
Some Aspects of Aeronautical Research in the United Kingdom

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The paper selects for brief discussion a very few of the successful aeronautical researches conducted in the United Kingdom in recent years. The selection includes illustrations of the work of Government Establishments, of Industry, and of Universities. Moreover, the choice made is intended to exemplify the principal fields of activity of the Aeronautical Research Council, as represented by its Standing Committees and group of Special Committees: aerodynamics, mechanics, propulsion, and special topics. The paper concludes with a plea for continued research on as large a scale as possible.

I. APOLOGIA PRO RATIONE SUA

... with one consent began to make excuse — LUKE 14, 18

To be asked, in the Centenary year of the Royal Aeronautical Society, to deliver a lecture lasting 45 minutes and dealing with the highlights of aeronautical research in the United Kingdom during an unspecified period, poses a problem in selection which is obviously well-nigh insoluble. One's choice of topics must necessarily be arbitrary, personal, and very limited. The fact that the Society is a hundred years old would provide an excuse for a historical survey, beginning with Cayley — surely the father of aeronautical research and, therefore, of aviation itself — and dilating on Wenham's first paper⁽¹⁾ to the Society — then the Aeronautical Society of Great Britain — which was the first research body in aeronautics. But there have been many excellent historical surveys, and it therefore seemed to me to be more appropriate to try to discuss some recent work. In any case, the invitation to lecture on this subject was not extended to me personally, but to the Chairman of the Aeronautical Research Council, which office I happen to occupy at the moment: there is no significance in the fact that I happen also to share the A.R.C.'s initials.

I shall therefore restrict myself to a very few of the topics in which the

Council has taken an active interest in the last few years. This limits my field for selection in time, but not to any extent in compass: although I am, of course, subject to the obvious limitations posed by national and commercial security. In making my arbitrary and personal selection, I am all too conscious that there remain many valuable researches which cannot be included, and that I must at the outset apologise to the workers in these fields. This I do without reservation. I must also thank the many friends and colleagues who have supplied me with information. The choice of topic has been mine only; but having made it, I invited the experts in each of my chosen fields to help me draft the lecture. They are, for the most part, mentioned in the text; to them and to any others who have helped I offer my warm thanks. I am also indebted to Sir Walter Cawood, Chief Scientist, Ministry of Aviation, and to Handel Davies, Executive Officer of the A.R.C., for their help in the promotion of the lecture.

2. THE AERONAUTICAL RESEARCH COUNCIL

There be three things which are too wonderful for me, yea, four which I know not — PROVERBS 30, 18

Although it cannot compete in age with the Royal Aeronautical Society, the Aeronautical Research Council is nevertheless a very old body; it was founded in 1909 as the Advisory Committee for Aeronautics, and Lord Rayleigh presided over its deliberations and reported on them to the Prime Minister. Its first Report ⁽²⁾ was published at a price of ½d. by H.M.S.O. For the past fifty years, it has been the duty of the A.R.C. to tender advice to the Minister responsible for the principal Government Research Establishments; and, in its modern guise, its terms of reference are very widely drawn. Not only is it concerned with research carried out at the Establishments, but also with industrial and university research in aeronautics; it is also required to keep in touch with research in the Commonwealth. It has a duty to consider, so far as they affect research, matters connected with aeronautical education. Finally, it is charged with the publication of the results of research; the well-known Reports and Memoranda series is nearly as old as the Council, and the Current Papers series is now well established.

In the discharge of its duties, the Council is assisted by three Standing Committees, each of which has a group of technical Sub-Committees and Panels, and by a fourth group of Special Committees: in all, there are upwards of two dozen bodies within the Council organisation. The three Standing Committees are concerned with the general subjects implied by their titles: Aerodynamics, Mechanics, and Propulsion. In the fourth group are Com-

mittees such as Noise Research, Powered Lift, Civil Aircraft Research, and Gust Research.

This breakdown of the interests of the Council suggests at once groups from which topics for this lecture may properly be drawn; and this is the plan I have adopted. Moreover, in selecting topics from each of the four main groups, I have tried to give examples of work done in the Establishments, in the Industry, and in Universities.

3. AERODYNAMICS

3.1. High speed

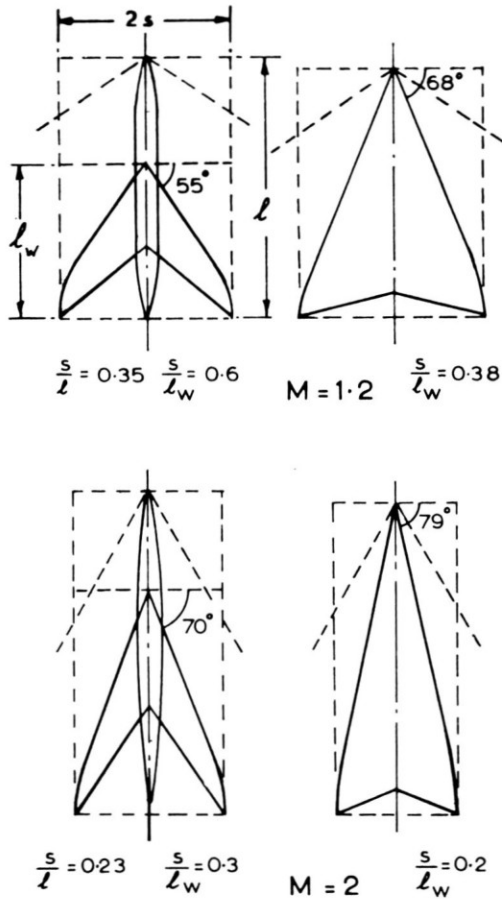
Thou shalt not be afraid . . . for the arrow that flieth — PSALM 91, 5

The development of planforms for supersonic speeds represents, in my view, one of the outstanding successes of fundamental research in this country. As long as twenty years ago, the evident potential of the gas turbine made it clear that supersonic flight must come; but suitable aerodynamic shapes for the purpose were quite unknown. The obvious studies of conventional straight wings were made at an early stage, and revealed that aircraft with such wings must be uneconomic; but perhaps more ominous were the difficulties of equilibrium, stability, and control associated with transition from subsonic to supersonic speeds, and the even worse troubles in the transonic regime due to the mixed flow conditions existing in it. However, swept and delta wings seemed more promising, and by 1956 a fair body of subsonic experience with these shapes had accumulated, while in that year the Fairey Delta 2 established a World Speed Record at a Mach number of 1.7. At the same time, Dr. D. Küchemann and his team at the Royal Aircraft Establishment had begun studies of sharp-edged slender wings, a delta variant which looked distinctly promising for economic flight at supersonic speeds. Up to that time, thinking about supersonic conditions had been largely dominated by notions of attached streamline flow; the R.A.E. work on separated flow opened up a completely new avenue of possibilities.

To examine these and related matters, the Ministry therefore set up the notable Supersonic Transport Aircraft Committee, chaired by M. B. Morgan, now President-Elect of the Royal Aeronautical Society. In its deliberations, the Committee considered, *inter alia*, straight, cranked, swept, slender, and yawed wings. It is of slender wings that I want particularly to speak today, since they have emerged to occupy a dominant place in British thought.

In a brief record of this kind one cannot go fully into the development of a research which, being conducted by a group and calling on the help and ideas of many others, grows organically; much more complete descriptions have been published elsewhere.^(3, 4) I can only trace two threads.

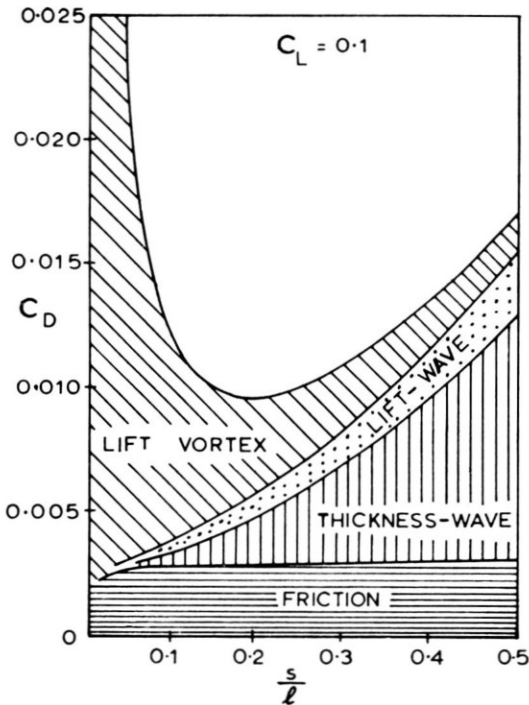
First, there was a general enquiry. The group looked back at conventional subsonic aircraft, to ask what features had made them suitable for their particular phase of aviation: they used in particular the Bréguet range formula, since this incorporates aerodynamic, structural, and propulsive characteristics as well as range, a main objective of transport flight. This, of course, tied up well with the known aerofoil, planform, and engine characteristics of conventional aircraft. A parallel investigation for supersonic conditions was then instituted; engines of constant thrust were stipulated in place of those of constant power, the expression for drag was modified by the addition of wave terms deriving from lift and volume, and so on. From this study there emerged, in place of the conventional aspect ratio, three geometric parameters: the semi-span to length ratio s/l of a 'box' enclosing the planform,



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FIG. 1 — The circumscribing box

the ratio p of planform area to the box area, and a volume parameter τ (Fig. 1). Then, for any given cruise condition, that is, for fixed Mach number, altitude, lift coefficient, and hence area, the parameters could be varied to find their optimum values. Thus, for example, affine transformations on the 'box' would determine optimum s/l (Fig. 2), and so on.



