres. A class experiment with powered model aircraft under radio control would have obvious student appeal, but is probably out of the question for most departments!

References

I have not been able to find any books at a level really suitable for this course. The references listed do, however, provide useful background material. To supplement standard physics texts we have therefore prepared a booklet which can be used for this part of the course, whether it is taught as an entity or, as I prefer, used primarily as a source of illustrative applications.

Acknowledgements

I am greatly indebted to Ken Dixon, Carl Merten and John Chapman for the contributions they have made to the design and construction of the experimental equipment.

References

"Modern Developments in Fluid Dynamics", ed. S. Goldstein (Oxford, Clarendon Press 1938).

"Essentials of Fluid Dynamics", by L. Prandtl (London 1952, Blackie & Son).

"Mechanics of Flight", by A. C. Kermode (London 1963, Pitman).

"Modern Airmanship", by N. D. Van Sickle (New York 1971, Van Nostrand Reinhold).

BOOK REVIEWS

A COURSE IN CONTINUUM MECHANICS, L. I. Sedov. Wolters Noordhoff, Holland, 1972. vol. 3 xx + 340 pp. vol. 4 xxi + 305 pp.

Reviewed by W. B. Fraser, Department of Applied Mathematics, University of Sydney, Sydney.

In volumes I and II of this work the general theory of continuum mechanics is set up. Volumes III and IV contain applications of this theory to fluid mechanics, and elastic and plastic solids, respectively. They are not entirely self contained, as reference is made throughout to the first two volumes. One particularly good feature of these two volumes on applications is the way in which the engineering theories of hydraulics and strength of materials are presented and related to the more general theory.

In the first chapter of volume III the description of the integral relations of fluid mechanics and the applications, particularly to pumps and gas engines, is excellent. The other two chapters of this volume contain a detailed treatment of potential flows, and a more introductory treatment of turbulence, boundary layer theory, and vortex motion.

Volume IV starts with a fairly conventional treatment of linear elasticity and variational methods. This is followed by a chapter on plasticity theory and finally a chapter devoted to plane elastostatic problems and a brief account of crack theory.

Each volume contains a summary table of contents for all four volumes and volume IV has an overall subject index.

I feel that most readers of these volumes will already have some familiarity with the usual material contained in undergraduate courses on elasticity and fluid mechanics, and I was disappointed that the author did