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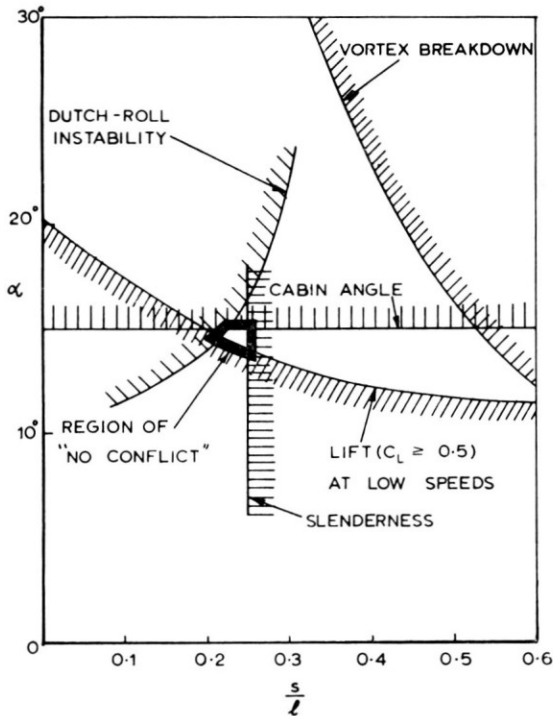
FIG. 2—Typical drag coefficients
 $M=2$ $p=\frac{1}{2}$ $\tau=0.04$ $S=6000 \text{ ft}^2$

So far, this was very general, and (*post hoc, propter hoc*) a fairly obvious line of thought. I must now turn to the second thread, the work on slender wings which was going on simultaneously, since it became apparent that the slender wing fitted the requirements of the parametric study admirably.

The important results of the work on slender wings are as follows. If the shape is roughly that of a dart, and if the leading edges are sharp, then over the upper surface the flow separates at the leading edge for any practical incidence; the resultant vortex sheets roll up into stable vortices which induce considerable suction over the upper surface. Moreover, provided the leading edges are always well within the Mach cone from the apex and are therefore subsonic, there will be no shocks on the wing surface in any flight condition.

Thus the flow is steady and stable; it changes quantitatively with Mach number and incidence, but remains qualitatively of the same type. This is perhaps the major virtue of the slender wing, but others emerged from the study. Provided the drag-producing volume and lift are carefully distributed, good economic values of lift-drag ratio are achieved for the cruise condition; and the vortex system gives a non-linear lift-incidence relation which is advantageous in the approach. Finally, tests of hand-launched models indicated that general flying characteristics would be very satisfactory.

As I have said, the slender wing, with these properties, was found to fit admirably into the parametric study. As a numerical illustration, for $M \sim 2.2$, $C_L \sim 0.1$ the optimum s/l is in the region of 0.25 or less; this fits neatly with the requirement for subsonic leading edges. The optimum distributions of lift and volume suggest a value for p around 0.5, the value for a delta wing; this approximate shape is that which gives orderly development of the vortex system. It remained to choose an actual shape; much work was done on such things as streamwise tips and camber. Even when an optimum choice has been made, there are, of course, quantitative limitations, such as are illustrated by Fig. 3, which shows an approach condition. The cabin angle must



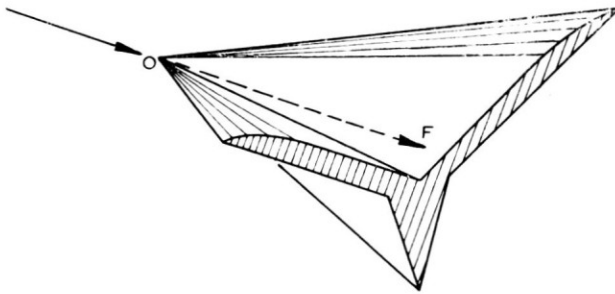
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FIG. 3 — Various typical limitations

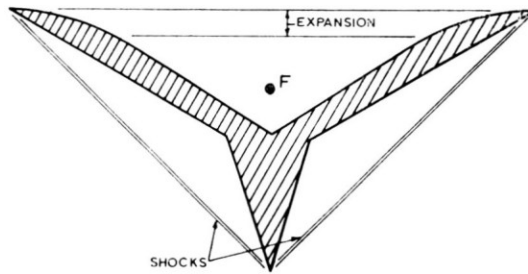
not be too great (e.g. 15°); the limit on s/l has been stated (0.25); lift coefficient must be high; Dutch roll and vortex breakdown (which can produce severe buffeting) must be avoided. But, as the Figure shows, these conditions can be met.

Here I conclude this brief review of the R.A.E. work on slender wings, remarking only that it is still continuing and that it includes work on experimental aircraft.

Before I leave the subject of high speed, I want to mention briefly one other relevant device, namely, the waverider. It was Professor T. E. Nonweiler of Glasgow University who suggested⁽⁵⁾ fitting a shape to a known plane shock; intuitively, one feels that such a system, since it gives constant pressure, is likely to be efficient and is worth study. J. W. Flower of Bristol University extended the concept⁽⁶⁾ by suggesting shapes to fit prescribed expansions, and showed that a large number of shapes with surfaces of single curvature could be incorporated in a waverider vehicle employing shocks and expansions; Fig. 4 shows a simple example. But most of the practical work on these shapes — including off-design studies, both



(a) PERSPECTIVE VIEW



(b) SECTION THROUGH TRAILING EDGE

FIG. 4 — Y-Delta waverider

theoretical and experimental — has been conducted at the R.A.E., and it appears that they have considerable promise for high Mach number flight. Since they employ strong shock (and expansion) attached flows, they form a new category of aircraft, but the type can well be regarded as a member of a developing series — classical, swept wing, slender wing, waverider aircraft — for progressively increasing Mach numbers⁽⁷⁾; the parametric studies mentioned earlier are the basis of the studies of waveriders, as of the other aircraft types.

3.2. Low speed

These ought ye to have done, and not to leave the other undone — MATTHEW 23, 23

In the thirty-odd years during which I have been connected with aviation, top speeds of aircraft have increased by a factor of ten, and conditions of flight from those in which Mach number effects were completely unimportant (except perhaps for the tips of propeller blades) to those in which compressibility of the air is a dominant characteristic. This enormous rate of advance has been preceded and prompted by appropriate research work, which has absorbed, not only in the United Kingdom, but throughout the world, much of the available research effort. In consequence, there have been many areas of subsonic flight which have been somewhat starved of research: in eagerly questing forward, we have tended to forget the old proverb that the best is the enemy of the good. One field of aviation starved of effort was pointed out to the Royal Aeronautical Society by its present Honorary President, the Duke of Edinburgh, when in 1954 he delivered the Tenth British Commonwealth and Empire Lecture⁽⁸⁾.

In this rapid advance, then, we have not been able to consolidate fully, and there are still many *lacunae* in our knowledge of low speed effects: and this despite the obvious fact that the low speed field is of vital importance even for supersonic aircraft. So far as the United Kingdom is concerned, there are many low-speed researches in progress which relate directly to modern advances; there are also areas where we are seeking to fill gaps in our knowledge which might have received attention much earlier had the pace of advance been slower and less demanding. It is of one or two of these gaps that I now want to speak.

The subject of aircraft drag at sub-critical Mach numbers is providing a major area of 'filling-in' research. Such a big subject obviously involves effort in industry, establishments, universities, learned societies, and elsewhere; it involves not only the finding of new information, but the analysis and correlation of the large amounts of existing data; and it requires a central focus. In the latter connection I must mention the part being played by A. B. Haines of the industry's Aircraft Research Association.

Drag is, of course, a difficult phenomenon: the number of contributory causes is legion, and some of them — e.g. pressure drag — are in the nature of small differences between large opposing forces. Nevertheless, it is surprising and salutary to realise that in this day and age, errors of drag prediction — even in the absence of shock waves, and even when based on wind tunnel tests rather than theoretical estimates — can sometimes be so large as almost to make nonsense of performance and economic studies. Current research aims at finding reasons for this, which in turn implies trying to obtain a real understanding of the origins of drag.

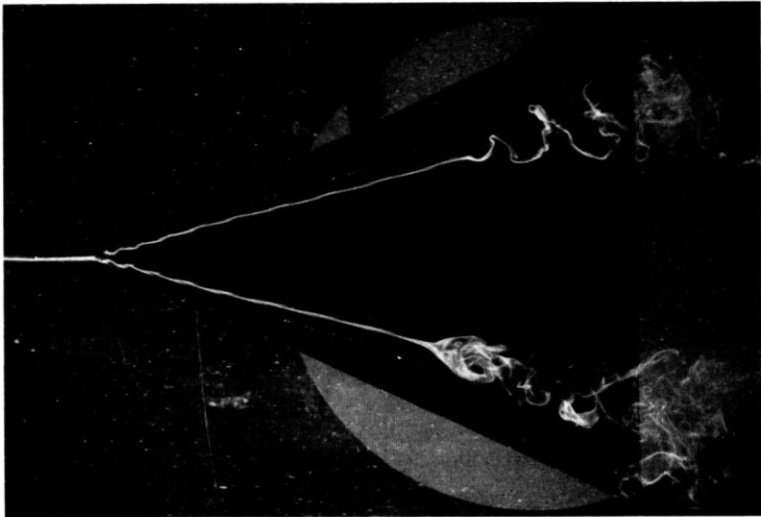
At speeds just below the critical there are, of course, Mach number effects; these are combined with Reynolds number effects, and the two are usually inter-dependent. At the N.P.L. and the R.A.E., new methods have been developed for taking account of these effects in the estimation of drag of two-dimensional aerofoils. The methods seem very promising, giving good agreement with experiment; for example, the calculated drag of an 18% thick aerofoil at $M = 0.68$ is in good agreement with both wind tunnel and flight measurements, whereas earlier methods are about 10% in error⁽⁹⁾. Attempts are now being made to extend the new method to three-dimensional swept wings. This will require a good deal of special experiment to provide a sound basis for comparison with the predictions. Methods of estimation of nacelle and body drag are also required; it seems, for example, that there can be surprising changes of nacelle drag with such things as geometry, Mach number, or mass flow. These changes may be due to interference, which in any event is a subject needing a new look: interference drag seems to vary in sub-critical conditions over much wider limits than at very low speeds, and to be much more sensitive to the relative positioning of components. As regards body drag, the upswept fuselage which goes with a high tail is now under scrutiny, while drag due to roughness and minor excrescences is only imperfectly understood. On the experimental side, in wind tunnel tests of models, it is by no means certain that such things as present techniques for representing intake and jet efflux effects are valid; finally, since the proof of the drag pudding is in the flying, for a satisfactory solution of these problems, we need first, more carefully calibrated flights, and second, more comparisons of wind tunnel and flight experiments.

All this sounds like a sea of troubles, and certainly it all adds up to a large and important research. It is interesting to observe, however, that many of the difficulties I have mentioned will be amenable to solution when we are able to understand and predict the behaviour of three-dimensional turbulent boundary layers. Much attention is being given to this fundamental subject, which holds the key to many of our problems in fluid mechanics.

In the only other research I have time to mention, no great amount of effort is being deployed, but the subject is both interesting and important: the decay and break-down of longitudinal vortices. An analytical solution of

the problem of decay of a two-dimensional laminar vortex was given in his classical book *Hydrodynamics*⁽¹⁰⁾ by Lamb; but the subject was neglected until recently. Two things have revived interest in it: the persistence near the ground of the wing-tip vortices from a heavy aircraft leaving an airfield, so that minutes later a light aircraft can be dangerously affected, and the instability and break-down of the vortices over a delta wing, which can cause serious buffeting.

On the question of decay of a vortex, studies have been made for both laminar and turbulent conditions by a number of people, from among whom one should perhaps single out the late Professor H. B. Squire⁽¹¹⁾. The matter is still attracting attention. On the vortex pair over a delta or slender wing, some very interesting work is being conducted at the N.P.L. by N. C. Lambourne. For a wing with highly swept, sharp leading edges at small incidence, the flow is steady and orderly, with two stable vortices above the wing; farther downstream the vortex pair breaks up. As the wing incidence is increased, or perhaps if it is yawed, the break-down point of one or both vortices moves forward: when with sufficient incidence it arrives above the wing, buffeting results. The break-down can occur in either of two forms, both of which are beautifully illustrated in Fig. 5, for which I am indebted



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FIG. 5 — Vortex bursting

to the N.P.L. The photograph shows dye traces in the water flow past a sharp-edged delta wing at 23° incidence. In one vortex, an almost axisymmetric bursting appears; in the other, the vortex suddenly develops a 'coiled coil'

form, twisting in a sense opposite to its own rotation. It may well be that studies of this kind may give us some insight into the generation of turbulence, that major unknown of fluid mechanics.

4. MECHANICS

4.1. Materials

Yea, a man of knowledge increaseth strength — PROVERBS 24, 5

One of the most promising and exciting developments of recent years is in the field of composite materials, which consist of bundles of very strong fibres (or of 'whiskers', which are single crystals grown with no dislocations) stabilised and supported by a surrounding matrix of some appropriate material which is fluid when the composite is being made. There is a very wide range of substances suitable for fibres, and another for the supporting matrices. At present, the commonest composite material consists of glass fibres in a matrix of plastic or resinous substance; as is well known, this is for many purposes very good, although it has limitations both in manufacture and use. It has become usual to describe such a material as 'fibre-reinforced plastic', but a better phrase is 'plastic-supported fibres', since the fibres provide almost all the important structural properties: the resin prevents damage to the fibres, effectively joins them and makes them resistant to bending.

At the R.A.E., a team including W. Watt, L. N. Phillips and W. Johnson has developed a process for the production of carbon fibres of almost indecently large specific strength and stiffness. Many of the details of this development are still classified, but I am able to say that a synthetic textile fibre is converted by controlled pyrolysis to carbon, the graphitic crystallites of which are very well aligned along the fibre axis. The fibres so produced have diameters of about 6 microns. In the table (Fig. 6) a comparison is given between some of the properties of high tensile steel, glass fibre, and

| | Steel S. 99 | Glass Fibre | R. A. E. Carbon Fibre | Carbon Com posite |
|---|----------------|----------------|-----------------------------|-------------------------|
| Specific gravity | 7.87 | 2.54 | 1.95 | 1.54 |
| Strength (tensile), psi x 10 ⁵ | 0.19 | 0.25 | 0.30 | 0.105 |
| Stiffness (E), psi x 10 ⁶ | 30.0 | 9.0 | 60.0 | 22.0 |
| Specific strength, psi x 10 ⁶ | 0.024 | 0.10 | 0.15 | 0.068 |
| Specific stiffness, psi x 10 ⁶ | 3.8 | 3.5 | 31.0 | 14.0 |

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FIG. 6 — Specific strength and stiffness

carbon fibre; also included are the properties of a composite containing 50% by weight and 40% by volume of carbon fibres.

It will be seen that the specific stiffness of the carbon fibre is an order greater than that of steel or of glass fibre. However, the important comparison is between the first and last columns: it appears that, even at this comparatively early stage of development, the specific strength of the carbon fibre composite is three times and the specific stiffness four times, that of high tensile steel.

The fibre is easily handled and does not appear to suffer from processes such as rolling or moulding; the bundles are very readily wetted by a variety of thermo-setting polymers; and the fibre surfaces are chemically inert, having no effect on the curing of resinous matrices, and being resistant in many conditions for which glass fibre would be unsuitable.

The strength and stiffness quoted are, of course, in the direction of the fibres; but it is clearly possible to mould, for example, a spar with a fork or lug end to achieve desirable properties around fixing bolt-holes. Altogether, the variety of possible applications is almost bewildering, not only for aerospace application, but in almost every field of engineering, and not only for static or quasi-static components, but also in mechanisms: the reinforcement of self-lubricating materials such as nylon is perfectly possible. I will leave my audience to invent applications for themselves.

Before leaving the subject of materials, I would like to add a word or two about a development in the study of (quasi-static) crack propagation. A prime consideration in the choice of engineering structural materials is their resistance to the propagation of cracks, which is characterised by the local specific work of tearing, R . Values of R are usually obtained from experiments, in which the load at which a crack spreads unstably is recorded. Deduction of the R values then involves a knowledge of the elastic stress distribution in the cracked test piece.

At Cardiff, Professor H. C. H. Gurney has developed a general theory of quasi-static crack propagation and has formulated the conditions for stability under monotonically increasing load and displacement⁽¹²⁾. He has shown that by suitable choice of test piece geometry, stability may be achieved and a plot of load and deflection as the crack spreads may be drawn experimentally. From this plot R values may be readily deduced without knowledge of the elastic stress distribution. He has obtained R values for glass, plastics, metal-to-metal adhesives, aluminium alloys and steel. For sheet materials under predominantly tensile stress at the crack front the R values are sensibly independent of the stressing conditions, but may vary significantly with the speed of the crack front. Gurney has also proposed a postulate governing the spatial path of a quasi-static crack: for an isotropic material the crack path is such that the rate of increase of the elastic compliance with crack area is greatest.

This important subject is, of course, still a continuing field of research at many centres in the United Kingdom.

4.2. Structures

Wisdom hath builded her house, she hath hewn out her seven pillars —
PROVERBS 9, 1

One of the highlights of British achievement in structural and dynamic analysis is the work done over the past fifteen years by Professor J. H. Argyris and his collaborators at Imperial College.

The use of matrices for limited forms of structural analysis was well established⁽¹³⁾ when the work began; but it was Argyris who recognised that the enormous potential of the emerging digital computer, allied to a consistent idealisation of the actual system in terms of matrices, would revolutionise the scale of thinking about structural problems. In the intervening years, Argyris has amply demonstrated the validity of this concept^(14,15,16). Initially conceived for the treatment of linear deformations of aircraft structures, his ideas have been extended to structures in all forms and to continuum mechanics; they can now treat non-linear elastic and plastic behaviour, including strain-hardening and the effects of large strains and deformations; and they have resulted in considerable developments in matrix theory and application.

Basically, whatever the system or continuum may be, it is represented by an aggregate of finite elements, which may have various geometries, and which are connected at appropriate 'nodal points'. Two methods of analysis, which may be mixed, are then available. In one, the matrix force method, static compatibility conditions are satisfied everywhere and kinematic conditions principally at the nodal points; in the other, the matrix displacement method, the kinematic compatibility conditions are satisfied everywhere and the static conditions correspondingly at the nodal points. For each element an individual, simplified behaviour pattern is prescribed. Evidently, by sufficiently increasing the number and complexity of the elements, a solution of the problem to any required degree of accuracy is achievable. Sizes and shapes of elements may be varied to suit the details of the problem; for example, in some analyses of stress concentration problems, triangular elements with sides of less than 100 microns have been employed. Application of the method to test problems having known exact solutions has shown that excellent engineering accuracy results.

Here I can give only three illustrations, all of which relate to non-linear problems. Fig. 7 shows the effect of uniform endload on a square rubber plate having a circular hole. It will be seen that the deformations and strains are very large; nevertheless, experiment agrees very well with the calculated planform changes. The same is true of thickness changes. Fig. 8 shows the

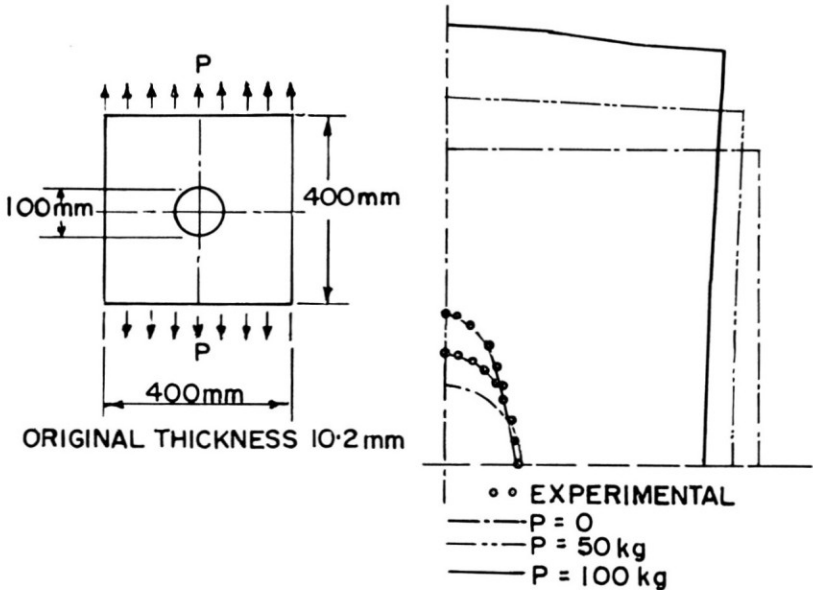


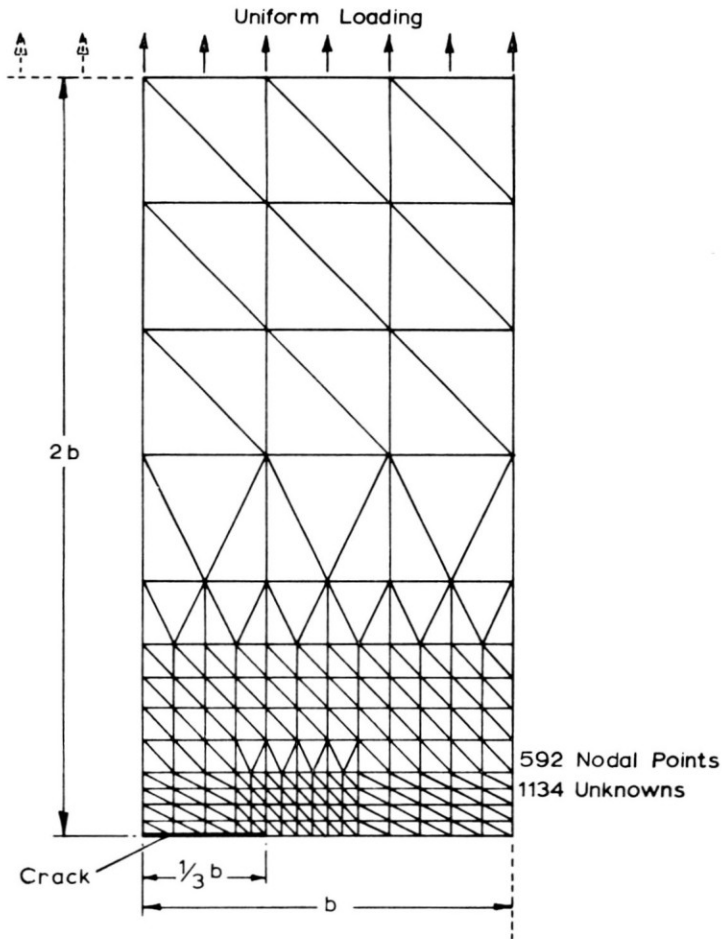
FIG. 7 — Rubber plate analysis

representation by triangular elements of a plate with a crack; under the influence of end load, plastic deformation occurs round the end of the crack: the calculated limits of the region of plastic flow are also shown. Finally, the snap-through instability of a hinged arch under off-set load is shown in Fig. 9; this also is a large-displacement problem.

Other problems for which the methods have been used include those of flutter and vibration, in which matrices of very high orders were employed, and those of optimisation: for example, the determination of structures of least weight, cost, or other criteria when there are many parameters involved.

A *sine qua non* for all this work is, of course, a very large and fast computer. Equally essential has been the associated software: progressive development of sophisticated computer programming languages, both pure systems for matrix interpretation and applied systems, orientated, for example, towards the automatic solution of structural problems by the displacement method. The development of these languages has occupied much of the time of Argyris and his group in recent years, and at least one remarkable new language, having recursive or self-adaptive properties, has been evolved.

Before I leave the subject of structural research, my mention of optimisation procedures prompts me to refer to a study, in which Professor W. S. Hemp of Oxford and H. L. Cox of the N.P.L. have taken a leading part, of Michell structures. Michell's original work⁽¹⁷⁾ on structures of minimum



Semi Crack
(One Quarter of Plate Shown)

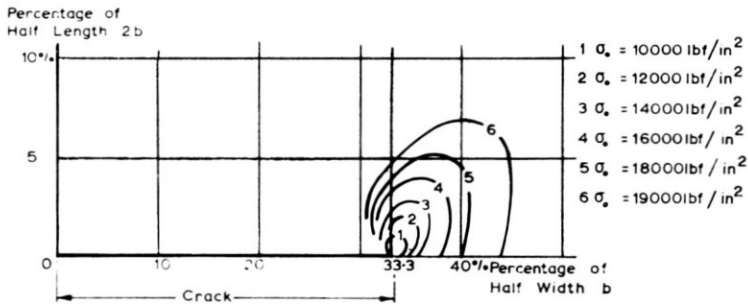


FIG. 8 — Extent of plastic deformation

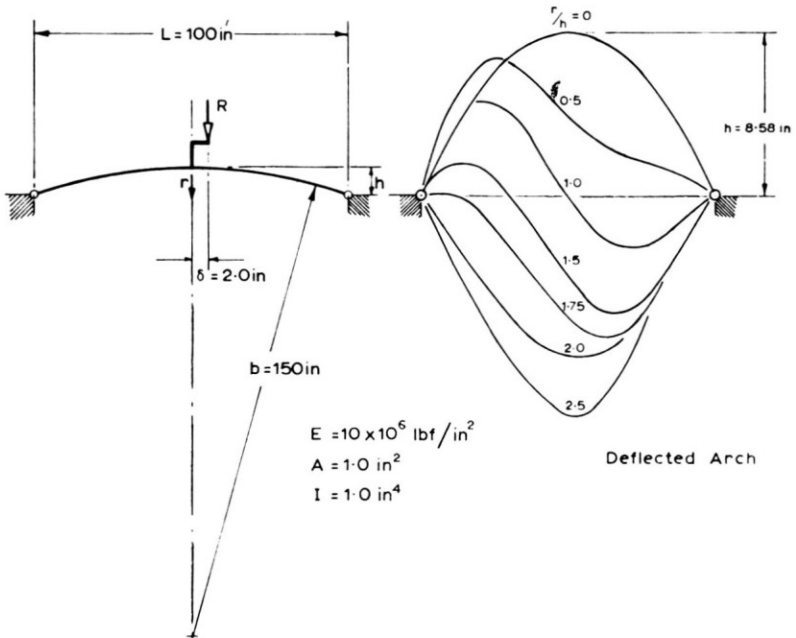


FIG. 9 — Snap-through of hinged arch

weight to support a given load has been overlooked for about fifty years. It appears that a Michell structure is the absolute optimum for a given duty, and so provides a basis for a criterion of the efficiency of an actual structure, which has been compared with the criterion for the efficiency of a heat engine given by the Second Law of Thermodynamics. Michell's original work related to plane or space frameworks, but the recent work has shown that his ideas can be developed for plate structures. For structural problems of any complexity, the mathematical computation of optima will require the use of computers; but the increasing availability of such facilities suggests that the understanding and use of Michell's principles should be of real practical help to designers.

5. PROPULSION

5.1. Engines for V/STOL

Behold, there appeared a chariot of fire — II KINGS 2, 11

I remarked earlier that in the past thirty-odd years aircraft speeds have increased by a factor of ten. In a shorter period, gas turbine thrusts have been

increased from the original 500 lb. of Whittle's engine by factors of up to fifty, and it seems certain that much larger figures still will be achieved: we are told in the press that the American 'jumbo jets' will be powered by engines of up to 40,000 lb. take-off thrust. All this implies that much of the spectacular advance of aviation can be credited to engine research and development. Many of the advances, from the original Whittle engine onward, have been made in the United Kingdom: the British aviation industry has been in the forefront of practically all the spectacular developments which have taken place in aircraft propulsion.

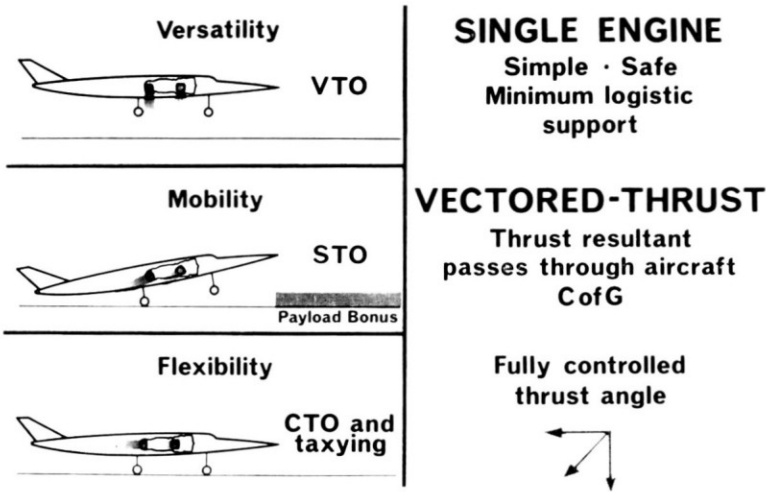


FIG. 10 — Vectored thrust characteristics

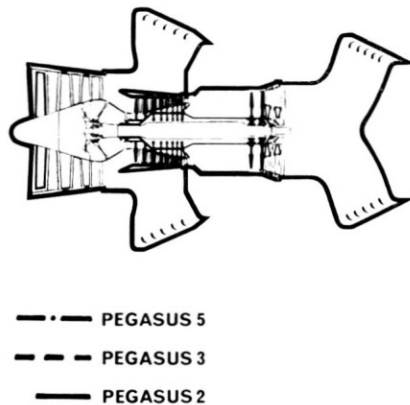
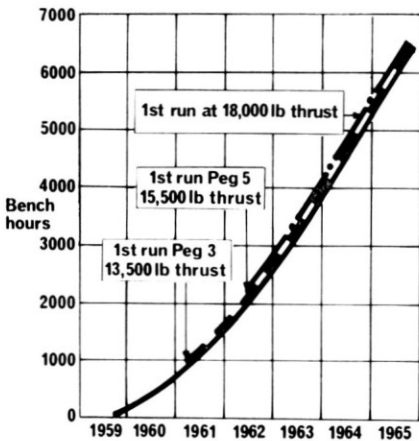


FIG. 11 — Pegasus development

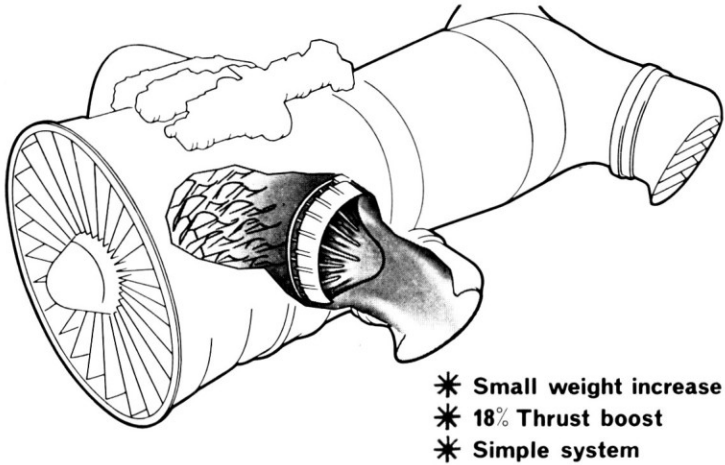


FIG. 12 — PCB arrangement

Since I have to limit myself severely here, I shall speak of only one application: engines for vertical and short take-off and landing. In this field, Rolls-Royce have specialised in the light-weight lifting engine, and Bristol Siddeley have evolved the vectored thrust concept. If I may deal with the latter first, I shall begin by allowing a short B.S.E. film† to describe the system and some of its properties for me. The film shows clearly that vectored thrust is a powerful V/STOL propulsion system, with many virtues. Some of its characteristics and advantages are set out in Fig. 10, while the past development history of the Pegasus engine is illustrated in Fig. 11. Plenum chamber burning (P.C.B.) — combustion in the by-pass air from the fan, for added thrust — is illustrated in Fig. 12; there is a special premium on high take-off thrust because of the added fuel which can be lifted.

Since it is research with which I am concerned today, may I just list for consideration five points.

- (i) The vectored thrust engine demanded a high by-pass ratio at a time when these ratios were small. This in turn demanded the highest possible flow per frontal area of the fan.
- (ii) To achieve (i) the engine has been designed with an overhung, transonic fan of rugged construction, with no inlet guide vanes; no anti-icing is therefore required.
- (iii) The nozzles, even though carrying hot gases, are simultaneously operable through 100° in one second.

† I am indebted to Dr. S. G. Hooker of B.S.E. for this film and the related figures.

- (iv) With a minimum of bearings, contra-rotating spools are used.
- (v) P.C.B., by boosting thrust for take-off and landing, enables a smaller basic engine to be used; but it required research on variable nozzle area and on special combustors.

If we think of the solution of these problems, we must, I suggest, concede that the development of the vectored thrust engine resulted from engineering research of the highest order.

I now turn to the light-weight lifting engine for VTOL, which has been pioneered by Rolls-Royce. Their famous Flying Bedstead experiment proved the possibility of stable and controllable jet-borne flight; specialised lift-jet engines were then developed for the first practical demonstration of vertical take-off in the Short S.C.I. Their light-weight lifting engines are now employed in the E.W.R.-Sud VJ 101 C in Germany and in the Dassault Mirage III V in France. The special problems which have demanded intense research effort are in this case:

- (i) Achievement of high thrust-weight ratio.
- (ii) Necessity for very rapid thrust response.
- (iii) The intake in the transition phase.
- (iv) Ground erosion and hot gas reingestion.
- (v) Jet deflection and engine swivelling.

Here also, engineering research of the highest order has provided the



FIG. 13 — Three generations of lift-jet

necessary solutions. Fig. 13† shows three generations of engine, with thrust-weight ratios rising to 20: it is of interest to note that emphasis is today being placed also on high thrust-volume and thrust-cost ratios. The achievement of these remarkable ratios is, in part at least, the result of a long and large programme of materials research, in which composite materials — the latest is HYFIL — are playing no mean part.

As regards rate of response, Fig. 14 shows that very rapid thrust changes

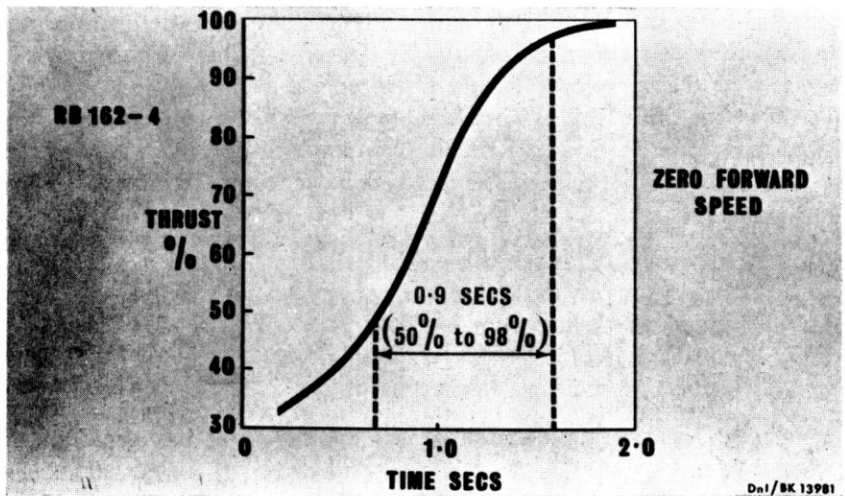


FIG. 14 — Lift-jet thrust response

are possible. The need for this in a VTOL machine was demonstrated by the Flying Bedstead experiment; its achievement has made it possible to use differential engine thrust modulation for stability and control of the VJ 101 C.

A major problem for a lifting engine is clearly that of achieving a smooth airflow into the face of the compressor during the transition phase. Rolls-Royce have done much work on this, examining such variants as flush intakes, scoops, and cascade intakes with different numbers of vanes. As a result, much know-how has been accumulated; although every new application will require further investigation.

Some of the factors affecting ground erosion are listed in Fig. 15. Once a surface begins to break up, erosion is rapid, and for loose surfaces some binding agent or protective covering may be needed. However, such requirements clearly limit the flexibility of an aircraft, and accordingly research has been directed to the reduction of the erosive effects of both lift-jets and pro-

† I have to thank A. A. Lombard of Rolls-Royce for these Figures.

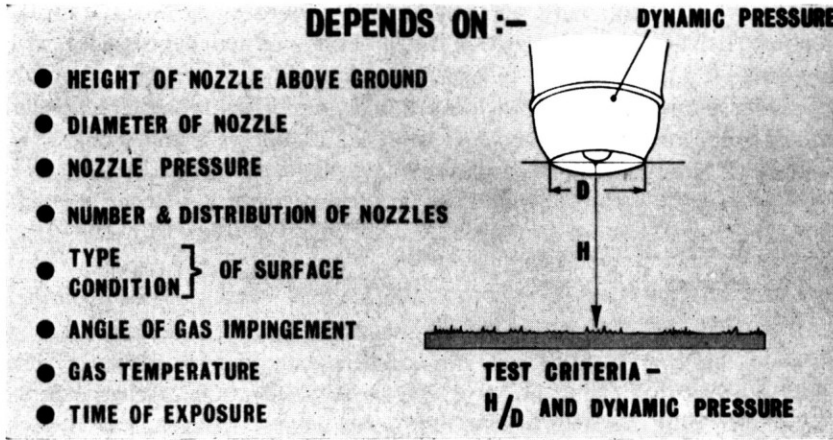


FIG. 15 — Ground erosion

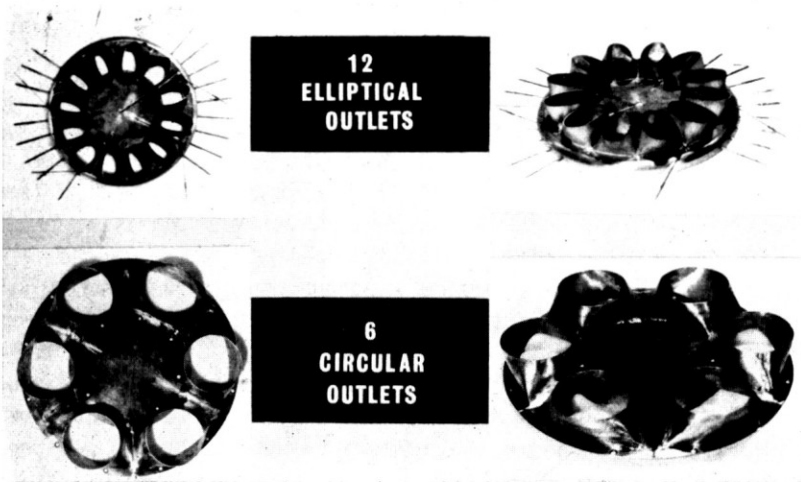


FIG. 16 — Rapid mixing nozzles

pulsion engines with deflected thrust. As a result, rapid mixing nozzles have been evolved (Fig. 16) which appear to have gone far in the solution of the erosion problem. Eroded material can, of course, be ingested into the engine; elimination of erosion is thus the safest preventative. It is more difficult to prevent recirculation of the hot gases, and reingestion; but as a result of research on this, configurations giving acceptably low intake temperatures have been evolved.

Finally, jet deflection can materially assist acceleration through the transition phase; a deflection of 15° gives a thrust of one quarter of the weight, with only a small ($3\frac{1}{2}$ per cent) loss of lift. A simple, light-weight spherical nozzle has been developed which can achieve this degree of jet deflection; alternatively, in some aircraft designs, a support which allows a small degree of swivelling of the engine can be employed.

5.2. Blade vibration and flutter

A reed shaken with the wind — MATTHEW 11, 7

As a general rule, engineering research work is directed to the discovery of solutions of existing problems: diagnosis rather than prognosis is usual. The work I am about to describe, however, was more in the nature of prognosis.

Cases have been reported of the failure, in what appeared to be a pure bending mode of vibration, of the blades of gas turbine rotors, and various attempts have been made to explain such occurrences. Dr. D. S. Whitehead of Cambridge studied in detail the possibility of such a phenomenon, and evolved a comprehensive theory⁽¹⁸⁾ from which predictions could be made of the circumstances in which such a form of flutter would occur. Subsequently, failure of turbine blades, during development tests of an actual engine, was found to accord closely with the predictions of Whitehead's theory.

In broad outline, the explanation of the phenomenon is as follows. Consider a (two-dimensional) cascade of blades which produces a uniform finite deflection of the flow through them, so that all blades are under load. Then any one blade lies in a velocity field having a gradient between its two neighbours. Movement of the central blade concerned in the direction of the row then implies that the relative gas speed, and hence the force, will change. The usual Wagner circulation effect produces, however, a phase lag between force and displacement which enables energy to be extracted from the air; when this energy equals that dissipated by aerodynamic damping, a critical condition clearly results. The force change due to translation in this case is analogous to that due to incidence change, with appropriate change of phase angle, in a classical bending-torsion flutter problem; it is interesting to note that in the present case only one degree of freedom is required, but that on the other hand the blade must be subject to a finite mean load.

Of course, if all the blades move in phase with equal amplitude, there is no relative motion between them and no instability; and it is unlikely that a single blade would vibrate by itself. However, if it is pre-supposed that all blades move with a phase difference between them which increases progressively along the cascade, instability can clearly result; and in fact the prediction of the Whitehead theory is that about 45° phase angle between the motions of two neighbouring blades gives the most critical condition.

There are, of course, many parameters in this problem: gap-chord ratio,

stagger, frequency parameter, inlet and outlet angles, and phase difference among them. To deal with these comprehensively a computer programme was written. It appears that, in any given working condition, the critical variable is frequency parameter $\omega c/V$. If an instability occurs the frequency parameter must be increased; since usually to vary c or V would mean a major redesign, this means the blade natural frequency must be increased. This is clearly a problem for which materials of high specific stiffness would be of great value. Alternatively, control over the phase difference between neighbouring blades, e.g. by the use of lacing wires, may be employed.

Whitehead has also considered flutter in a single torsional mode of blade vibration; conditions here are somewhat different, but the critical criteria can be presented in a similar way. However, while his theories are in many ways comprehensive, there are further aspects needing enquiry: of these perhaps the most important are compressibility effects, three-dimensional effects and mechanical damping. All in all, this is an important and rewarding research.

6. SPECIAL TOPICS

6.1. Acoustics, noise, and vibration

A dreadful sound is in his ears — JOB 15, 21

With the rapid and enormous increase in the power of aircraft engines, the problem of noise has assumed alarming proportions in the past few years and has given rise to a great deal of research work, both experimental and theoretical; the latter may be said to derive, for the most part, from Lighthill's classic investigation^(19,20).

I want now to refer briefly to the work carried out at Southampton University under Professor E. J. Richards, whose Institute of Sound and Vibration Research is one of the acknowledged world centres in this field of enquiry. Following initial research grants from the Ministry of Aviation to the University in 1951, work began on the mechanism of discrete frequency sounds emanating from over-choked jets, and on notched and ejector nozzles for sound reduction. Later, as the research team grew, studies began of the noise of axial compressors and of the effects of pressure fluctuations, both in boundary layers and on the surfaces of slender wings under their vortex systems. The latter led in turn to studies of noise associated with the vortex systems of helicopter rotors, of the associated blade vibration, and of the phenomenon of slap. Throughout this period, much attention has also been given to the sonic boom.

The establishment of a central body of knowledge on these topics led, in 1963, to the establishment of the Institute of Sound and Vibration Research

to concentrate on postgraduate studies in the subject. The teams concerned with the topics I have cited, and with matters deriving from them — correlation, structural damping, the theory of structural fatigue and crack propagation under acoustic loads, and so on — have been supplemented by others. For example, subjective work on sonic booms has been extended to all kinds of impulsive sounds, and annoyance studies to those of deafness; for this research an Audiology section has been set up, which employs physicians as well as physiologists, scientists and engineers, and which has received a large grant from the Medical Research Council. The Institute has also begun work on such things as the noise of commercial fans and compressors, of diesel engines, textile machinery and even computers: these are all good examples of the 'spin-off' from aviation into other technologies.

Space allows me only two illustrations of this work. The first is concerned with sonic booms (Fig. 17). The simulation of sonic booms for laboratory study is no easy matter; but at Southampton special sealed headphones have

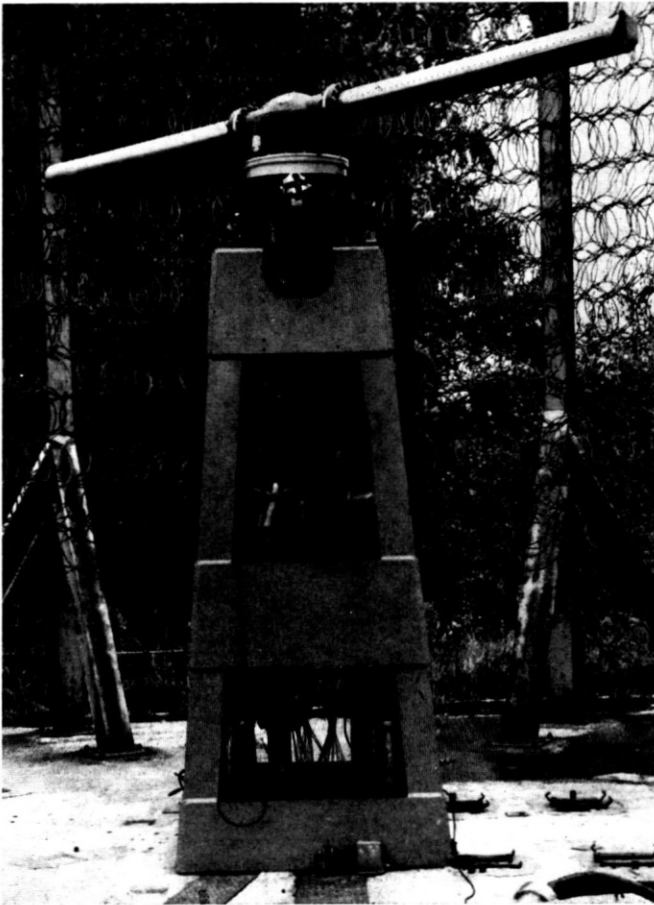


FIG. 17 — Sonic boom rig

been developed in which various kinds of sonic boom signature are reproducible. A jury of listeners has compared relative loudnesses of these booms with standard continuous noise; it has emerged that the significant factor in a boom is the rate of rise of the pressure jump. Since this rate of rise may be affected by, for example, low level turbulence, it seems that the equivalent

loudness of a boom may vary by as much as 15 dB in a distance of 100 yards: thus the overall assessment of the annoyance of a boom will require a good deal more study.

The second illustration concerns acoustic fatigue, a topic in which there are a number of separate but closely allied fields. Recent emphasis has been on the development of computational systems for dealing with acoustic loads on typical aircraft structures; theoretical and experimental studies of the damping — and methods of increasing damping — in stiffened skin structures are in hand; work on fatigue relates to random loading (e.g. from jet noise) on shells and to crack propagation in tensioned plates. Finally, the laboratory work is supplemented by tests on jet aircraft. As a result, data sheets are in



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FIG. 18 — Controlled-circulation rotor rig

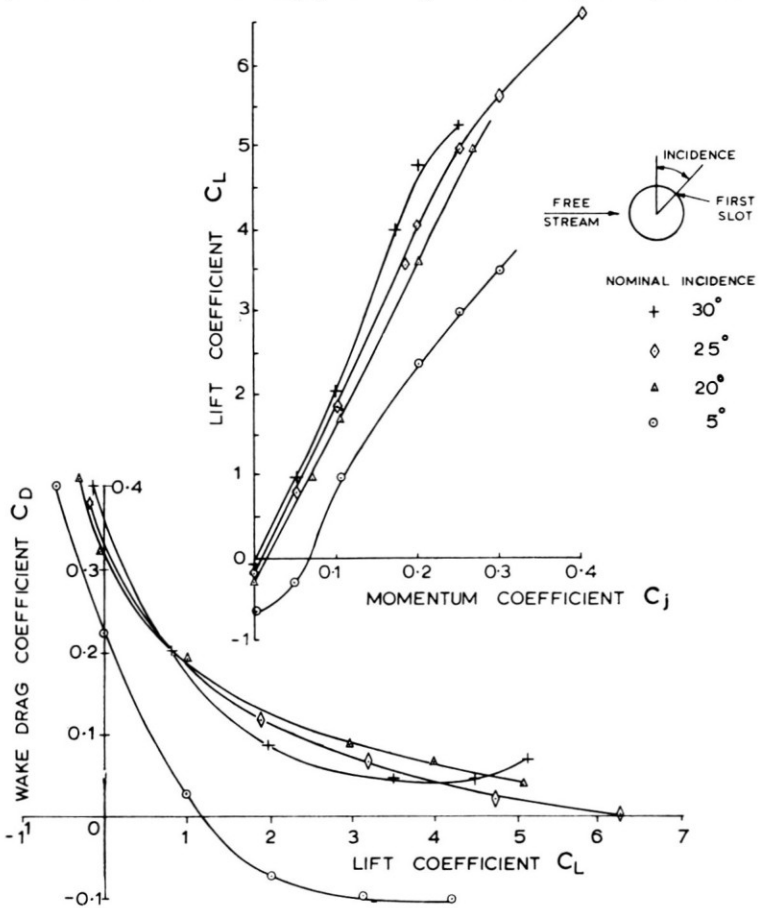
preparation which are shortly to be published by the Royal Aeronautical Society.

A full description of the work at Southampton was given by Professor RICHARDS in the Eighth Lanchester Memorial Lecture.⁽²¹⁾

6.2. The controlled-circulation rotor

Make them like a wheel — PSALM 83, 13

In recent years, the National Gas Turbine Establishment has conducted a continuing research on the integration of lift and propulsion systems. One interesting and ingenious offshoot of this work is the controlled-circulation rotor developed by Dr. I. C. Cheeseman and his collaborators. In its initial form, the rotor consisted simply of a rigid circular cylinder, as shown in



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FIG. 19 — Lift and drag of a circulation controlled circular cylinder

Fig. 18. Circulation round the cylinder, and hence lift, are generated by blowing compressed air from narrow spanwise slots, appropriately positioned and directed; the rotor itself can be made to revolve either by a mechanical drive or by tip blowing — the latter method gives no torque reaction. In the rig shown, the rotor diameter is 12 ft. and the cylinder diameter 5.6 in.; there are no hinges, since the lift can be controlled through control of blowing.

Wind tunnel tests of the blown cylinder gave results such as those shown in Fig. 19; it is of interest to note that the cylinder lift coefficient, C_L , varies nearly linearly with momentum coefficient, C_j , of the air blown from the slots. Wake drag coefficient, C_D , can be small or negative; it includes, of course, the thrust of the blown air. The blowing 'cleans up' the ordinary zero-lift flow round a cylinder to a remarkable degree; Fig. 20 shows a comparison of the experimental and theoretical pressure distribution round a cylinder

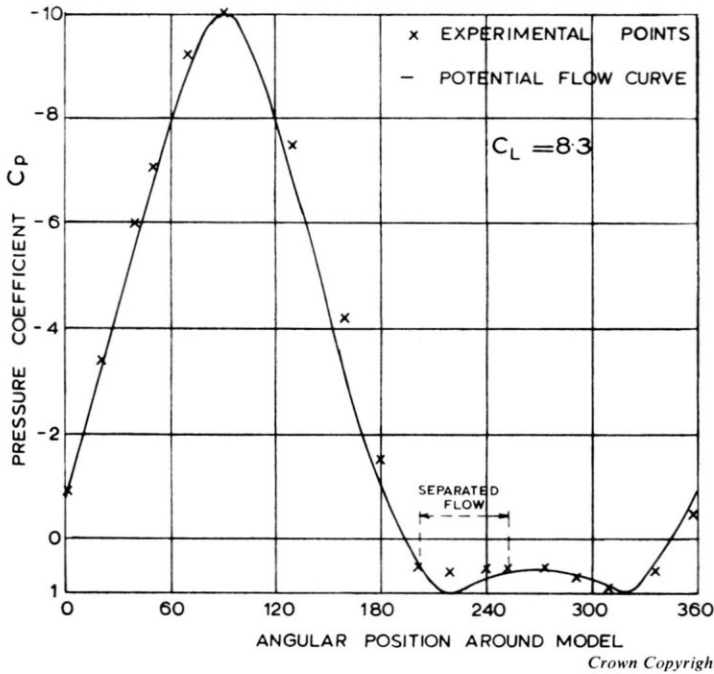


FIG. 20 — Pressure distribution at high lift

with a circulation giving a lift coefficient of 8.3. The very small region of separation, compared with the well-known zero-lift case, should be noted.

It is of interest to list some of the virtues of the blown circular cylinder as a basis for a lifting rotor:

- (i) High C_L is achievable, requiring small cylinder diameter.
- (ii) The cylindrical section is structurally suitable for non-articulated rotors.

- (iii) Cyclic blowing control, even in forward flight, can make lift independent of azimuth angle.
- (iv) Lift is insensitive to gusts, since the lift-incidence slope is virtually zero.
- (v) If forward flight is wing-borne, the blown rotor can be stopped and parked without the difficulties facing conventional rotors.
- (vi) Rigid blades require only small clearances and little maintenance.
- (vii) Tests of the N.G.T.E. rotor in the R.A.E. 24 ft. wind tunnel showed that the ratio of lift force to slot thrust varied only slightly (lying between about 30 and 40) with advance ratios up to about 0.5 and lift coefficients up to 5.

There is, of course, a reverse side to the coin. For example, to avoid compressibility effects, the tip speed of the rotor must be kept low, and this in turn leads to high induced power. In an attempt to overcome this difficulty the N.G.T.E. has experimented with a rotor in which the section changes with increasing rotor radius from a circle to an ellipse. This means compromising some of the virtues listed above; but most good engineering involves compromise.

This brief account may be completed by Fig. 21. It represents a B.A.C.



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FIG. 21 — Converted B.A.C. One-Eleven

One-Eleven aircraft 'converted' to a twin rotor VTOL machine. It is calculated that the aircraft is able to hover at maximum A.U.W. at an altitude of 5,000 ft. at I.S.A. plus 20°C on one Spey engine and that, including the weight

penalty of the rotor installation and normal reserves, the range at full payload, with vertical take-off and landing is 300 n.m.

6.3. Surface effect machines

One is so near to another, that no air can come between them — JOB 41, 16

Since the invention of the Hovercraft by Christopher Cockerell, a considerable body of research work has been built up in the United Kingdom; it is perhaps open to question whether it can properly be described as aeronautical research, but I regard that issue as unimportant: the device has attracted the attention of so many aeronautical engineers in the industry, establishments, and universities that it has quite properly come under the scrutiny of the A.R.C.

Perhaps the greatest fillip to the progress of the Hovercraft as a practical vehicle was the development of the flexible skirt; this itself has many facets on which investigations have been required. Stability and control — two attributes perhaps less closely related for Hovercraft than for aircraft — are still actively being studied, and require knowledge of both internal and external aerodynamics. And methods of propulsion are still under development.

The R.A.E. has borrowed ideas from both Hovercraft and rocket practice to look into the possibility of building inflatable surface effect machines for the transport of heavy weights over difficult terrain; the structure, which may be of various kinds, is stabilised by internal pressure, and internal pressure also provides the air cushion for movement. Finally I must mention a research conducted at the College of Aeronautics on the so-called 'ram-wing' effect, in which the dynamic pressure resulting from forward movement provides part of the pressure of the air cushion in surface effect machines.

6.4. Industrial aerodynamics

The wind bloweth where it listeth — JOHN 3, 8

Diversification is the order of the day in aviation, and just as the A.R.C. has taken note of surface effect machines, so it has given some consideration to industrial aerodynamics. Aviation has, of course, been for years the leading technological industry, and its influence on industrial structures and power has for long been considerable⁽²²⁾. Industrial aerodynamics has come later, but in the past ten years has become well established as a new science. It has recruited its staff largely from aeronautical engineers; but I think it may well, before long, requite its mother science by giving back to aviation the fruits of its work on aeroelasticity and on the structure of the natural wind. Certainly a considerable effort is now deployed in industrial aerodynamics; the symposia organised in 1963 by the N.P.L. and last year by the Royal Aeronautical Society⁽²³⁾ gave evidence of wide and active interest in the subject.

Industrial aerodynamics is concerned with wind effects on large structures, as well as with the many but more mundane problems of internal flow in pipes, heat exchangers and so forth. Externally, it is the aerodynamics of separated flow and vortex generation which are involved, since most of the structures affected are bluff bodies. Some of the most difficult but most interesting problems are those of aeroelasticity; unstable oscillations of suspension bridges, conductor cables, or steel chimneys pose the questions to be answered. Here the structures are large, heavy, elastic and poorly damped; if there is a critical condition it implies that an oscillation can in each cycle extract a quantum of energy from the wind: the force-displacement relation is usually non-linear, so that a limit cycle oscillation results. One such phenomenon has been shown to involve forces similar to those which produce 'swing' of a cricket ball.

From oscillations of chimneys it is a small step to the efficient dispersal of effluent gases from chimneys and funnels; this is an area of research requiring far more knowledge than we possess at present of the structure of the natural wind — its profile, gustiness, and the scale and intensity of the turbulence in it.

British work in this field has its focus at the N.P.L. in the group headed by C. Scruton; but many universities and research associations are actively interested, as well as the Meteorological Office. At one time, too, the Ministry of Fuel and Power was examining various types of windmill for the generation of power; there is now, however, much less activity in this field in the United Kingdom than in many other countries. I have described some of the problems of industrial aerodynamics in the First Nilakantan Memorial Lecture read before the Aeronautical Society of India⁽²⁴⁾.

7. LINQUITUR UT PLURA ESSE INUESTIGANDA PUTEMUS

Wise men lay up knowledge — PROVERBS 10, 14

At the conclusion of this lecture I am more than ever conscious that no mention has been made of many excellent researches: for example, the achievements of the Blind Landing Experimental Unit should surely have been described. Perhaps my audience can be persuaded that the lecture is like a milliner's shop window, with only one or two hats on show to whet the appetite; there are very many others, just as good, inside.

If this is accepted, it will be recognised that there is a large research programme in being in the United Kingdom. Unfortunately, my lecture is being delivered, not only in the Centenary Year of the Royal Aeronautical Society, but also in a year of serious financial stringency, when we have been told that British effort in aviation must be reduced. It is my view — and here I speak personally, and not as the Chairman of the A.R.C. — that whatever else happens, research should be maintained at least at its present level. Research

is the *fons et origo* of all new technological developments, and to opt out of research is to fail to sow the seed, without which there will be no future harvest.

Research, in the nature of things, should be prosecuted over the broadest possible front, whether or not a useful outcome can be foreseen. There are, of course, areas in which we are actively interested which need continuing directed research: to give only two examples, helicopters and the Concorde. No one, I suppose, can deny that the helicopter is today a vital link in the aviation chain: it needs research, from the neglected subject of aerofoil sections for rotor blades to transmission systems, from new forms of gearing to the convertible rotor proposed by R. Hafner. Regarding the Concorde and future supersonic developments, we need further aerodynamic studies of slender wings, of vortex stability, of skin friction, wave drag, stability and control; fatigue, creep, and aeroelastic effects need much more work; nozzle and intake efficiencies must be improved — the list is unending.

On the other hand, there are areas where we are not at present so actively engaged, and my plea is that we must not abandon fundamental research in these areas. On the contrary, even if we do not contemplate development and production, research should be actively pursued at least to the hardware stage: thus, for example, research aircraft are better than none at all. This will cost money, and there are those who argue that if we cannot see a useful outcome for research, we should not put our resources into it. I would remind them of the reply made by Michael Faraday to the lady who asked him, after one of his early demonstrations at the Royal Institution, what was the use of electricity: he answered, 'Madam, what is the use of a new-born child?'

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